MEMORANDUM

Date:	September 13, 2023
To:	Kit Loo, PE (Interim Director – Roadway Structures)
From:	Gregory A. Banks, PE, SE (Pacific Mountain West District, Structures Director)
Subject:	West Seattle High-rise Bridge – One Year Since Opening Monitoring Summary (Contract 20-017)

EXECUTIVE SUMMARY

This memo provides an update on the structural state of the West Seattle High Bridge (bridge) after completion of the load testing on September 14, 2022 and recommendation by WSP USA, Inc. (WSP) that the bridge be put back into service. Based on review of the monitoring system output and visual inspections the bridge is performing as expected.

On March 23, 2020 the bridge was closed due to continual propagation of observed cracks at the face of the concrete box girders. Following installation of a structural health monitoring system, extensive analysis and the eventual execution of stabilization work, permanent repairs allowed the bridge to be restored and reopened for public use on September 17, 2022. The recommendation to reopen the bridge to public use was based on the measured behavior of the bridge, during the load test, falling within the predictive bounds which indicated a passing load test. The recommendation was also based on the understanding that the load testing marked the culmination of a series of other successful tests that had been conducted since the bridge was closed on March 23, 2020:

- Condition Testing – the condition of the bridge concrete and post-tensioning were evaluated using non-destructive testing methods in May, 2020 and no condition issues were identified. In addition, throughout the construction of the stabilization measures and the rehabilitation measures, there were no indications of systemic condition issues.
- Environmental Testing – the bridge has experienced extreme weather conditions, including snow build-up in excess of 12-inches and summer heats over 100 degrees Fahrenheit. For over 36 months, we have gathered data showing how the bridge reacts to environmental conditions. Analytically predicted responses have been compared to actual measured responses and show close correlation, which means the bridge is behaving in a predictable manner through the full spectrum of environmental conditions the bridge experiences.
- Stabilization Testing – as part of the stabilization construction work, predicted bridge responses were compared to actual measured behavior during hoisting of the temporary work platforms, and during post-tensioning operations. Analytically predicted responses correlated well with actual measured behavior from the structural health instrumentation that exists on the bridge. This allowed us to comfortably say that we have calibrated analytical models that can predict how the bridge will behave to applied loadings.
- Final Rehabilitation Testing – as part of the final rehabilitation construction work, predicted bridge responses were again compared to actual measured behavior during hoisting of the

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temporary work platforms, and during post-tensioning operations. Predicted responses of the rehabilitated structure correlated well with actual measured behavior, which gave us confidence that our models remained calibrated after the final rehabilitations were completed.

As part of the initial closure of the bridge, a calibrated structural health monitoring system was put in place and has been pivotal in providing a detailed understanding of the bridge's behavior through correlation with the bridge structural analysis models. The system continues to be used while the bridge is in-service. Currently the system is localized to discrete locations on the bridge. The system will be augmented to be continuous throughout the superstructure by the fiber optic system that has been installed and is being actively calibrated. This system will be in service by the end of Fall. This augmented system will be consistent with a proactive asset management practice used by many agencies on their larger assets and allow for proactive early detection and focused inspections on areas of the bridge that may behave in a manner different than expected. The monitoring system has thresholds set to alarm the City should the bridge exhibit behavior beyond what is anticipated (i.e., different than predicted from our structural analyses) under service loadings.

MONITORING

One of the first tasks completed after the closure of the West Seattle Bridge was construction of an automated structural health monitoring system, lacing the length of the bridge with sensors to detect strain and deformation in the concrete structure of the bridge and provide alerts if anything unexpected were to occur. This same system was used to validate the structural analysis and repairs by monitoring the movement of the bridge during major repair operations and by observing strains from the load test completed in September 2022, wherein trucks weighing nearly 1 million pounds moved across the bridge in preset patterns to validate the repairs.

Since the West Seattle Bridge has reopened, this monitoring system has continued to record the movements of the bridge under temperature and traffic, and it gives us confidence in the continued performance of the bridge.

