HEAVY MOVABLE STRUCTURES, INC.
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Hood River Lift Bridge
Unique Solutions to Interesting Problems

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**MARRIOTT'S RENAISSANCE HOTEL AT SEAWORLD
ORLANDO, FLORIDA.**

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Introduction

In December 2015, The Port of Hood River (POHR), which acquired and has operated the Hood River-White Salmon Interstate (Hood River) Bridge since the 1950s, notified its insurance company of their intent to file a claim for damage that may have resulted from a barge or vessel strike of the north pier of the bridge, near the water line in September 2015.

Wiss, Janney, Elstner Associates (WJE) was engaged by POHR's insurance company to make an independent assessment of the operational reliability problems with the structure, and more specifically determine if a vessel allision could have caused or contributed to the problems the bridge was experiencing. To complete the evaluation of the structure, WJE would investigate the bridge foundation and the bridge superstructure, while Stafford Bandlow Engineering, Inc. was engaged to provide engineering services to determine if the mechanical and electrical systems had sustained any damage.

During the initial visit to the bridge, Stafford Bandlow engineers were unable to witness the operation of the lift span due to a previous testing mishap. This testing mishap resulted in the bridge being out of service to marine traffic due to damaged span guides that had not been repaired. As a result of this initial inspection of the bridge, Stafford Bandlow Engineering (SBE) engineers concluded and reported that there was no evidence that the operational problems with the lift span were caused by a vessel striking the bridge. Further, it was noted that the lift span lacked the necessary monitoring, interlocks, safeguards, and controls to prevent a skew failure similar to the failure that caused damage to the span guides.

Recognizing Stafford Bandlow Engineering's expertise with the mechanical and electrical systems of this type of movable bridge, The POHR retained SBE to design and implement a low-cost, but safe and effective interim skew monitoring and control system that allowed the lift span to be operated without the concern of a skew failure. SBE also oversaw the testing and commissioning of the new skew control system and returned the lift span to service.

Once the lift span was safe to operate, SBE investigated and solved a unique operating issue that manifested itself in the form of random and concerning pulsations during operation.

History and Description

The Hood River-White Salmon Interstate Bridge is a vital Columbia River crossing in the central Columbia Gorge bi-state region connecting Hood River, Oregon with the communities of White Salmon and Bingen in Washington State. The Bridge, nearly one mile long, is constructed of steel trusses on concrete pier supports with very narrow lanes (lanes are only 9 feet, 4.75 inches wide, with a 14 feet, 7 inches height restriction). The Bridge is limited to a total gross weight limit of 80,000 lbs, with each single axle limit of 20,000 lbs. The Bridge serves an average of 4 million users annually and is open every hour of every day, except during periods scheduled maintenance or emergency closures.

Often referred to simply as the Hood River Bridge, the aging structure is deficient by modern standards, but remains an essential transportation link between Oregon and Washington. The Bridge's narrow lanes (9 feet, 4 inches) were characteristic of the 1924 era in which it was built, when horse-drawn carriages and Model-T's crossed the Columbia on what was then a state-of-the-art structure.

The Hood River Interstate Bridge was essentially rebuilt in 1938 when the construction of the Bonneville Dam caused water levels to rise and made the addition of a lift span necessary. Nowadays, the lift span is raised several times a year and has become the iconic symbol of the historic bridge purchased by the POHR in 1950.

The POHR takes its responsibility to assure the bridge's safety, operation and useful life into the foreseeable future extremely seriously, planning ahead and taking proactive action. The POHR has invested over $22 million in capital improvements and maintenance in the past two decades, and expects sizable investments in the near and long term to keep the structure functional and operating safely into the future.

The Port of Hood River continues to work with state and federal agencies as a supportive partner in the effort and pursuit of bridge replacement. As years pass, the cost of bridge replacement, currently estimated at $250 million, continues to increase, meaning that funding for a new bridge will likely require pooled resources among local, regional and federal governments and agencies.[1]

The movable span of the bridge is a through truss tower drive vertical lift bridge. The bridge spans 262 feet 6 inches between live load supports and provides a clear channel width of 246 feet. When open for vehicular traffic the vertical clearance is 54 feet and after rising 81 feet to its normal open lift height the bridge provides 135 feet of vertical clearance.

The bridge is operated from a control house located within the limits of the north tower of the bridge. Due to the narrow lanes on the bridge, all bridge operations and maintenance personnel are transported to the movable span by Port of Hood River Personnel.

Bridge machinery consists of span drive machinery, span support machinery, span lock machinery, span and counterweight guides and air buffers. The bridge power and control systems consist of a motor control center (MCC), an operators control console, a control relay panel and termination cabinets housed

[1] "Hood River Bridge", Accessed July 1, 2018, https://portofhoodriver.com/bridge/.

in the bridge operators house. A code compliant vehicular traffic control system consisting of traffic lights, warning and barrier gates is provided at both bridge approaches. Marine traffic navigational aids are provided at the bridge in the form of navigational lighting.

The majority of the machinery dates to original construction of the lift span in 1938. The high speed end of the span drive machinery (motor, brake, high speed reducer and coupling) and the entire electrical system was replaced in circa 2000. The span drive motor is a two speed motor with no speed control. Due to ongoing concerns related to skew control the high speed setting for the motor has been disabled. As a result the motor operates at 600 rpm and raises the bridge to its full lift height in approximately 13 minutes.

Basis of Insurance Claim

The Port of Hood River had reason to believe that the bridge had been struck by a vessel at the north pier of the lift span. This evidence included the following:

- An apparent recent scar in the concrete at the north pier.
- Credible witness and navigation records showing a stalled tow under the bridge for 15 minutes coincident with the witnesses' observations (these later turned out to be erroneous).
- Notably rougher bridge operation following the suspected allision.
- An engineer's report indicating changes in the operational performance of the lift span as observed in October 2015 as compared to the baseline documented in 2014 as follows:
  - Grinding of the span guides on the guide rails
  - Vibration of the lift span when operating up and down
  - Observed lift span misalignment when lift up out of the bearings.

The above information led the Port to believe that the bridge had been struck by a vessel and that the vessel caused damage to the bridge.

Accident Investigation

Initial Contact

You never know where your next job will come from and once in a while the phone rings and you have an interesting assignment that wasn't even on the radar. On December 29, 2015 Brian Santosuosso from Wiss Janney Elstner Associates (WJE) contacted Paul Bandlow at Stafford Bandlow Engineering (SBE) to discuss the Hood River Bridge and a potential project that he wanted the firm to get involved with. WJE had been contacted by an insurance company regarding the Hood River Bridge. The insurance company had been notified of the Port of Hood River's intent to file a claim for damage sustained to the lift span of the bridge resulting from a vessel allision at the north pier of the lift span. The insurance company wanted WJE to determine if the reported damage was the result of the vessel allision. WJE wanted SBE to provide engineering services to determine if the mechanical and electrical systems had sustained any damage. WJE would investigate the bridge foundations and the bridge superstructure. This was an unusual assignment and one that SBE could not pass up.

The initial work began with the usual process of gathering all available information and reviewing this information to get a basic understanding of the bridge and more importantly to find out what if any facts existed with regard to the damage claim. In addition SBE needed to develop a scope of work for the field inspection and coordinate the inspection with WJE.

