Final Report

Alaskan Way Viaduct Independent Technical Review

Prepared for

Seattle Department of Transportation

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CH2MHILL®

1100 112th Avenue NE Suite 500
Bellevue, WA 98004

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Acronyms and Abbreviations

CFRP	Carbon Fiber Reinforced Polymer
RFP	Request for Proposal
SDOT	Seattle Department of Transportation
SESMP	South End Settlement Mitigation Plan
STP	Seattle Tunnel Partners
TBM	Tunnel Boring Machine
WSDOT	Washington State Department of Transportation

1 Introduction

1.1 Background

The Alaskan Way Viaduct, an elevated section of State Route 99 along the Seattle waterfront, was constructed in the early 1950's. It is currently being replaced with a deep bored tunnel that will extend from the Stadium District to South Lake Union. On February 28, 2001, the 6.8 magnitude Nisqually Earthquake struck the region, resulting in damage and settlement to sections of the viaduct structure. At Bents 97-100 between Yesler Way and South Washington Street, WSDOT performed repairs to the structure. In addition, in 2007, WSDOT stabilized four viaduct foundations at Bents 93 and 94 that had experienced ongoing settlement after the earthquake.

In 2011, WSDOT initiated the SR99 Bored Tunnel Project with Seattle Tunnel Partners (STP) in a design-build contract to construct a deep bored tunnel, allowing for demolition of the existing viaduct structure along the waterfront after the completion of the tunnel. The tunnel boring machine (TBM) began tunneling in July 2013 at the south tunnel portal. In December 2013, tunneling was stopped after approximately 1,000 feet when damage was discovered in the machine's seal system.

WSDOT's design-build contractor, STP, developed a plan to repair the tunnel boring machine. A 120-foot deep ring-shaped access repair pit was dug in front of the TBM near South Main Street to provide a means of removing the front end of the boring machine. Groundwater is being pumped from dewatering wells around the repair pit to reduce hydrostatic pressure below the excavation and stabilize the soil at the bottom of the pit. Groundwater pumping began in November 2014 and may be associated with ground settlement in the vicinity of the repair pit. The viaduct structure also experienced settlement during this time frame.

Work at the repair pit is currently ongoing. The front end of the tunnel boring machine has moved into the pit and the cutter head has been removed from the TBM and lifted to ground level so that it can be repaired before being reattached to the TBM. Once the machine is fixed and the repair pit backfilled, the dewatering pumps will be turned off and tunneling will resume. STP expects to complete repairs by late summer of 2015.

1.2 Purpose of Evaluation Study

The recent settlement of the Alaskan Way Viaduct in the vicinity of the repair pit has prompted a desire for a third party review of the structure. The Seattle Department of Transportation (SDOT) hired CH2M HILL to perform a technical review of existing structure settlement assessments, analyses, and strengthening design calculations prepared by WSDOT, STP, and their consultants, to evaluate the effects of observed structure settlement on the structural capacity of the Alaskan Way Viaduct. This report includes an evaluation of observed settlement of the structure to date, as well as a summary of the technical review of existing studies, reports, and design calculations prepared by WSDOT and STP.

CH2M HILL's review was limited to the Alaskan Way Viaduct structure and did not consider settlement impacts on utilities, roadways, or other structures. In addition, the review did not include effects of seismic loading on the Alaskan Way Viaduct. The review was based on as-built drawings, bridge load rating reports, bridge inspection reports, structure settlement measurements, and settlement analyses provided by WSDOT and STP. The validation of these data was not within the scope of this review.

2 Overview of Evaluation Study

2.1 Study Area

The area for this study consists of the south end of the existing Alaskan Way Viaduct and is shown in Figure 2-1. This area was selected because of the proximity of the deep bored tunnel and the magnitude of observed settlement for this portion of the structure near the access repair pit.

The study area includes the following portions of the structure:

- **Mainline Bents 91 to 100:** This portion of the mainline viaduct structure consists of 3-span units of double-deck cast-in-place reinforced concrete rigid frames supported by steel piling. Each 3-span unit consists of two lines of columns along the eastern and western edges connected transversely by crossbeams and longitudinally by girders and stringers, as depicted in Figure 2-2. Span lengths vary from 65 feet to 85 feet and each unit is separated from adjacent units with expansion joints. There are double columns at the end of each frame, meaning that the columns of adjacent units share a common foundation at the expansion joint locations. This portion of the mainline structure experienced significant settlement in the 2001 Nisqually Earthquake and was damaged, requiring emergency repairs in 2001. In addition, four column foundations at Bents 93 and 94 were stabilized in 2007. As shown in Figure 2-1, this portion of the viaduct is located where the deep bored tunnel will pass underneath the existing structure. STP performed structural evaluation and retrofit for this part of the viaduct to mitigate potential impacts from anticipated tunneling settlement. This portion of the structure is discussed in Section 3.1.
- **Mainline Bents 100 to 121:** This part of the viaduct consists of a rigid frame structure similar to that of Bents 91 to 100. Due to its proximity to the deep bored tunnel, WSDOT performed a structural evaluation of a typical frame from Bents 106 to 109 to evaluate the ability of the structure to accommodate settlement from nearby tunneling. The evaluation suggested that strengthening was required to provide a sufficient safety margin against settlement-induced overstress. The design-build contractor, STP, elected to construct an underground wall (referred to as the SESMP wall), consisting of large diameter concrete piles, to limit settlement from tunneling. This portion of the structure is discussed in Section 3.2.
- **Railroad Way Ramp:** The Railroad Way Ramp is a reinforced concrete rigid frame structure in which the elevated roadway transitions from a double deck structure to single deck side-by-side roadways. WSDOT performed structural evaluation of a portion of the ramp and concluded that it could accommodate expected differential movements due to construction. The south end of the east ramp was removed and replaced with a temporary ramp as part of the SR99 S. Holgate to S. King Viaduct Replacement Stage 2 Project. The temporary ramp was designed by WSDOT’s consultant and constructed by Skanska and is not included in the study area. This portion of the structure is discussed in Section 3.3.
- **Columbia Street and Seneca Street Ramps:** The Columbia Street and Seneca Street Ramps consist of series of simply-supported precast concrete I-girder structures supported by single column bents. At the west end of each ramp where it abuts with the mainline viaduct, the end spans are supported by straddle bents consisting of a two-column frame and crossbeam. WSDOT performed structural evaluation of the two ramps and concluded that the ramps could accommodate expected differential movements due to tunnel construction. This portion of the structure is discussed in Section 3.4.

- **Mainline Bents 73 to 91:** This portion of the mainline structure consists of a rigid frame structure similar to that of Bents 91 to 121. Significant historical settlement has been observed near Bents 75 and 76, near the west end of the Seneca Street Ramp. WSDOT performed structural analysis for the three span frame between Bents 73 and 76 and repaired one of the columns. This portion of the structure is discussed in Section 3.5.