The temperatures recorded inside the bridge and the results of four long "floor sensors" are shown in the graph below (Figure 1). These floor sensors each span across segment joints in four quadrants of the main span of the bridge, close to the regions of cracking that led to the bridge closure in 2020.

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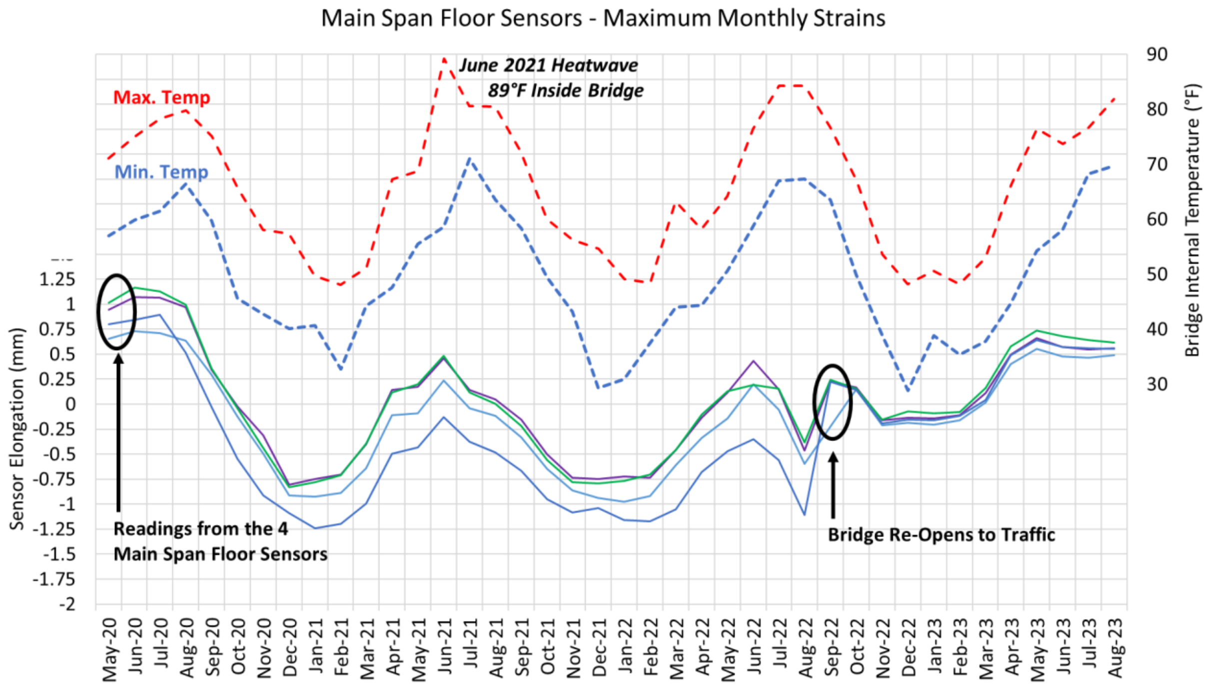

Figure 1 – Main span floor gage movements since activated in May 2020.

Deformations of the bridge are dominated by temperature, and the greatest readings (positive and negative) observed by the floor sensors were within the first 12 months of observation, before the installation of the Phase 2 strengthening repairs. Deformations since reopening have been less than those observed prior to opening (both in a temperature-relative sense, and in absolute terms). These observations are indicative of the rehabilitation/strengthening measures performing as anticipated.

The system will continue to provide 24/7 monitoring of the bridge going forward.

The shear cracks in the concrete webs of the boxes that propagated in the Spring of 2020, leading to the closure of the bridge, are monitored using the same system. For critical cracks in each of the four quadrants of the bridge, gages are oriented to measure any opening (widening) or slipping (differential movement) along the crack interface, as seen in Figure 2. The retrofit repairs constructed in 2021 and 2022 were designed to maintain continued access to these cracks for future observation and continuous monitoring. No unexpected movement has been observed from these sensors after the bridge closure in 2020, and sensor values remain nominal one year after reopening.