Scope of Work

SBE proposed to do the investigation work in phases as required. The scope of work for Phase 1 included the following:

1) Review available documentation for the bridge including inspection reports, drawings and other information as deemed necessary to determine the condition of the bridge prior to the alleged impact and to understand the extent of the damage (if any) that occurred as a result of the impact.
2) Conduct a field inspection of the bridge's mechanical and electrical systems to determine if there was evidence of damage to the bridge mechanical and electrical systems that was consistent with an impact to the north pier. The scope of the inspection included the following:
    a) Verification of the mechanical and electrical findings in the following reports to the extent that was warranted to determine if changes occurred that were the result of an impact with the north pier. We did not measure machinery parts to determine wear as it is not likely that significant wear would have resulted from an impact. Rather we inspected the various mechanical and electrical systems for conditions such as impact damage and changes to alignment.
        i) Hood River Interstate Bridge over the Columbia River, Hood River, Oregon. Mechanical and Electrical Inspection Report, February, 2014.
        ii) Pier Impact & Lift Span Assessment. Draft Report, Hood River – White Salmon Interstate Bridge, Port of Hood River, Hood River, OR, December 14, 2015.
    b) Visual inspection of the mechanical and electrical systems of the movable span of the bridge with an emphasis on those systems that may have been affected by the alleged impact. Our inspection was limited to areas of the bridge that do not require special access equipment.
    c) Measurements of alignment and clearances that may have been affected by an impact to the north pier. During Phase 1 of the investigation measurements were limited to those measurements that could be taken will hand tools ordinarily used in the inspection of movable bridge mechanical and electrical systems. We did not recommend special surveys for the Phase 1 inspection but advised our client that special survey work might be required based on the finding of the Phase 1 of the investigation. If special surveys were required this work would be done as Phase 2. The Phase 2 work was not required.
    d) Operational testing of the bridge to include a minimum of 4 complete bridge operations. Electrical measurements to determine the operating characteristics of all motors as part of the operational testing.
    e) Installation of strain gages on the span drive machinery to determine the bridge operating loads for correlation with the electrical test data, to determine system imbalance and to determine system friction.
3) Preparation of a comprehensive report of the findings of the investigation to include the following:
    a) Commentary on prior reports referenced above.
    b) Inspection findings.
    c) Conclusions on findings with emphasis as to whether the findings were likely to have been caused by an impact to the north pier.

d) Recommendations for further investigation as required.
e) Recommendations for work that may be required to return the bridge to a reliable operating condition.

In order to conduct the investigation SBE informed their client that they assumed the following:

1) The bridge would be operational for the full lift height at the time of our inspection.
2) The bridge would be operated for a minimum of 4 complete opening cycles throughout the course of the inspection.
3) SBE could complete the inspection in a maximum of three 8 hour days at the bridge.
4) Bridge maintenance and operations personnel would be available to answers questions regarding the operation of the bridge.

Field Work

The initial investigation was conducted by Paul Bandlow (mechanical investigation) and Gareth Rees (electrical investigation). The investigation was conducted from May 11-13 2016. Due to a problem that occurred as part of a separate investigation by others the bridge was not operational at the time of the inspection and therefore some of the scope items including electrical recordings during operation and strain gage testing were not performed as part of the field work. Despite the non-operational status of the bridge, sufficient work was performed to provide an opinion regarding damage to the mechanical and electrical systems that could have resulted from an allision with a marine vessel.

Mechanical

The mechanical inspection included the following:

1) Visual inspection of trunnion bearings and measurement of trunnion bearing clearances and journal to bushing alignment.
2) Visual inspection of pinions and ring gears to determine alignment and for evidence of changes to alignment and measurement of pinion teeth to determine wear.
3) Visual inspection of speed reducer output shaft couplings.
4) Visual inspection of speed reducer and verification of oil level.
5) Visual inspection of wire ropes.
6) General observation of the counterweight.
7) Visual inspection of the counterweight guides.
8) Visual inspection of accessible wire rope sockets at the counterweight.
9) Visual inspection and clearance measurements of the upper span guides and span guide rails.
10) Visual inspection of the counterweight ropes and rope terminations.
11) Relative tensions in the counterweight ropes using the fundamental frequency method.
12) At the bottom chord of the bridge, the lower span guides, span guide rails, and live load supports were inspected.
13) Visual inspection of the intermediate supports and clearance measurements at the intermediate supports.
14) Visual inspection and lateral clearance measurements at the span lock tongue and clevis.

Electrical

The electrical inspection work concentrated on a determination of the status of the power and control systems of the bridge to safely and reliably operate the bridge, performing an assessment as to whether the control system had been compromised by the reported allision event and if any physical damage was visible to the bridge electrical equipment and devices that could be attributed to the reported event. The electrical inspection included the following:

1) Visual inspection of the bridge relay panel.
2) In-depth inspection of the bridge motor control center.
3) Visual inspection of the operator's control console.
4) Visual inspection of termination cabinet for all field devices.
5) Visual inspection of conduits, wireways and cable trays in the operator's house.
6) Visual inspection of the span drive motors and brakes.
7) Visual inspection of the position resolvers and rotary cam limit switches.
8) Visual inspection of the span lock actuators and limit switches.
9) Visual inspection of the span seated limit switches.
10) Visual inspection of general bridge lighting, electrical power and control distribution raceways and cabling.

Significant Findings

The mechanical findings presented in this paper are findings associated with the primary purpose of the investigation which was to determine if there was evidence to support a claim that the bridge was struck by a vessel with resulting damage to the bridge. Other mechanical findings that may be significant in general but are in not related to the primary purpose of the investigation are not presented. The electrical findings include those findings that could adversely affect the operation of the bridge.

Mechanical

Clearance measurements and bushing to journal alignment at all trunnion bearings were found to be within acceptable limits. The maximum clearance was 0.027" and is within the limits of an ANSI RC9 fit which is commonly cited as a limit for rehabilitation. Maximum taper over 10" was 0.005" and is considered acceptable. All clearances were found at the top of the bearings. Trunnion bearing measurements are tabulated in Table 1 below.

Table 1: Trunnion Bearing Clearance Measurements

Trunnion Bearing Clearance Measurements			
North Tower			
Bearing Identification	Max Clearance	Location	Taper over 10"
West Outboard	0.014"	Top	0.000"
West Inboard	0.019"	Top	0.005"
East Outboard	0.011"	Top	0.002"
East Inboard	0.025"	Top	0.005"
South Tower			
Bearing Identification	Max Clearance	Location	Taper over 10"
West Outboard	0.009"	Top	0.005"
West Inboard	0.010"	Top	0.002"
East Outboard	0.019"	Top	0.005"
East Inboard	0.027"	Top	0.004"

The racks and rack pinions are the only open gearsets. Visual inspection as well as cleaning of representative gear teeth indicated that the gear tooth wear pattern was consistent with the pattern in the gear lube indicating that there was no change to the alignment of the racks and rack pinions.

Figure 2: General view of rack and rack pinion.

Figure 3: Rack pinion tooth cleaned for inspection.

Figure 4: Rack teeth lube pattern

Figure 5 shows a picture of a typical trunnion bearing. No movement was noted between any of the trunnion bearings and the supporting structure.