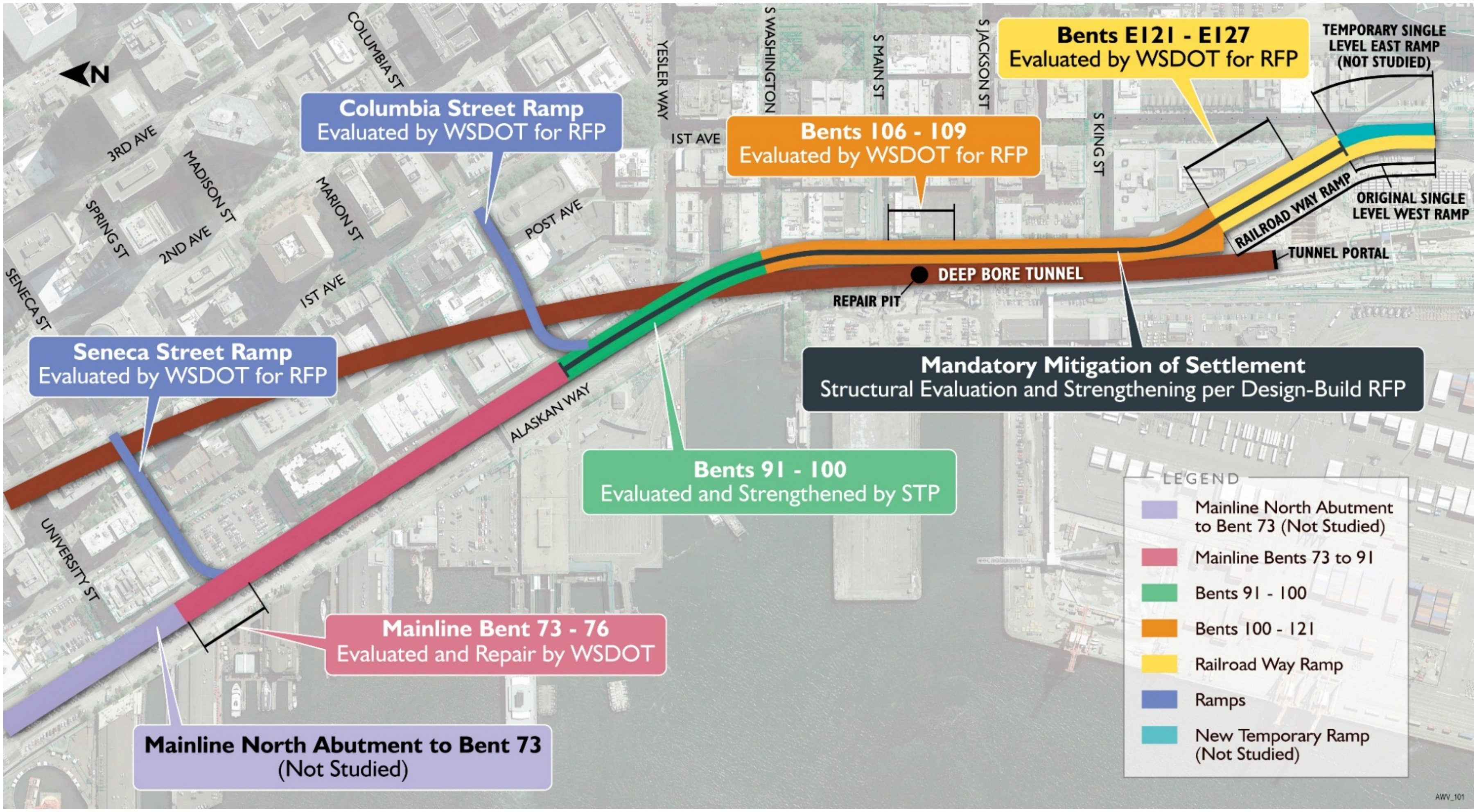

FIGURE 2-1
Overview of Study Area

2.2 Settlement of Viaduct Structure

Settlement can cause distress in components of a structure, depending on the magnitude and location of the settlement. For multi-column rigid frame structures like the Alaskan Way Viaduct, distress can result from differential movements between supports within the frame. As Figure 2-1 shows, the portion of the viaduct structure from Bents 91 to 121 was specified in the SR99 Bored Tunnel Design-Build Project to require mandatory mitigation of settlement due to tunneling. Settlement mitigation required the design-build contractor, STP, to perform a ground settlement analysis that assessed the expected ground deformations and impacts on the viaduct structure due to tunneling. STP was also required to perform a structural evaluation that included design and implementation of structural strengthening measures where the structural demands were in excess of the capacity. The imposed demands included dead and live loads and structure movements consisting of differential vertical and horizontal movement between columns within a bent (transverse direction) and between bents (longitudinal direction). These imposed movement demands are summarized in Table 2-1 and are shown graphically in Figure 2-2.

TABLE 2-1
Imposed Differential Movements on Viaduct Structure [a]

Differential Movement	Imposed Movement	Location
Bents 91 – 121		
Transverse Vertical Movement	1.0 inches	Measured between ends of transverse crossbeams
Transverse Horizontal Movement	0.5 inches	Measured between bent column/footing pedestal interface
Longitudinal Vertical Movement	0.5 inches	Measured between ends of exterior longitudinal girders
Longitudinal Horizontal Movement	0.5 inches	Measured between bent column/footing pedestal interface
Bents E121 – E130		
Transverse Vertical Movement	0.5 inches	Measured between ends of transverse crossbeams
Transverse Horizontal Movement	0.5 inches	Measured between bent column/pile cap interface

[a] From Section 2.52.5.4.6.4 of the Conformed Request for Proposal (RFP) for the SR99 Bored Tunnel Project.

Settlement measurements of portions of the viaduct structure have been taken since the 2001 Nisqually Earthquake. The frequency and type of measurements vary depending on the location within the structure. Originally, these measurements consisted of gutter line vertical elevation surveys taken by WSDOT on a regular basis when the viaduct was closed for inspection. Starting in 2010, WSDOT also began taking vertical column movement measurements. These measurements were recorded near the base of the column at ground level. Based on the collection of survey information provided, Figure 2-3 summarizes available vertical settlement measurements recorded by WSDOT. In addition to the gutter line and column survey data