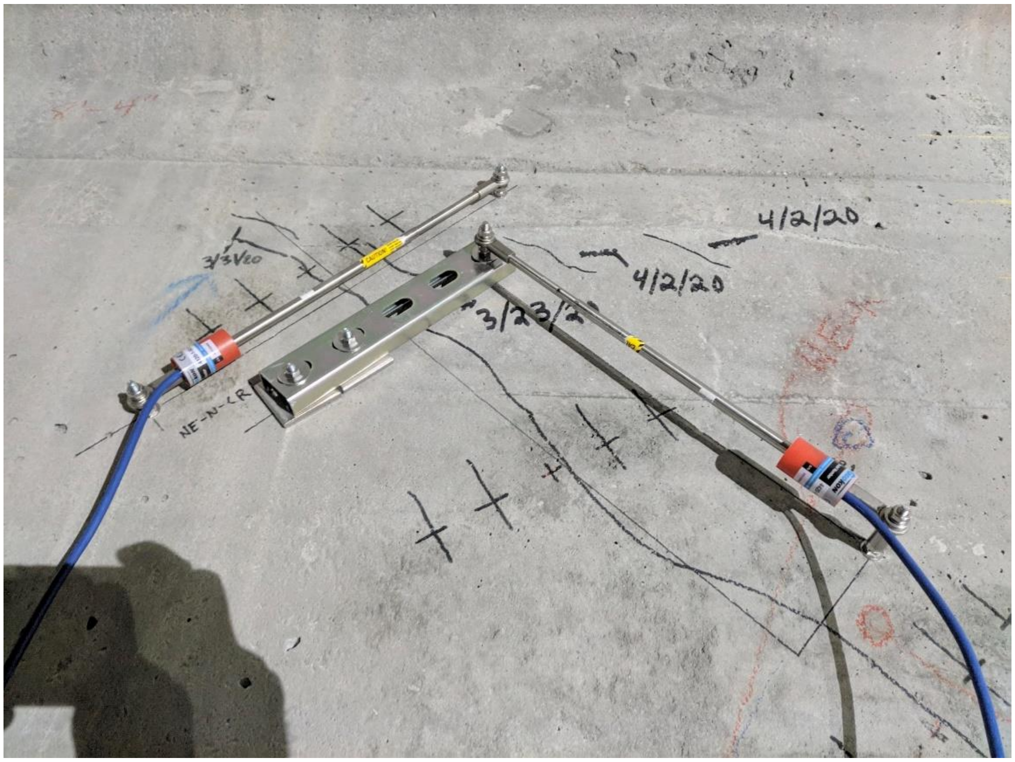

Figure 2 - Shear crack strain gages measuring slip and width changes.

ANALTICAL CORRELATION

Actual measured data from the structural health monitoring system gets correlated to predictive behavior from the structural analysis models. One of the predominant loadings the bridge sees is environmental loads (i.e., temperature variations). The plot below (Figure 3) shows the correlation of actual measured bridge movements by the Shape Array sensors (i.e., the blue line) to predicted movements by our structural analysis models (i.e., the black and orange lines for different stiffness assumptions). As can be seen, the analytical predictions match both trends and magnitudes of the actual measured response.