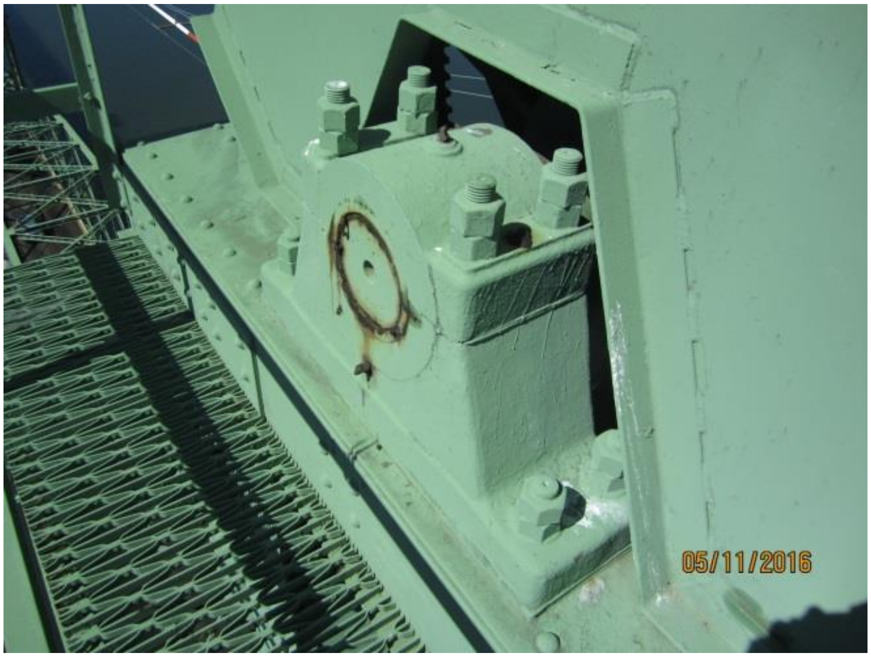

Figure 5: Typical trunnion bearing. There was no evidence of movement between the bearing and the supporting steel or between the bearing cap and base.

No significant wear was noted at any of the counterweight guides.

Damage was noted at all upper span guides in the longitudinal direction. This damage did not appear recent and was likely due to an excessive skew condition. Evidence of heavy contact was found at the southeast span guide location where the rivets that secure the guide rail to the structure are worn. The guide rail at this location was not worn indicating improper adjustment of the lower guide that allowed the guide to contact the rivets prior to contacting the guide rail. The lower span guide at this location was recently replaced and the original guide was not available for inspection.

Figure 6: Southeast span guide rail. Note damage to rivets that secure the guide rail to the structure at the right side of the guide rail but no damage to the guide rail.

Figure 7: Close up of photo in Figure 6

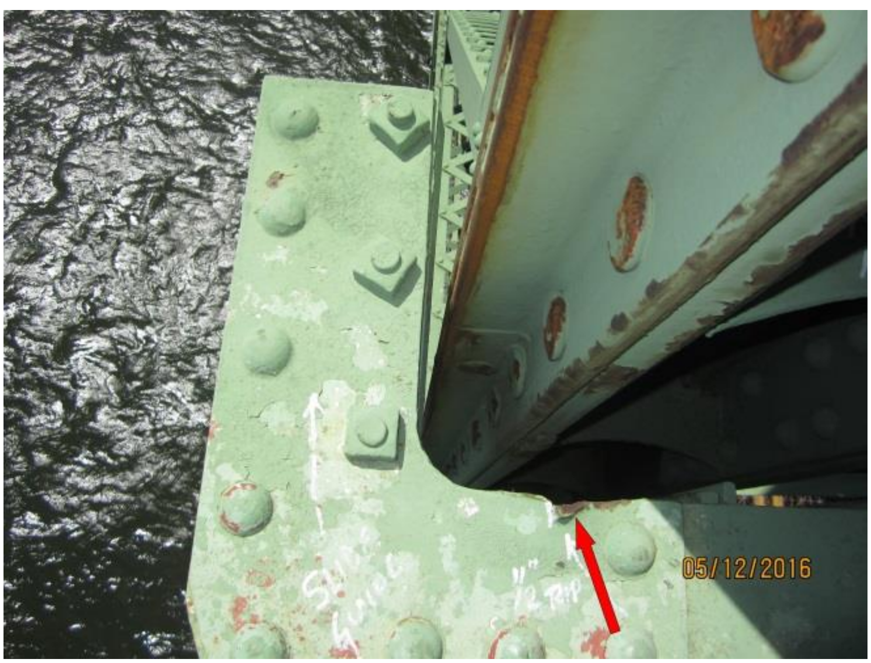

Figure 8: Southeast upper span guide. Note damage in longitudinal direction due to over-skew condition (arrow).

Wire rope tension measurements were taken using the fundamental frequency method. This method of measurement provides relative tensions and not absolute values for tension. Typically for a new installation, the ropes would be adjusted to within 5% of the average tension for the ropes at each corner of the bridge (NW, NE, SW, and SE). At the time of our investigation all but two ropes were within 10% of the average tension at each corner which is acceptable. One rope at the SE corner varied from the average tension at that corner by 14.9% and one rope at the SW corner varied from the average tension at that corner by 17.0%. The measured distribution of rope frequencies is not usual based on our experience measuring wire rope tensions on vertical lift bridges.

Rope tension measurements are tabulated in Table 2.

Table 2: Hood River Bridge Rope Tension Measurements - May 11 and 12, 2016

Hood River Bridge Rope Tension Measurements - May 11 and 12, 2016												
Location	$Time_{40}$ (sec.)		Avg. Time	Tension (kips.)	% Difference from Avg.	Location	$Time_{40}$ (sec.)		Avg. Time	Tension (kips.)	% Difference from Avg.
SE	1st	2nd				**SW**	1st	2nd			
1	14.76	14.86	14.81	150.9	7.8	1	17.43	17.14	17.29	110.8	17.0
2	15.03	15.02	15.03	146.7	4.8	2	15.22	14.995	15.11	145.1	8.7
3	15.15	15.26	15.21	143.2	2.3	3	15.45	15.44	15.45	138.8	4.0
4	16.7	16.65	16.68	119.1	14.9	4	15.23	15.61	15.42	139.2	4.3
			Group Total	559.9					Group Total	533.9	
			Average Tension	140.0					Average Tension	133.5	
			Average Time	15.4					Average Time	15.7	
Location	$Time_{40}$ (sec.)		Avg. Time	Tension (kips.)	% Difference from Avg.	Location	$Time_{40}$ (sec.)		Avg. Time	Tension (kips.)	% Difference from Avg.
NE	1st	2nd				**NW**	1st	2nd			
1	15.19	15.11	15.15	144.2	5.9	1	15.4	15.41	15.41	139.5	0.3
2	16.08	16.11	16.10	127.8	6.1	2	15.69	15.68	15.69	134.6	3.8
3	16.39	16.31	16.35	123.8	9.1	3	15.43	15.32	15.38	140.1	0.2
4	14.88	14.95	14.92	148.8	9.3	4	15.09	15.11	15.10	145.2	3.8
			Group Total	544.6					Group Total	559.4	
			Average Tension	136.2					Average Tension	139.9	
			Average Time	15.6					Average Time	15.4	
Note: Tensions are relative and are not based on the unsupported rope length for this bridge. As such, tension values are only useful in determining variation in tension among the ropes.											
$Time_{40}$ - Period for 40 oscillations as measured via stopwatch (0.01 second accuracy)											

The north end of the movable span had shifted west relative to the north tower. Evidence of this included clearance at the northwest span guides, contact between the west side of the northwest live load rocker and the fixed support and contact between the northeast span guide and the northeast span guide rail.

Figure 9: Northwest lower span guide. The span guide is not in contact with the guide rail.

Figure 10: Northwest live load support. Note evidence of contact with the fixed structure at the left side of the rocker.