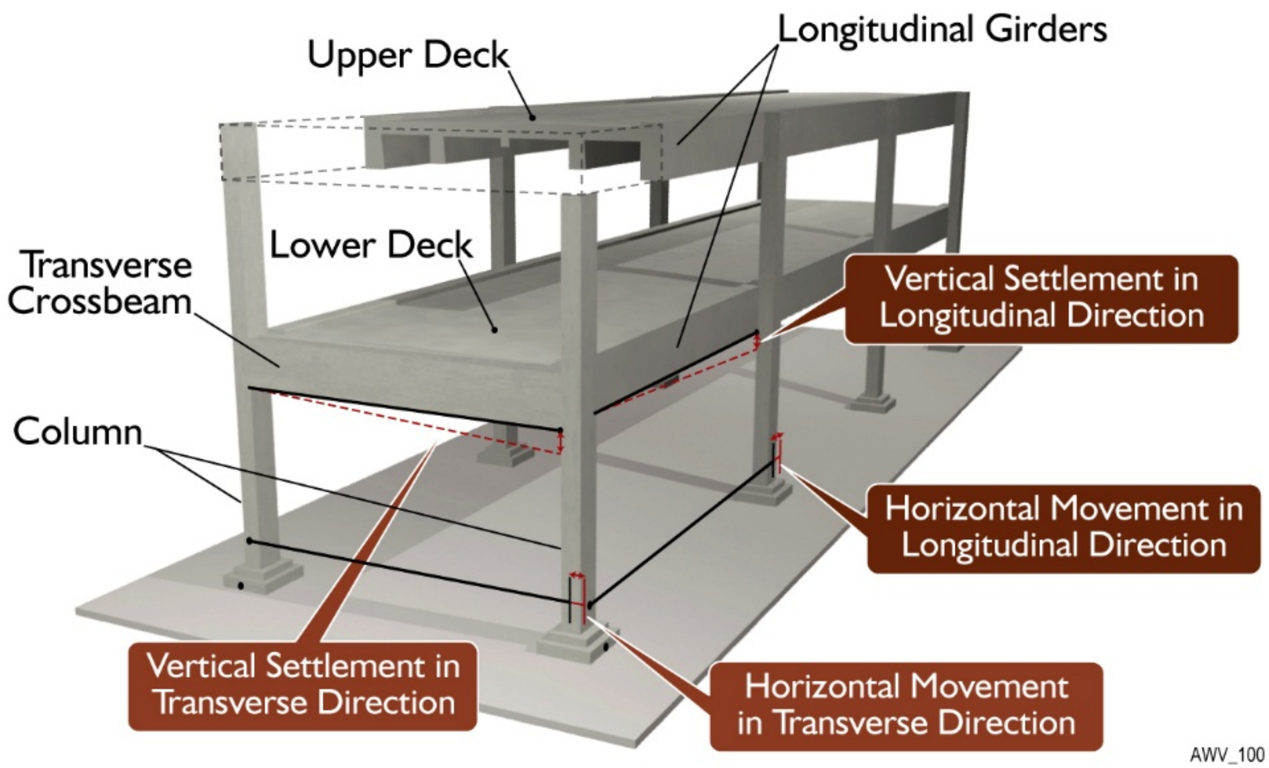

FIGURE 2-2
Differential Movements

collected by WSDOT, STP has been measuring structure movements since 2012 and recording them in a database referred to as GEOSCOPE. STP's survey includes vertical and horizontal movements of the structure, as well as data measuring tilting or leaning of the columns at certain locations. The approximate time duration of GEOSCOPE data is also shown in Figure 2-3. Because of the limited time period of GEOSCOPE data, CH2M HILL's review has focused on WSDOT survey data. GEOSCOPE data are used as a supplemental source either to validate WSDOT's data, or to fill in gaps where WSDOT survey data are not available.

The dewatering that began in November 2014 to construct the tunnel repair pit has coincided with observed ground settlement measured by WSDOT that is shown in Figure 2-4. This figure includes ground settlement from 2010 to December 2014. It should be noted that ground settlements are measured at the ground surface, while structure settlements are measured at locations on the structure.

Because the viaduct structure is supported on deep foundations that tend to mitigate the effects of adjacent ground settlement, the values of ground and structure settlements do not necessarily agree. Nevertheless, the trend of ground settlement correlates well with the observed structure settlements from October 2014 to January 2015 in Figure 2-5, which shows structure settlement over the time period when STP was performing dewatering. The maximum structure settlement during this period is approximately 0.9 inches. A comparison of the gutter line and column survey results indicates that the two sets of data show the same settlement trend, although column survey data south of Bent 101 do not exist prior to December 2014.

Although much recent attention has focused on settlement since dewatering began in November 2014, the structure has experienced settlement dating back to at least 2001 and likely back to the time before regular survey measurements were started. For the purposes of this review, there are three time periods of interest in structure movement that are discussed in this report. These periods are as follows:

- Settlement prior to the start of survey measurements (April 2001): The historical settlement from when the structure was built until shortly after the 2001 Nisqually Earthquake in February 2001.
- Settlement from Spring 2001 to Spring 2011: The settlement from shortly after the Nisqually Earthquake to when the construction of SR99 Bored Tunnel Project began.
- Settlement since Spring 2011: The settlement from the beginning of the SR99 Bored Tunnel Project to now, which includes the time period when STP was performing dewatering.

Figure 2-6 shows measured structure settlements from Bents 88 to 121 over the time frame from as-built conditions to March 2015. The values shown are the differences between the elevations reported on the as-built drawings and the elevation measured by survey along the East and West gutters of the viaduct on March 2015. The figure shows significant settlements at Bents 93-94 and Bents 98-99.