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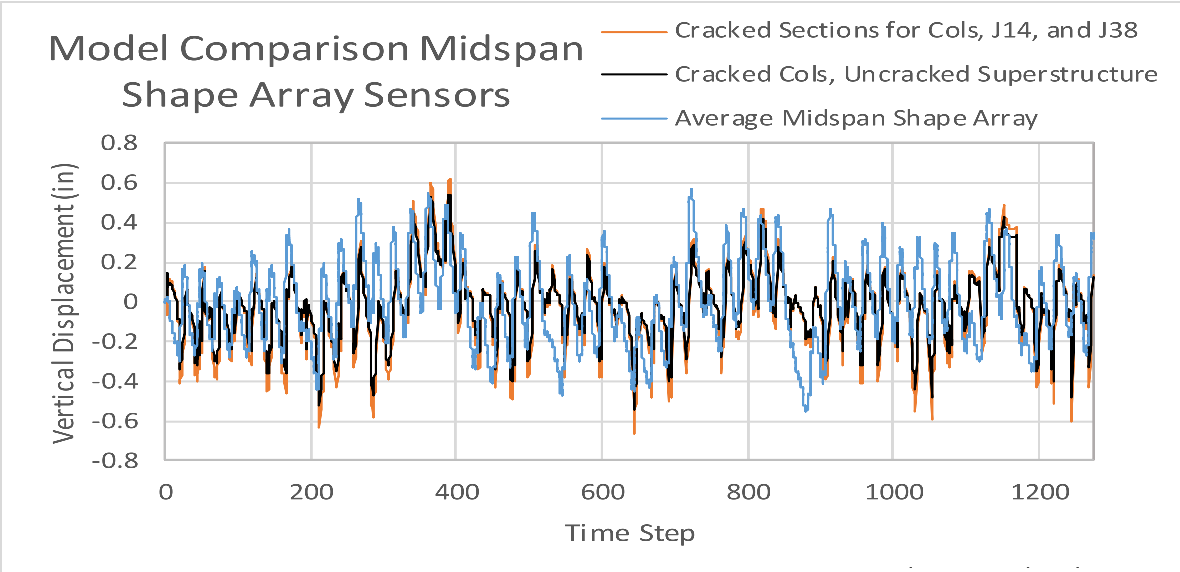

Figure 3 - Comparison between predicted and observed vertical displacements of the bridge.

INSPECTION

Over the past year a regimen of inspections has ensured that nothing is amiss. The bridge is being inspected at a higher frequency than is required by FHWA for the first two years after being returned to service, with walkthrough inspections of the bridge periodically to ensure that the carbon fiber wrapping and post-tensioning repair systems are performing as expected. In bridge inspection, there is no greater news than no news at all, and the inspectors observed no signs of distress. A system of inspection platforms and a new internal lighting system (see Figure 4), installed as part of the retrofit, allows inspectors to get up close to inspect in a way that was never before possible. A full inspection of all elements of the bridge was carried out in June of 2023 (see Figure), including inspection of the exterior with an Under-Bridge Inspection Truck (“UBIT”). Photos taken of the bridge during this inspection are shown in Figure 6 and Figure 7. A list of noteworthy inspection observations, along with recommendations/comments, has been developed and is provided in the Attachment.

NEXT STEPS

The bridge structural health monitoring (SHM) system will continue to monitor the bridge 24/7. The results for the previous inspections as well as the data from the SHM system is indicative of a bridge functioning as it should. The frequency of the physical inspections will shift back to the mandatory 2-year cycle; any changes to the physical inspection cycle will be based upon need or if the data from the SHM system deviates from defined data ranges that we expect from the movement of the structure.

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Figure 4 - New inspection platforms and lighting installed inside the bridge

Figure 5 - June 2023 inspection of the underside of the bridge using the UBIT

Figure 6 - View from UBIT of the exterior of the bridge, showing strips of CFRP strengthening