Figure 11: Northeast lower span guide. Note the addition of a wedge shaped shim

Although the shift of the span relative to the bridge could have indicated damage due to an impact, there was significant evidence that the observed shift was not a recent condition. The following was noted:

1) A wedge shaped shim, shown in Figure 11, was welded to the northeast guide rail in an attempt to either shift the bridge to the east or to prevent the bridge from moving farther west. The shim had not been recently installed.
2) The north span lock tongue (on lift span) was reasonably well centered in the mating clevis (on pier). Clearance on the east side of the tongue was 3/16". Based on measurements taken during the investigation, if the bridge were centered on the span guides the tongue would not engage the receiver. Therefore the bridge was shifted to the west when the span locks were installed circa 2006.

Electrical

The most significant electrical findings relate to the bridge electrical control system and the inability of the installed control system to properly protect the bridge from damaging events including significant skew events that have caused damage to the structure. The most significant deficiencies include the following:

1) No method of automatically controlling skew was provided in the installed system.
2) No over-skew protection was provided in the installed system to safeguard the movable structure from a catastrophic skew condition failure.

Accident Investigation Conclusions

The investigation found no evidence that an allision occurred that resulted in damage to the bridge mechanical and electrical systems. Therefore there was no basis to substantiate a claim regarding an allision at the north pier of the movable span.

Other conclusions based on our investigation were provided as follows:

1) Lubrication was marginal and improved maintenance was required.
2) Additional weight added to the top of the counterweight was cause for concern with regard to trunnion fatigue, and wire rope and trunnion bearing stresses.
3) The span drive machinery has only one brake compared to two brakes required by AASHTO.
4) The installed brakes apply unnecessary impact loads to the bridge operating system.
5) The wire rope sheaves are smaller than required by AASHTO. While it may not be practical to increase the size of sheaves, the effect of the sheave size on the wire rope stress should be analyzed.
6) The live load supports have significant wear, are not properly adjusted and do not effectively transmit the live load of traffic to the pier.
7) Two of the counterweight wire ropes are not adjusted properly and may require adjustment. Analysis of the wire rope loads should be conducted to see if the variation in the wire rope tensions is a significant concern.
8) The span drive motor was not specified for the prevailing duty. The motors should be capable of being driven by a variable speed drive and provided with controls that are capable of automatically controlling their speed.
9) No method of automatically controlling skew has been designed or installed. This places undue responsibility on the bridge operator to address an operating skew condition and is a potential cause of failure.
10) No over skew protection has been provided to safeguard the moveable structure from a catastrophic skew condition failure.
11) The span lock current monitors are ineffective in protecting the span lock actuators against a catastrophic jam condition and should be replaced with the actuator manufacturer recommended power monitors.

Skew Control System

During the field portion of our work, the Port of Hood River approached SBE and asked if we could work with them to help resolve operational issues they were having with the bridge. This request created a conflict as we were then working as a sub-consultant to WJE who was in turn working for the insurance company. We told the Port of Hood River that we would be happy to work for them if it was acceptable to the insurance company.

The insurance company was fine with us working for the POHR provided that the POHR would not pursue a claim related to the allision based on the findings of the investigation. The POHR agreed and SBE began working for the POHR with our first assignment to implement a skew control system so that the bridge could be safely operated without concern for a severe skew event.

At this point the bridge had been out of service to marine traffic for about 7 months as a result of a failure which occurred during operation. Our investigation revealed that the failure revolved around the inability of the existing bridge control system to recognize, take action, or correct a bridge skew condition. Due to the length of time the bridge was out of service there was urgency associated with getting the bridge back in service. Going the usual route of design, bid, build would require significant time and did not seem appropriate. We suggested and the POHR agreed to have SBE effectively design build a rudimentary but safe and effective skew control system and skew over travel protection system that could be implemented quickly using only SBE forces and a POHR contracted electrician.

The schedule for the implementation of the control system additions and modifications was as follows:

- July 1, 2016 – Begin design of skew control system.
- July 26, 2016 – Begin installation of skew control system.
- August 10-11, 2016 – Successful test operation of bridge.
- September 6-8, 2016 – Install additional bridge protective devices, commission bridge, and place bridge into service.
- November 22, 2016 – Bridge failure due to false skew indication. Bridge out of service to marine traffic.
- November 29-30, 2016 – Failure addressed and bridge returned to full service.
- November 30, 2016 – Present. No additional skew failures reported.

The skew control system provides the following features:

1) The over skew transducer and associated intelligent meter has been arranged to monitor the moving span for skew and has been set to trip the tower drive motors at an angle of skew of 0.2 degrees (11 inches out of level) in either direction (north or south). The bridge control logic has been modified such that it recognizes the direction of skew and configures the logic to enable automatic correction of skew commanded by the bridge operator.

2) Ultimate skew can only occur if the over- skew has failed or a catastrophic failure has occurred to the bridge mechanical system. The ultimate skew consists of a tilt switch that has been set to trip the tower drive motors at an angle of 0.4 degrees (22 inches out of level) in either direction. The bridge control logic has been modified such that it prevents the operator from operating the bridge under an ultimate skew condition and disables the normal bridge drive control functions. In the event of an ultimate skew condition, the operator must inform the designated qualified bridge maintenance person. The designated qualified bridge maintenance person shall switch the bridge control system to maintenance mode using his key to manually operate the bridge to correct the ultimate skew condition and return the bridge to service.

3) The motor starter control circuits for the tower drive motors were revised as part of the control system modification work to install motor current monitoring relays. The relay outputs have been configured to block operation of the bridge unless both tower drive motors are energized.

4) The speed of the span drive motor has been limited to 600 RPM versus the maximum motor speed of 1800 RPM.

System Calibration and Testing

The following testing and associated results were documented as part of the system calibration and testing.

1) Skew Monitoring Control System Modification Testing
   The control system modified wiring was point-to-point checked for continuity against the bridge control system modified drawings prior to energizing the bridge control system. This was completed satisfactorily and all wiring discrepancies re-wired.

   The over-skew inclinometer with its intelligent meter and the ultimate skew tilt switch, both were calibrated and accurately set by programming in accordance with the manufacturer's guidelines.

   The control system was energized and the status of all control system devices checked against the modified drawings for accuracy. The bridge was next raised to a height of approximately 5' followed by returning the moving bridge to its seated position. The functioning of the control system and skew devices were monitored for correct operation. It should be noted that no skew was observed and the over-skew meter skew indication remained unchanged.

2) Skew Device Testing
   Following the successful conclusion of the first partial raising of the bridge to a height of approximately 5', skew device testing was performed. This consisted of forcing the bridge into a skew condition and determining the accuracy of the skew monitoring devices and their metering outputs. Note that the forcing of the bridge into a skew condition was carried out in both directions of skew and was achieved in bridge maintenance mode by only operating a single motor to create skew. The trip points were accurately set and tested for consistency. Both the over-skew and the ultimate skew produced excellent repeatability to within 0.01 of a degree. The accuracy of the skew devices was checked by physically measuring the actual skew and comparing it with the output from the over-skew monitor.

   Following the first successful operation of the bridge to a height of 5' this was repeated to a height of approximately 30' in increments of 5' to determine if skew was an issue in bridge operation and to determine if there were any physical issues associated with operating the bridge.

   The bridge operated smoothly for the most part, however there were periods during travel where the span seemed to stutter. This condition persisted during all test openings of the bridge but did not appear to be caused by the electric drive system for the bridge.

3) Under Current Relay Testing
   The under current relays and their logic were tested to confirm that the bridge could not be operated unless both tower drive motors were energized. All possible reasons for motor failure were tested:

   a) Open motor starter disconnect switch.
   b) Remove starter control fuse.
   c) Trip starter overload.
   d) Disconnect one of the motor leads.

   The relays operated correctly and the bridge could not be operated if any one of the above conditions was applied.