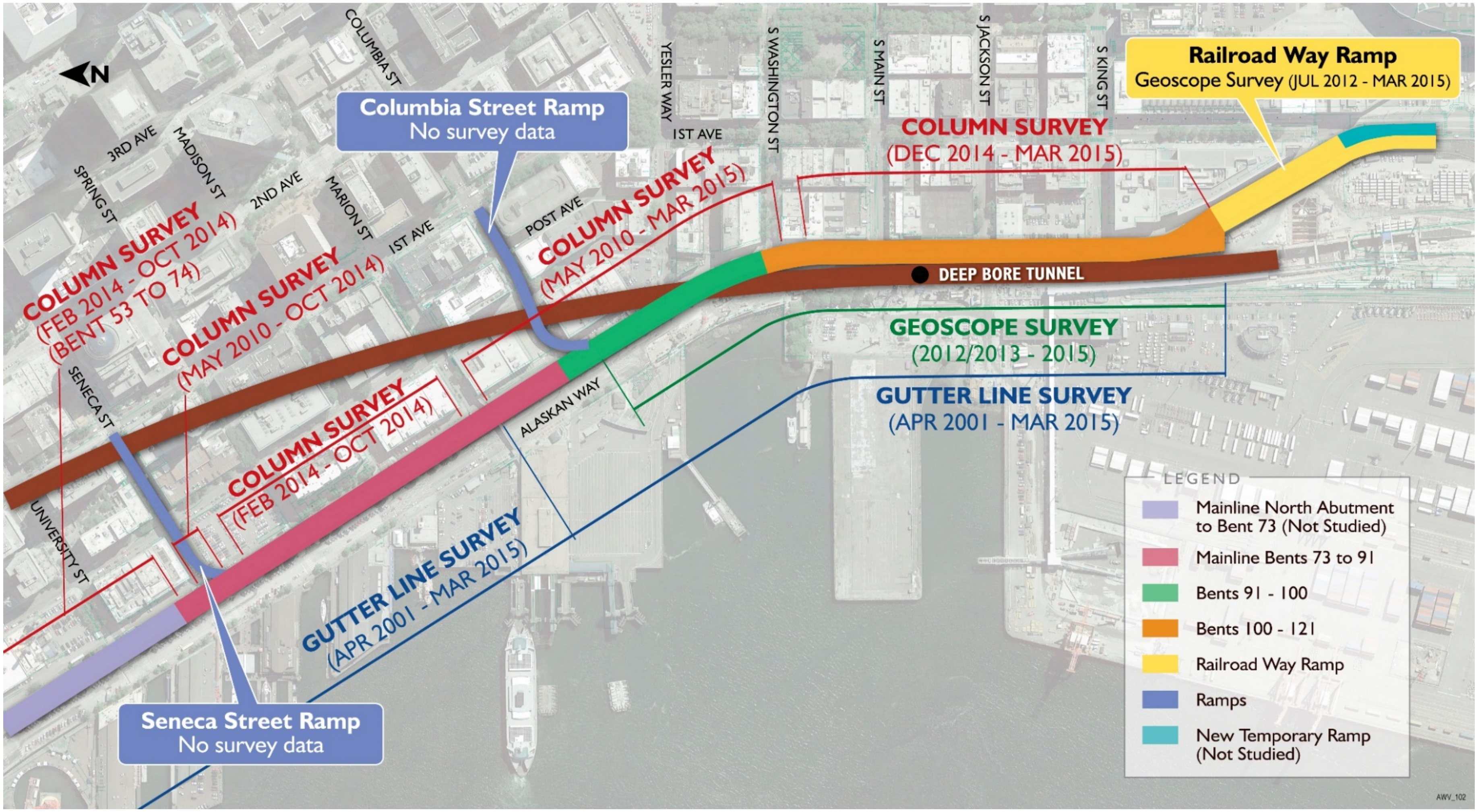

FIGURE 2-3
Available Survey Data

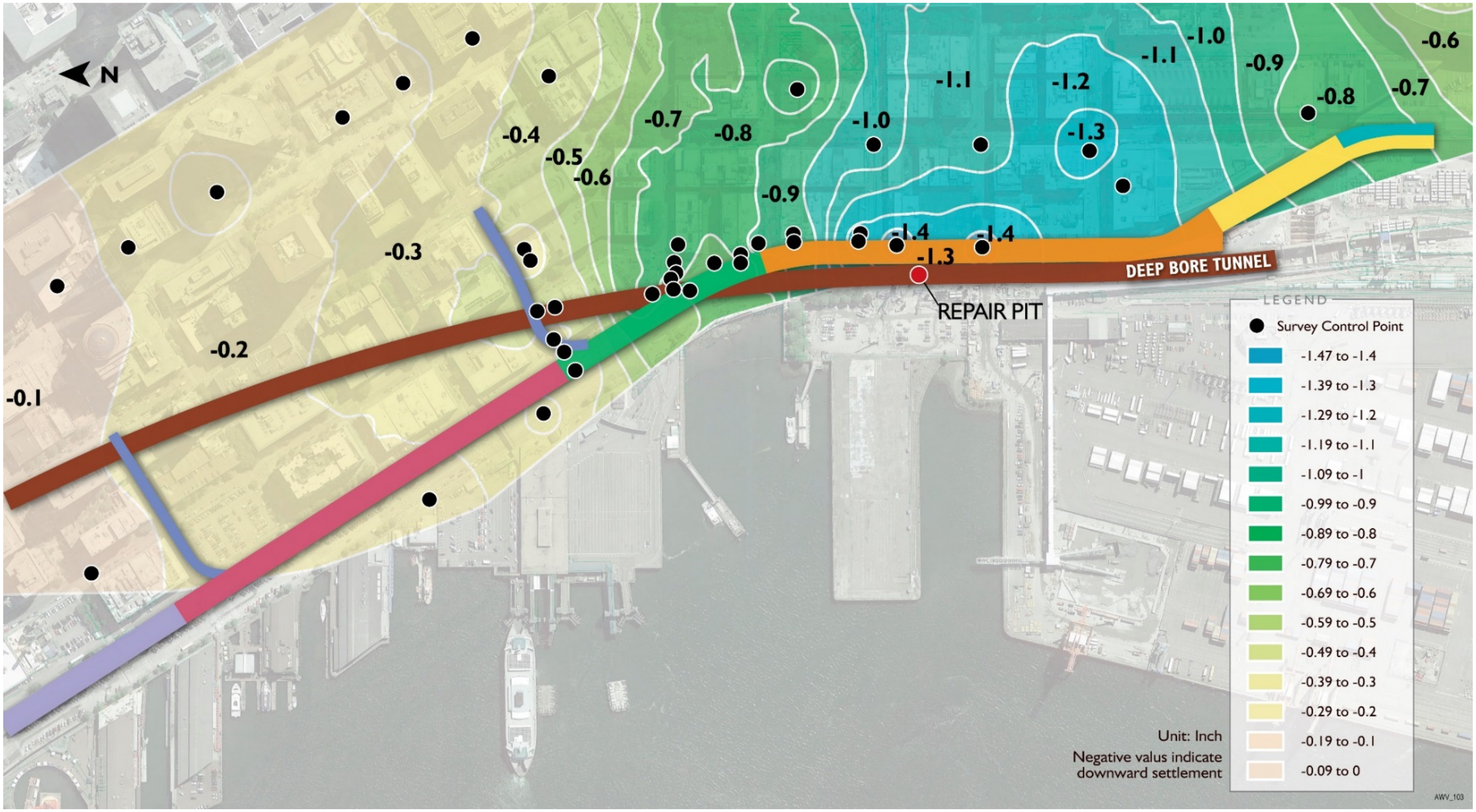

FIGURE 2-4

Ground Settlement from 2010 to Dec 2014

(Source: WSDOT Media Release, Dec 11th, 2014)

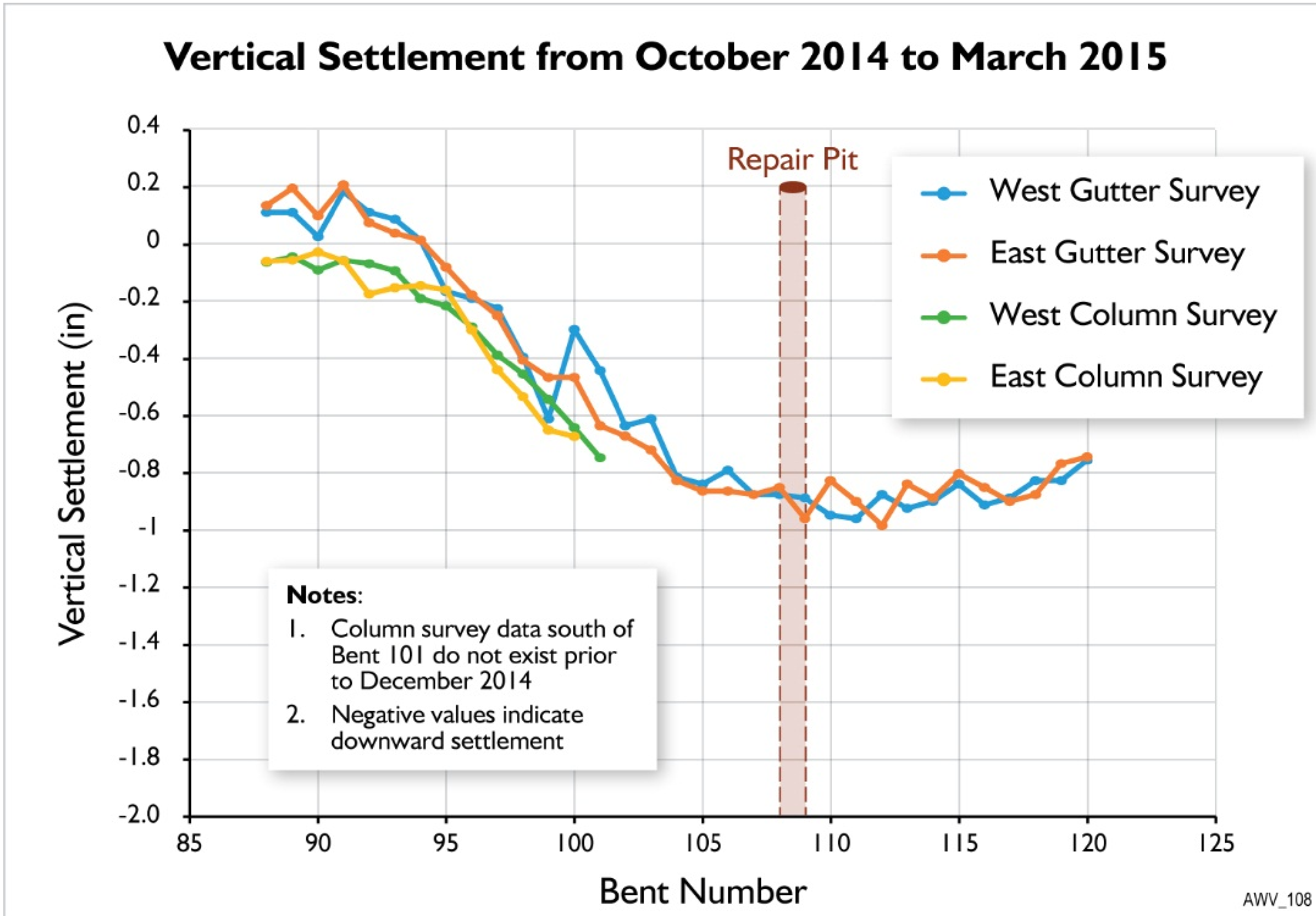

FIGURE 2-5

Structure Settlement – Bents 88 to 120 (From October 2014 to March 2015)