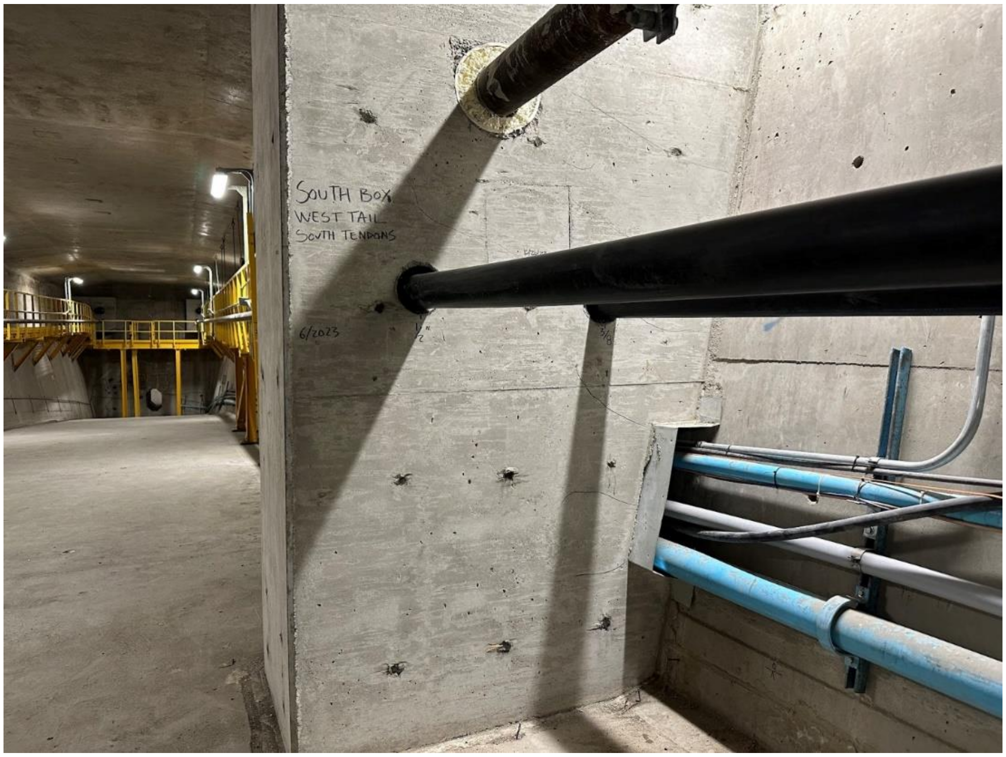

Figure 7 - View inside bridge looking at a new post-tensioning deviator, from the June 2023 inspection

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Attachment – Inspection Observations

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Below is a summary of the findings and recommendations from the inspections since the bridge reopened:

Finding	**Recommendations**	**SDOT Response**
No new cracking in original concrete observed	Continue to check during each inspection	Will be checked in each subsequent inspection.
Minor cracking in new concrete elements can be attributed to expected shrinkage cracks	Continue to observe Small interior cracks do not pose any structural concerns. All new concrete elements are interior to the bridge and do not pose concerns for deterioration of steel.	Will be checked in each subsequent inspection.
1/16" cracks in deviators originating from sharp corners of utility blockouts	Continue to observe Due to contractor's design change and do not pose any structural concerns.	Will be checked in each subsequent inspection.
All access openings and some concrete pour holes show signs of leaking water around patch perimeter, minor rust staining at one location	Recommend SDOT seal from the top with local overlay (MMA or similar) before the next rainy season	Openings were sealed in Summer 2023.
Minor surface corrosion on stabilization post-tensioning strands where epoxy coating was stripped off during construction	Test methods for permanent corrosion protection. One method (spray applied wax) was tested in April 2023. Zinc based spray will be tested for comparison in June 2023. The corrosion does not pose any structural concerns and would take many years to cause any section loss. Permanent corrosion protection should be applied to all locations within two years.	Test methods have been deployed and are being compared to strands with no protection. There have been no observable differences between methods and the bare strands to-date. This will be continued to be checked in each subsequent inspection.
Minor imperfections in CFRP due to original placement of fiber, including frayed fibers where holes were drilled and coating is missing in a few places	Imperfections should be addressed by grinding and placing epoxy. Coating should be touched up where missing. Exterior is higher priority than interior due to UV exposure.	To be completed before the end of 2023.

Stormwater pipe is leaking in SE end span	Recommend directing leak to not cross segmental joints before the next rainy season. No structural concerns if addressed within two years.	To be completed before the end of 2023.
BDI sensor cabinets near midspan are tall and heavy, might not fare well in an earthquake	Recommend bracing with a strut to the web.	To be completed before the end of 2023.
BDI sensors on the floor could be better protected from being stepped on	Recommend replacing existing covers with more robust covers	To be completed before the end of 2023.