4) Calibrating Existing Height Metering
The existing panel mounted bridge height indicator meters were found to not reflect the true height of the bridge and appeared to be indicating almost two times the actual raised height of the bridge. SBE re-calibrated the height indicators for both towers and confirmed during bridge operation that both indicators were accurately reflecting the actual height of the operating bridge.

5) Test Openings
Test openings of the bridge were conducted following the commissioning of the revised skew monitoring system and the above described adjustments.

The bridge was successfully raised to a height of 66’ with no electrical control problems and no indication of a skew condition. There did appear to be the previously reported stuttering of the movable span for a portion of the raising cycle of the bridge.

Investigation of Operating Issues

SBE mechanical engineers were on-site during the testing for the skew system modifications to record strain during bridge operations. Strain gages were mounted on both rack pinon shafts at the north and south span drive machinery.

During the span operation it was observed that the movable span had a period during the opening cycle where the bridge had noticeable irregular movement. There is also a period during the closing cycle where similar behavior occurred but for a shorter duration and to a lesser magnitude than on the opening cycle. These periods of irregular movement did not occur at the same lift height. On the opening cycle the irregular movement occurred between 7 ft. and 23 ft. and on the closing cycle the behavior occurred between 51 ft. and 47 ft. The movement was characterized by short duration start-stop cycles observed at the counterweight sheave, the rack and rack pinion, and when standing on the movable span during an operation. The start-stop behavior was not noted at the high speed end of the drive. This behavior was noted at both ends of the bridge during the strain gage testing on both days of testing. Figure 12 and Figure 13 for the north and south towers respectively demonstrate the areas of irregular movement.

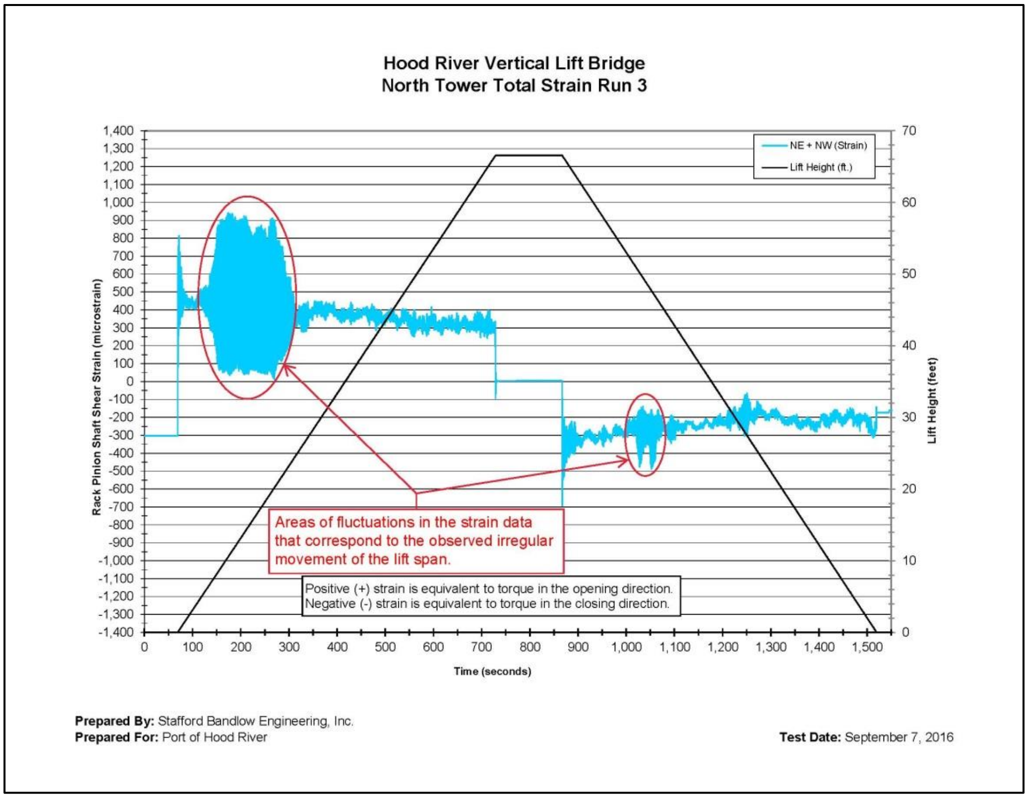

Figure 12: North Tower Strain Data

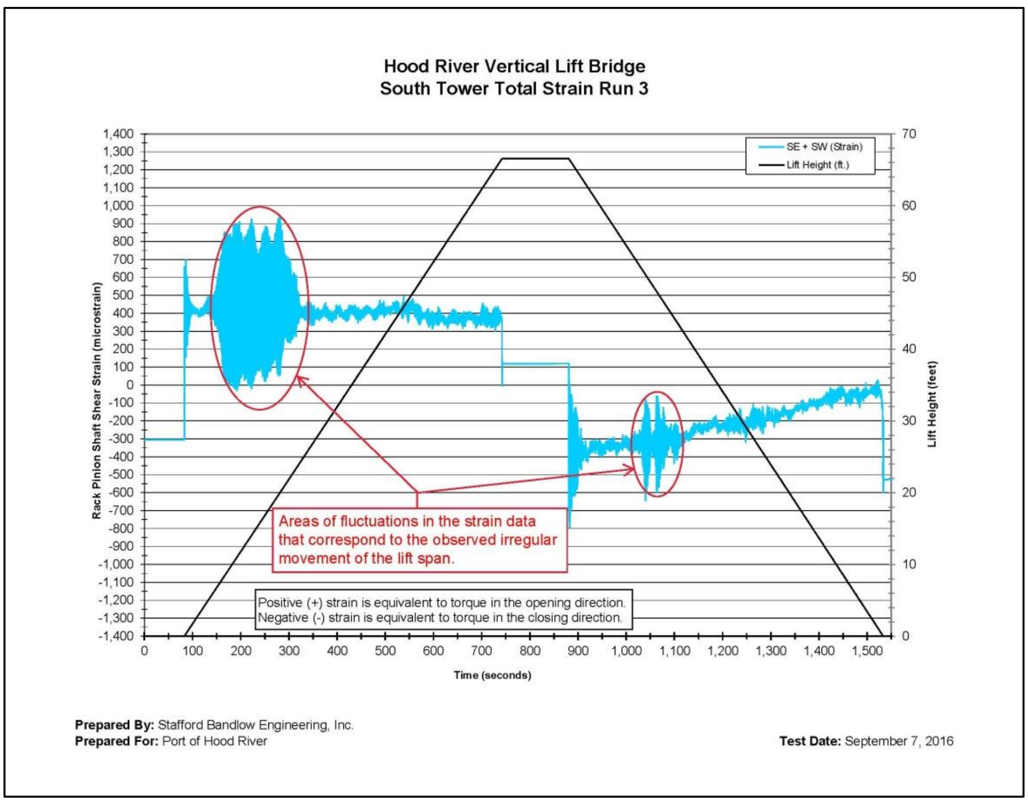

Figure 13: South Tower Strain Data

The observed behavior is somewhat consistent with stick-slip phenomena with the likely source being the trunnion bearings. Typically, some amount of noise is associated with stick–slip conditions however no unusual noises were noted during operation. The observed behavior is clearly seen in the strain gage recordings as a build-up and release of strain. It was noted in the strain gage report that the friction values for the bridge are very high. This friction is from the rack pinion bearing, the rack and pinion gear mesh, the trunnion bearings and the span and counterweight guides. No significant contact was noted at the span and counterweight guides, therefore friction from this source is considered negligible. Since the trunnion bearings are the most heavily loaded bearings, it is likely that the majority of the friction is from the trunnion bearings. It is not clear if the high friction is a factor in the observed behavior.