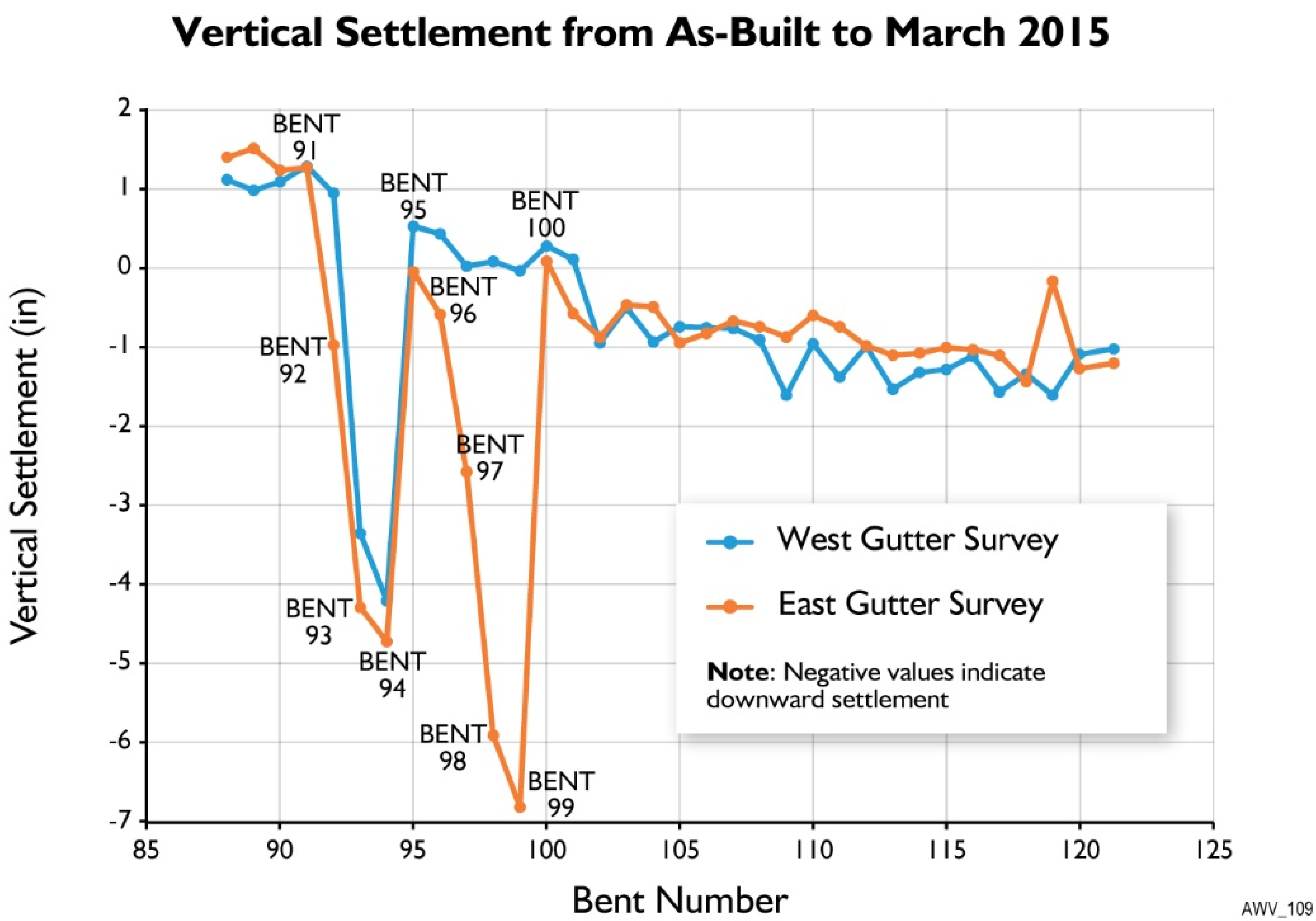

FIGURE 2-6
Structure Settlement – Bents 88 to 121 (From As-Built Elevation to March 2015)

3 Evaluation of Existing Structural Analysis

Settlement impacts to the Alaskan Way Viaduct have been extensively studied over the past several years. This section presents an evaluation of the settlement impact assessments that have been performed to date by WSDOT and the SR99 Bored Tunnel design-build contractor, STP. The scope of this effort was to perform a technical review of the existing structural studies, reports, and design calculations to evaluate the effects of observed structure settlement on the capacity of the Alaskan Way Viaduct.

This evaluation focuses on the portion of the viaduct structure that is within the area of the recent observed ground settlements shown in Figure 2-4. Specifically, the viaduct structure covered in this evaluation includes the mainline structure between Bents 73-121, the Railroad Way Ramp, the Columbia Street Ramp, and the Seneca Street Ramp. Each portion of the structure will be discussed in detail in the following sections.

3.1 Mainline Bents 91-100

3.1.1 Introduction

The Alaskan Way Viaduct mainline structure between Bents 91 and 100 is a double-decked reinforced concrete structure consisting of three semi-independent three-span rigid frames: Bents 91S-94N, Bents 94S-97N, and Bents 97S-100N, as shown in Figure 3-1. The span lengths vary between 68’-6” and 84’-11”, with a total length of each frame equaling approximately 222’. At each bent location, the frame consists of two columns connected by transverse crossbeams at both upper and lower deck level. Bents are connected longitudinally by a series of longitudinal girders. The deck slabs at the upper and lower deck level are supported by the longitudinal girders and a number of small longitudinal and transverse stringers. Each frame is separated from the adjacent frame with expansion joints. The columns of the adjacent frame at the expansion joint share a common footing.

The three-span frame between Bents 97S-100N experienced significant damage during the 2001 Nisqually Earthquake. Immediately after the earthquake, WSDOT issued two emergency earthquake repair contracts to provide temporary repairs to the structure. These repairs included steel “sister” columns, shoring and transverse post-tensioning of the transverse crossbeams, and carbon fiber wrap flexural and shear strengthening of the crossbeams and longitudinal girders, as shown in the photograph in Figure 3-2.

Approximately 4 to 5 years after the Nisqually Earthquake, the foundations of Bents 93 and 94 were found to have experienced significant settlement. In response, WSDOT performed foundation stabilization for these two bents in 2007 to limit further settlement. The foundation stabilization system included installing micropiles around the existing pile caps and pile cap strengthening.

As required by the SR99 Bored Tunnel Project, the design-build contractor, STP, performed settlement mitigation measures, as well as structural evaluation and targeted retrofit for this portion of the viaduct structure. As shown in Figure 3-1, settlement mitigation measures consisted of below-grade micropile curtain walls and grade beams aimed at reducing the anticipated settlement of the viaduct structure due to tunneling operations.