An attempt was made to eliminate the stick-slip by lubricating the trunnion bearings and rack pinion bearings on the second day of testing. The trunnion bearings at the south tower were lubricated during operation of the bridge by John Mann of the Port of Hood River and the bearings at the north tower were lubricated by engineers from SBE during operation of the bridge. Strain gage measurements were recorded at the north tower to see if the lubrication had any effect on the operation of the bridge. Strain gage measurements were not recorded at the south tower on the day the bearings were lubricated. Although there was a shift in friction values from the northwest corner to the southwest corner the, the overall magnitude of friction at the north end of the bridge did not vary significantly with the application of lubricant.

Later on the last day of testing, while standing on the bridge deck for an operation, it was noted that the start-stop movement nearly went away for one operation but returned on a subsequent operation.

We found no evidence of contact between the span guides or the counterweight guides that could cause the observed behavior. The one difference between this bridge and many of the other bridges we have worked on is the steady wind at the bride site. Throughout the testing the wind was continuously in the 15-25 mph range based on a hand held anemometer. Although we had no evidence that the wind was causing the observed start-stop behavior, lack of other evidence to explain this behavior resulted in the thought that the wind might the cause. Subsequent information from the Port of Hood River is that the start- stop behavior occurred during a period of no wind indicating that the wind is not the source of the irregular movement.

We did not believe that the electrical system was causing the observed behavior.

At the time of the testing we had no explanation for the observed behavior and therefore additional investigation was required to find the source of the problem.

Additional inspection and testing was conducted from October 27- 29, 2017.

All eight trunnion bearings caps were removed and visually inspected with the bridge closed and then again after raising the bridge to observe the bottom half of the journal which is not visible with the bridge closed. The top half (bridge seated) of the trunnion journals was found to be well-polished and in good condition with only minor scoring and light bronze embedment on some journals. The bottom half (bridge seated) of the trunnion journals had light scoring and light bronze embedment. In addition, these areas had minor corrosion and dried lubricant. The corrosion was found to be limited and both the dried lubricant and corrosion were removed at the time of the inspection using emery cloth and Scotch-Brite™ pads.

Figure 14: Typical top half of trunnion bearing journal.

Figure 15: Typical bottom half of trunnion bearing journal.

Figure 16: Typical bottom half of trunnion bearing journal after cleaning.

In addition to the trunnion bearings, the condition of the rack pinion bearings was a potential contributor to friction problems. A clogged lubrication fitting was previously noted at the northwest rack pinion bearing cap. There are four rack pinion shaft bearings with one bearing at the inboard side of each rack pinion. As part of the inspection, the northwest, southwest, and southeast bearing caps were removed by maintenance personnel to permit an in-depth inspection of the wearing surfaces of the bearings. Maintenance personnel were not able to remove the northeast bearing cap due to corroded fasteners.

The condition of the inspected rack pinion bearings varied from fair to poor. The southeast bearing was found in fair condition with ample lubrication and only minor deficiencies. The northwest and southwest bearings were found in poor condition with moderate to heavy corrosion and dried lubrication deposits on the journal. The bearing caps at these locations had evidence of fretting corrosion (due to inadequate lubricant), dried lubrication deposits, and clogged lubrication ports. The northwest and southwest bearings were cleaned to the extent possible with the bridge in the closed position using penetrating lubricant and emery cloth to remove lubricant deposits and corrosion around the circumference of the journal. The depth of corrosive pitting at the journals was significant as the pits could not be removed by hand polishing. After cleaning, the journals were lubricated by hand and the bearings caps were installed prior to operating the bridge.

Figure 17: Northwest rack pinion bearing. There was no evidence of recent lubrication.

Figure 18: Southwest rack pinion bearing. Note the corrosion and heavy pitting on the journal.

Figure 19: Northwest rack pinion bearing after cleaning.

Figure 20: Northwest rack pinion bearing cap. Note clogged lubrication port and lubrication grooves

Figure 21: Northwest rack pinion bearing cap after cleaning.

Although significant work was done on October 27 and 28, 2016 to improve the condition of the trunnion and rack pinion shaft bearings, the operational behavior of the bridge remained problematic as the stuttering behavior remained. The inspection team had run out of ideas and places to look to solve the problem. On a hunch, the inspection team decided to spend the next day flushing the trunnion journals with diesel fuel and polishing the journals with Scotch-Brite™ while operating the bridge over as many cycles as possible. Since diesel fuel is very light oil, it acts as a lubricant and there was no significant risk of causing damage to the journals. So the inspection team along with maintenance personnel gathered up some Scotch-Brite™ and purchased $3 worth of diesel fuel to prepare for the next day.

On Saturday October 29, 2016 the bridge was operated repeatedly throughout the day while spraying diesel fuel on the trunnion journals and hand polishing the journals with Scotch-Brite™. Slowly the bridge responded and the stuttering appeared to dissipate. At first we were not sure if it was wishful thinking or if the stuttering was actually dissipating. As the day went on it was obvious that the flushing was having a significant effect on the operation of the bridge. By the end of the day maintenance personnel said that they had never seen the bridge operate so smoothly.

Although not completely eliminated, the work at the trunnion bearings (corrosion removal, flushing, and lubrication) led to a significant reduction in the duration and magnitude of the strain fluctuations. The strain fluctuations were eliminated when the span was rising and the strain fluctuations were reduced when the span was lowering. The strip charts in Figure 22-Figure 25 show the effects of the work done at the trunnion bearings.

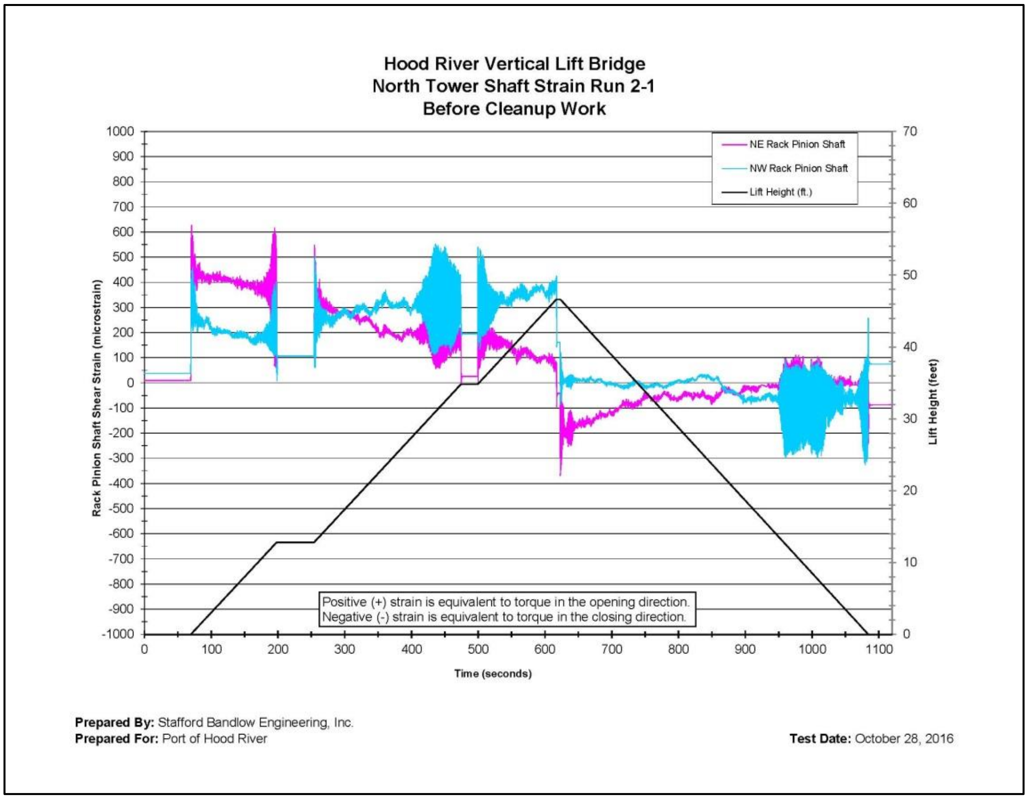

Figure 22: Strip Chart Recordings North Towner Shaft Strain Run 2-1 – Before Cleanup Work

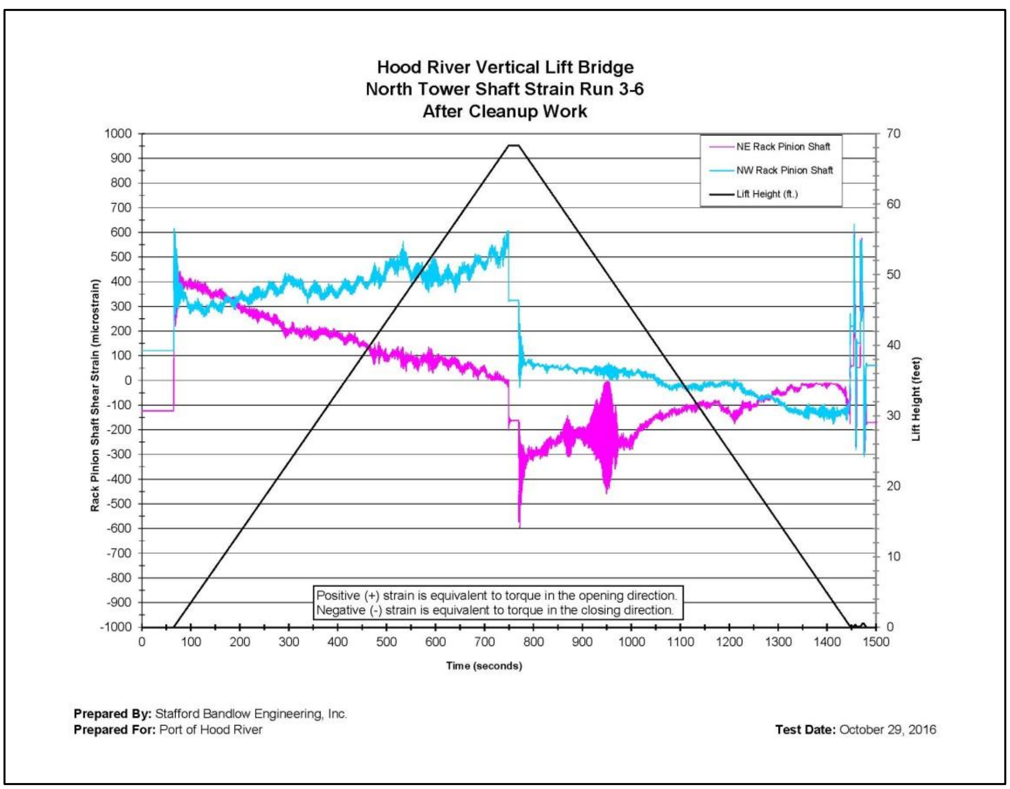

Figure 23: Strip Chart Recordings North Towner Shaft Strain Run 3-6 – After Cleanup Work

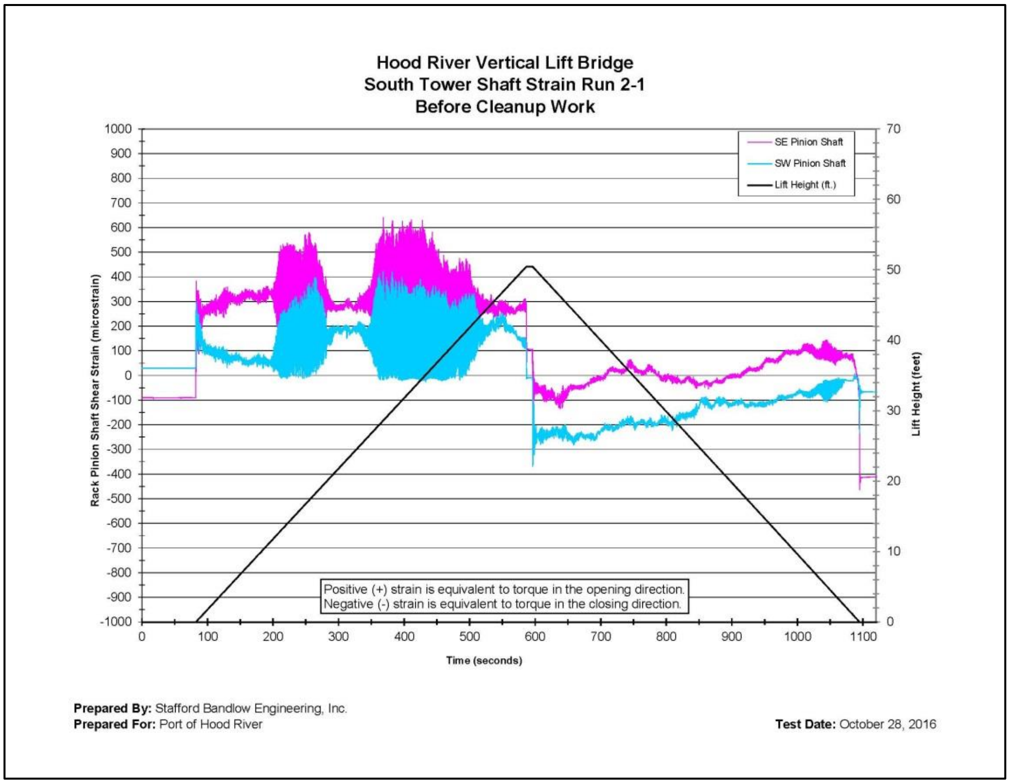

Figure 24: Strip Chart Recordings South Tower Shaft Strain Run 2-1 – Before Cleanup Work