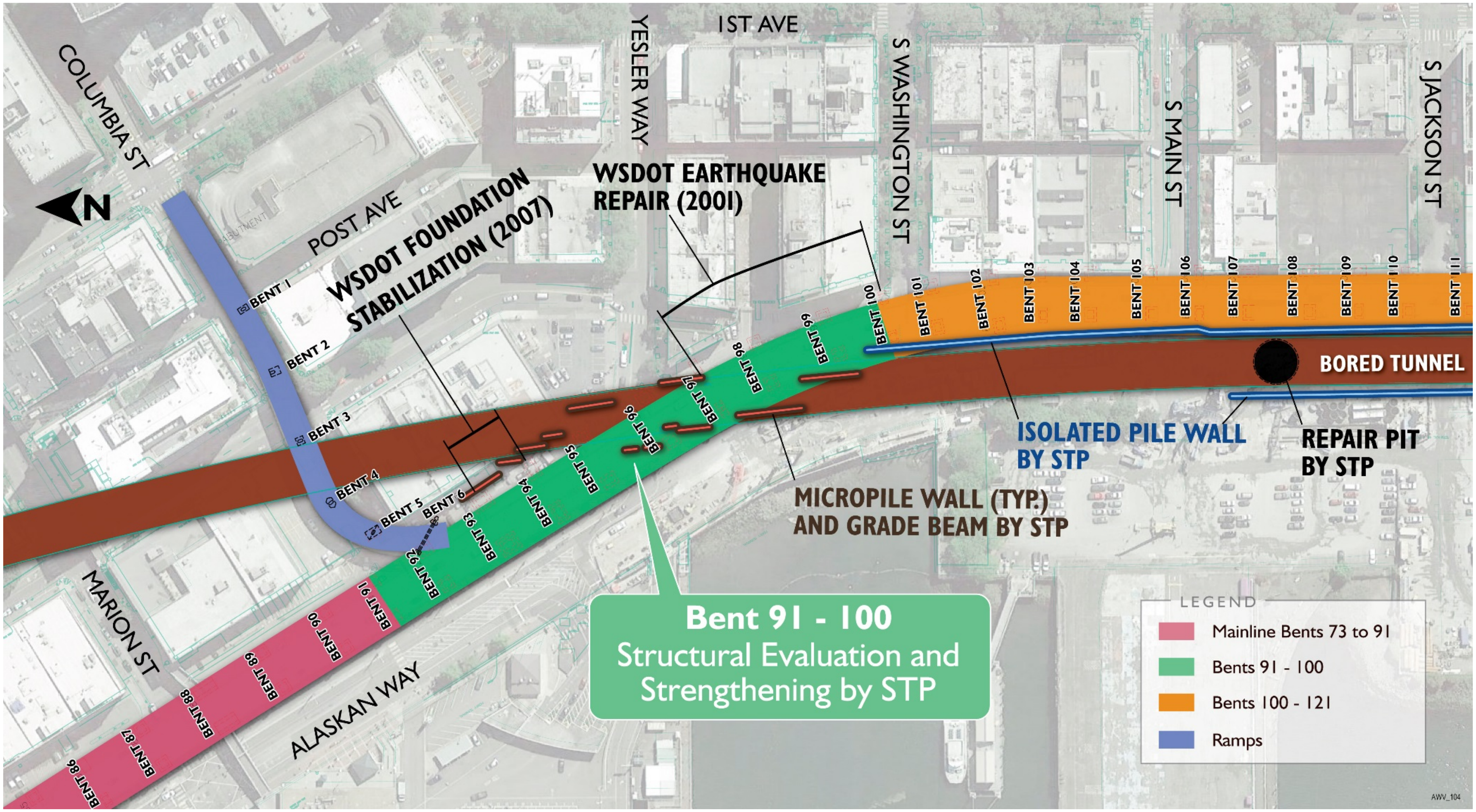

FIGURE 3-1
AWV Mainline Bents 91-100

FIGURE 3-2
Alaskan Way Viaduct Bents 91-100

The SR99 Bored Tunnel Project Request for Proposals (RFP) contained a set of minimum imposed settlements that the viaduct structure must be evaluated for in anticipation of future tunneling settlements. These requirements are listed in column (2) of Table 3-1 below. These prescribed settlement values were based on preliminary empirical and numerical settlement analyses. Later, WSDOT's design-build contractor, STP, performed a separate deformation analysis to predict the anticipated tunneling settlements, taking into account the settlement mitigation measures constructed by STP (i.e., micropile curtain walls). In one of the cases (for longitudinal vertical differential movement), the predicted tunneling settlement by STP shown in column (1) of Table 3-1 exceeded the minimum requirements from the contract RFP. STP opted to adopt a higher (and more stringent) settlement limit of 1" for their structural evaluation and strengthening design, as shown in column (3) of Table 3-1.

TABLE 3-1
Predicted and Prescribed Differential Movements of Viaduct due to Tunneling

Differential Movement [a]	(1) Maximum Predicted Movement [b]	(2) Prescribed Minimum Movement (per RFP requirements)	(3) Movement Used for Strengthening Design
Transverse Vertical Movement (inches)	0.68	1.00	**1.00**
Transverse Horizontal Movement (inches)	0.35	0.50	**0.50**
Longitudinal Vertical Movement (inches)	0.66	0.50	**1.00**
Longitudinal Horizontal Movement (inches)	0.36	0.50	**0.50**

[a] See Table 2-1 for locations of differential movement measurements.

[b] Predicted movements from deformation analysis performed by WSDOT's design-build contractor (STP).

Because of the significant historical settlements that have been experienced by this portion of the viaduct that are shown in Figure 2-6, STP performed a step-by-step structural analysis both to establish the condition of the viaduct at the time when the analysis was performed (2011) and to predict the anticipated structure response due to tunneling settlement.

The analysis procedure for flexural strengthening is shown graphically in Figure 3-3. To establish the structure condition at the start of the SR99 Bored Tunnel Project in 2011, the viaduct was subjected to incremental foundation settlements. The settlements were increased linearly until a plastic hinge formed in the structure. Then the structure model was modified to account for the appearance of the plastic hinge and the modified structure model was subjected to subsequent settlements. The settlements were increased in a step-by-step process until all observed settlements up to the first quarter of 2011 were accounted for. This condition was subsequently referred to as the "present day" condition.

Next, the structure was subjected to the settlements in column (3) of Table 3-1 to compute anticipated structure response due to tunneling settlement. The structure response was used to compute component demand/capacity ratios and determine which members needed to be strengthened. The demands were then used to design Carbon Fiber Reinforced Polymer (CFRP) flexure strengthening. Due to the fact that some of members of the structure had already been experiencing demands exceeding their elastic capacities prior to the start of the SR99 Bored Tunnel Project, the performance criteria of the strengthening design consisted of life-safety. Cracking or yielding of members at non-critical locations of the structure was deemed to be acceptable by STP given the short duration of the remaining structure life.

The approach for designing CFRP shear strengthening was more conservative and involved using an elastic model to predict the anticipated response of the structure due to settlement. Both CFRP flexural and shear strengthening of the viaduct structure between Bents 91-100 were completed prior to 2014. Columns, beam-column joints, and foundations were also examined and were found to need no strengthening.

3.1.2 Review Methodology

CH2M HILL reviewed the available structure survey data for this portion of the viaduct to determine the differential structural settlements that have been observed to date. Past bridge inspection reports, load rating reports, and as-built drawings were reviewed to gain an understanding of the condition of the existing structure. In addition, the structural evaluation calculations and strengthening design performed by STP for Bents 91 to 100 were also reviewed. The review of the calculations focused on verifying STP's assumptions and analysis approaches. The review examined representative computer models that the calculations were based on. The review also consisted of line-by-line checking of representative calculations at selected locations of the structure.