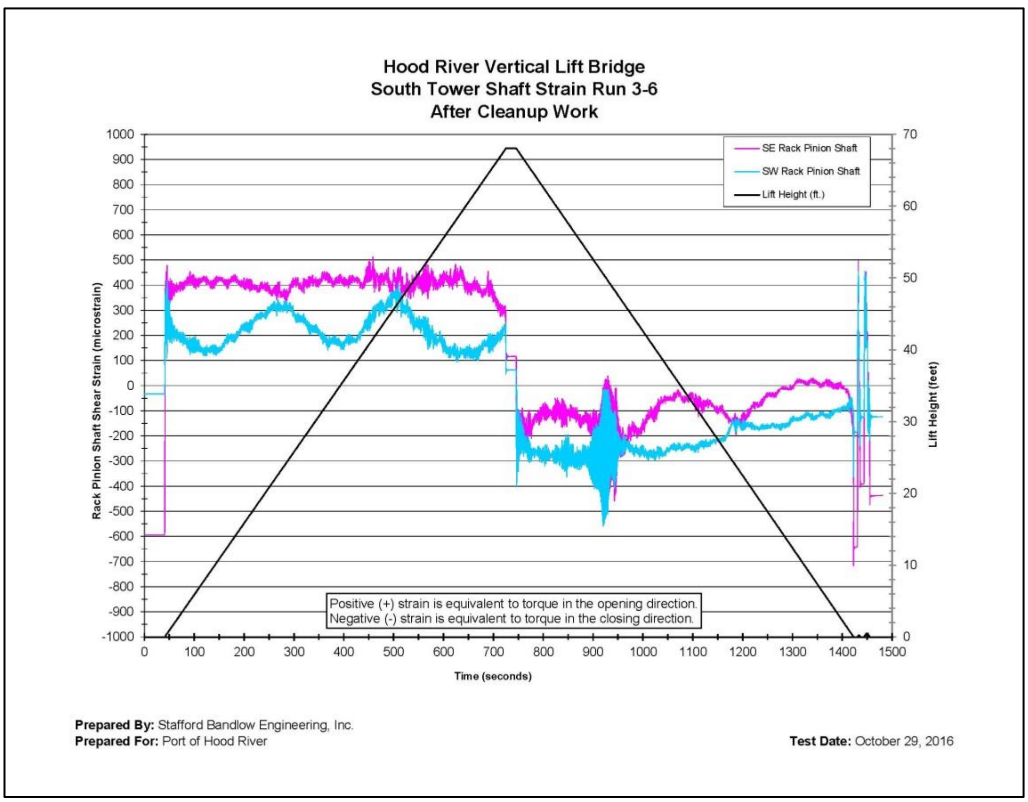

Figure 25: Strip Chart Recordings South Tower Shaft Strain Run 3-6 – After Cleanup Work

Through continued flushing and lubrication as part of a regular maintenance program the strain fluctuations have been completely eliminated as seen in the strip charts in Figure 26 and Figure 27 from our October 2017 balance testing.

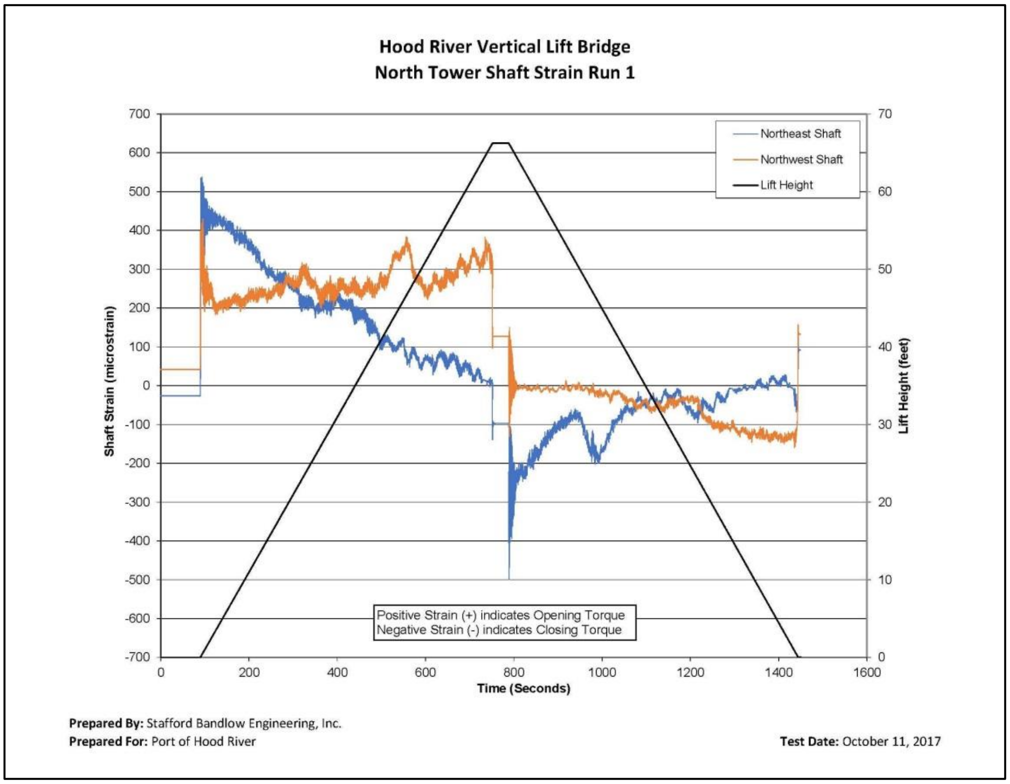

Figure 26: Strip Chart from October 2017 Balance Testing - North Tower Shaft Strain Run 1

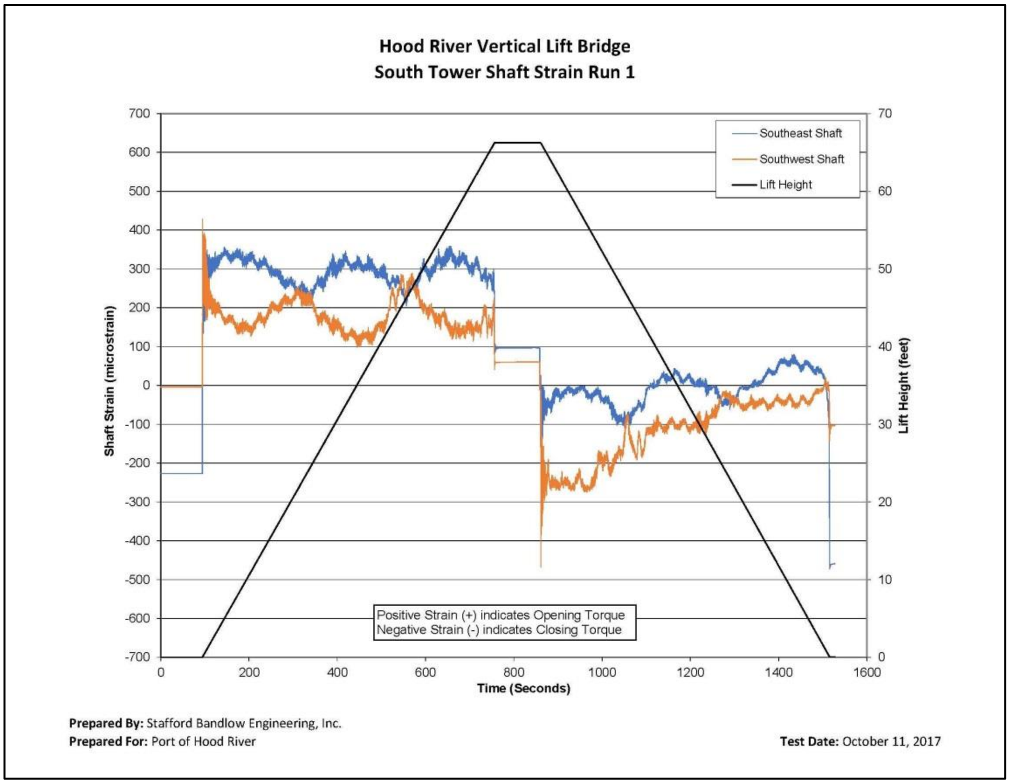

Figure 27: Strip Chart from October 2017 Balance Testing - South Tower Shaft Strain Run 1

Current Status

SBE recommended permanent changes to the bridge control system to provide fail safe operation of the bridge, enhanced span control and eliminate operator intervention in controlling skew. This design included utilizing the capabilities of the drives for primary skew control with a control system skew control algorithm used as backup and over-skew protection.

The design necessitated the replacement of the existing tower two-speed drive motors, addition of variable frequency drives and modifications and additions to the existing bridge control system. The design is presently ongoing and it is anticipated that the drives and motors will be advanced procured in August or September, 2018 with installation, testing, and commissioning of the replacement system taking place during the winter of 2018-2019.