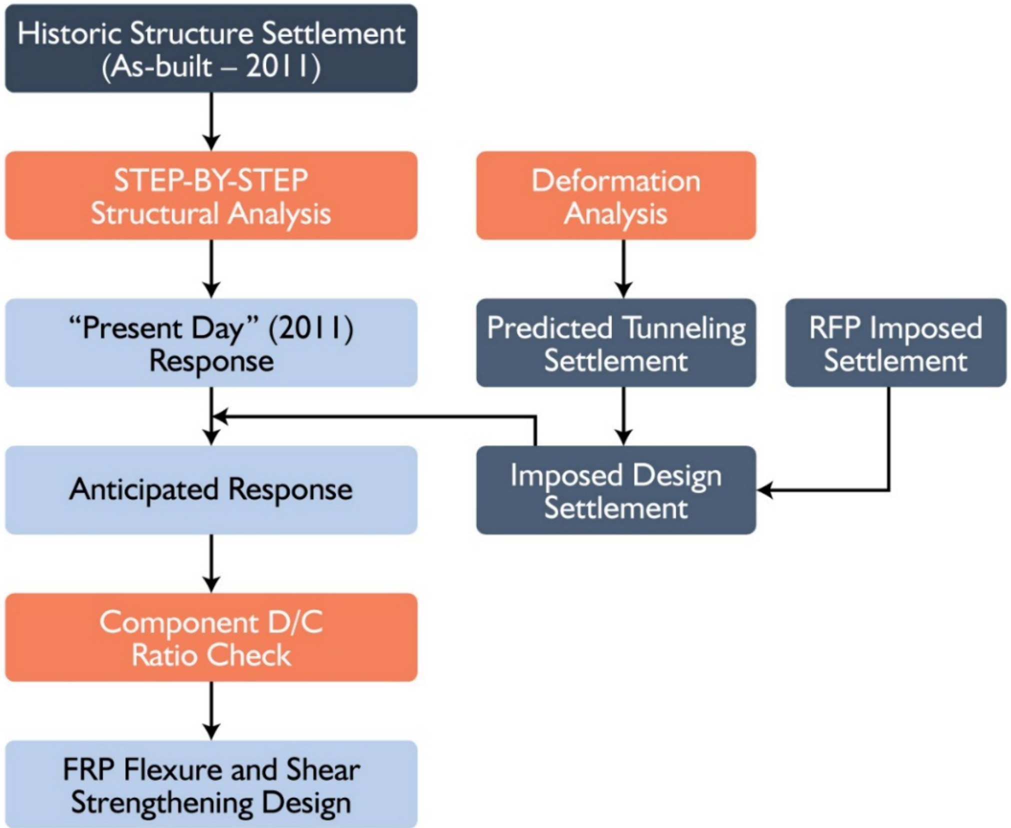

FIGURE 3-3
Structural Evaluation and Retrofit Procedure Performed by STP – Bents 91 to 100

3.1.3 Findings

Review of available survey data found that the viaduct structure has experienced significant longitudinal and transverse differential settlement between Bents 91 and 100. The maximum magnitude of the vertical differential settlement appears to have exceeded 5 inches between Bents 94 and 95 and 6.5 inches between Bents 99 and 100 (Figure 2-6). Compared with vertical survey data, the availability of horizontal survey data is limited. Based on the horizontal survey data available, the magnitude of horizontal differential movement appears to be small.

Discrepancies were found between the two sets of available structure survey data from WSDOT, the column survey and the gutter line survey. Although the general trends of the survey data correlate relatively well, the differential settlements computed from the two sets of data vary. Based on discussion with WSDOT, who provided both sets of survey data, it is believed that the column survey data are of higher accuracy compared with the gutter line survey data. However, for comparison purposes, results from both sets of the survey data are presented in the discussions below. Both sets of WSDOT survey data were also compared with the GEOSCOPE data provided by STP to determine the relative accuracy of each data set; however, the results were inconclusive.

Review of load rating reports of the viaduct revealed that many members do not have sufficient elastic capacity to carry current highway standard loading. As a result, WSDOT has posted lane restrictions for the viaduct, limiting trucks to the right-hand-lane only in each direction and not allowing overload trucks. The viaduct has also seen significant damage and distress over its life, presumably both from aforementioned settlement and extreme events such as the 2001 Nisqually Earthquake. Some of the structural members are in poor condition when compared with standards normally used to evaluate new structures. In view of these facts and the planned demolition of the viaduct after the tunnel is complete, WSDOT considers the viaduct as a temporary structure and is willing to accept a reduced level of serviceability such as cracking of the structural members. WSDOT has set life safety as the main performance criteria of the structure.

The review identified some issues in the structural evaluation performed by WSDOT's design-build contractor, STP. While the basic assumptions and the overall analysis approach appear to be reasonable, the review has raised questions regarding the structural modeling methods used in STP's calculations. Most significantly, the method used by STP to account for inelastic action of the structural members and the procedure for applying anticipated structural settlements has been questioned. CH2M HILL has informed SDOT and WSDOT of these issues and is currently in contact with WSDOT and STP in the process of resolving them. Although the impact of these potential discrepancies is not yet clear, successful resolution of these issues will be critical to the validation of STP's viaduct strengthening design.

The review also identified a gap in the accounting of some of the historical and current structure settlement. Because STP performed its evaluation and strengthening design in 2012, differential structure settlements that have occurred since 2011 have not been included in the structural analysis. Figures 3-4 and 3-5 show bar charts of differential structure settlements in both the transverse and longitudinal directions from January 2011 to March 2015 for gutter line and column survey data. The dark blue bars represent the differential settlements that have occurred since STP's analysis was conducted. The green bars next to the dark blue bars show the total expected differential settlements when the expected tunneling settlements are added to the observed differential settlements since 2011. At some bent locations, tunneling is expected to induce differential structure settlement in the opposite direction from that measured since 2011. In these cases, the tunneling settlement offsets the differential settlement at these particular bents and the maximum expected differential settlement is not expected to increase from present condition. As Figures 3-4 and 3-5 show, the observed and predicted maximum differential settlements at some bent locations exceed the settlement limit of 1" that STP used in the strengthening design. In the transverse direction, the maximum observed and expected differential settlement is about 1.25". In the longitudinal direction, the maximum expected total differential settlement is approximately 1.28".

STP's strengthening design of the longitudinal girders and transverse crossbeams included a safety allowance (or factor of safety). Exceeding the 1-inch design settlement has likely reduced this safety allowance, but may not necessarily pose a safety concern. It is recommended that this safety allowance be reevaluated. In addition, pending the successful resolution of the structure modeling issues discussed previously, it is recommended that this portion of the viaduct be actively monitored for both settlement and signs of structure distress. If the magnitude of the differential settlement continues to increase, or if certain signs of structure distress (such as increased cracking in the members) start to develop, remedial action may become necessary.

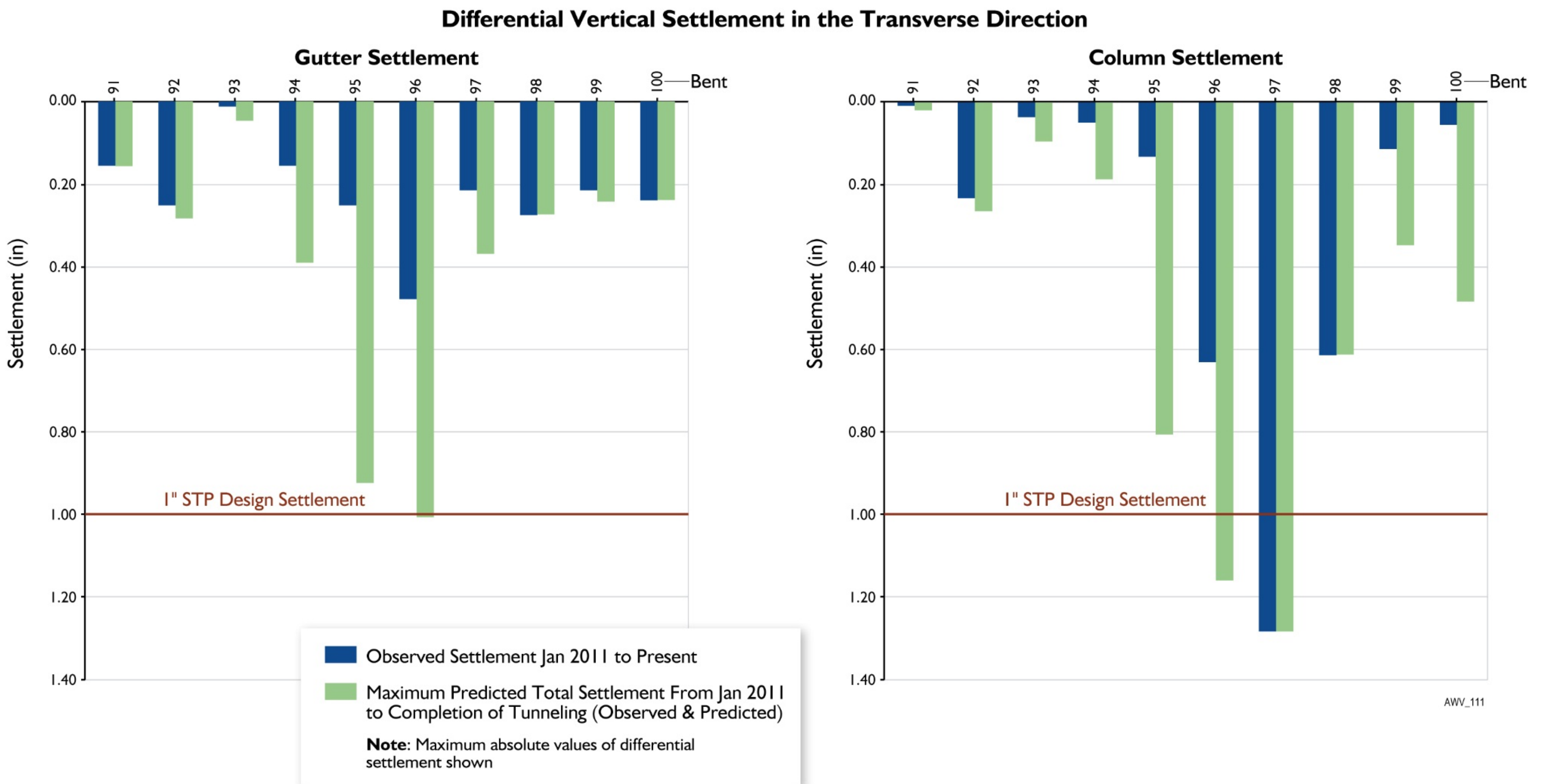

FIGURE 3-4
Differential Vertical Settlement in the Transverse Direction

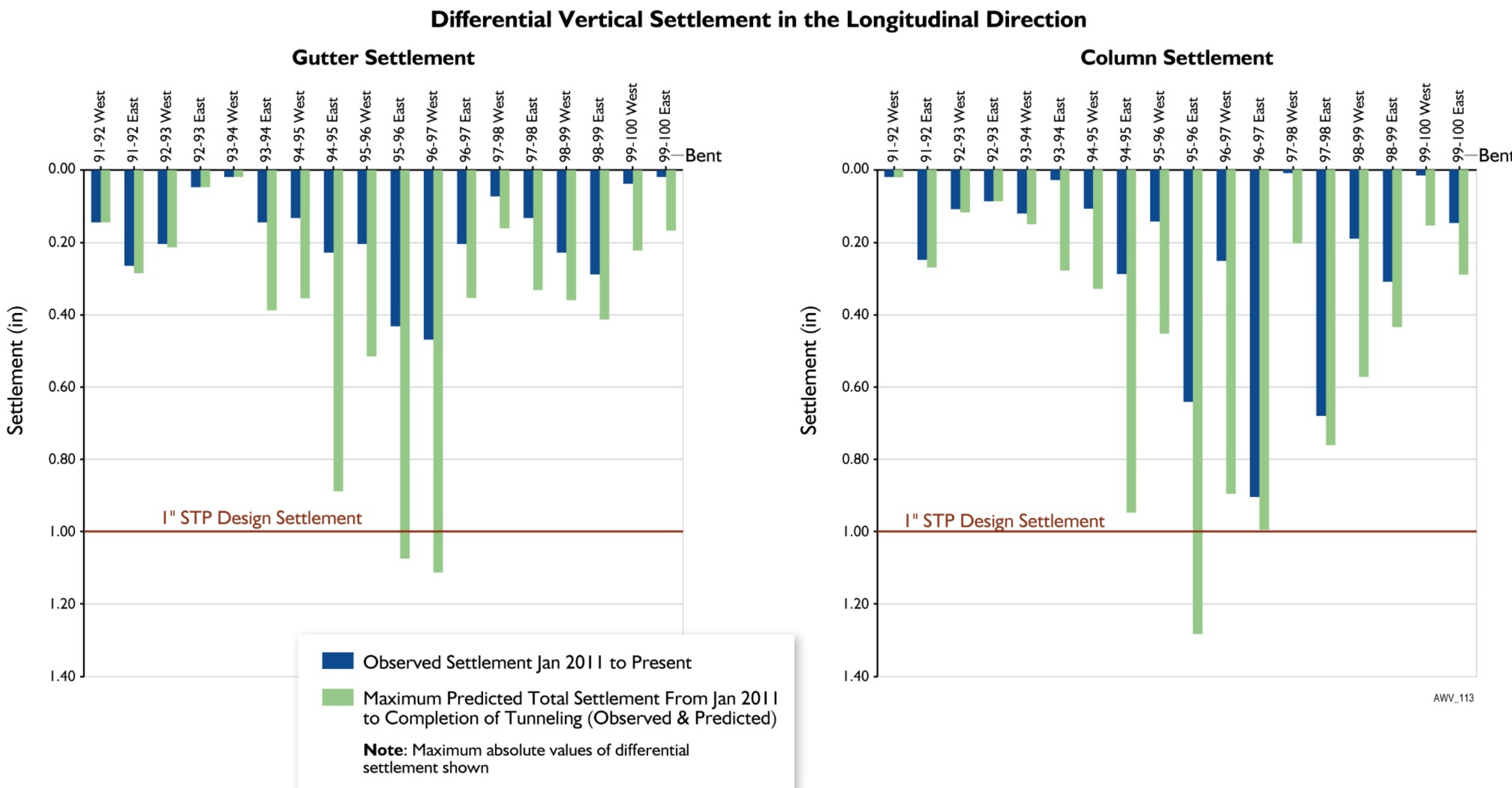

FIGURE 3-5
Differential Vertical Settlement in the Longitudinal Direction

3.2 Mainline Bents 100-121

3.2.1 Introduction

The Alaskan Way Viaduct mainline structure between Bents 100 and 121 shown in Figure 3-6 is a double-decked reinforced concrete structure consisting of seven semi-independent three-span rigid frames. The lengths of the frames vary between approximately 180’ and 222’. With the exception of the south-most frame between Bents 118 and 121, the configuration of each frame is similar to the viaduct structure between Bents 91 and 100. The frame between Bents 118 and 121 is somewhat irregular as the upper and lower deck of the viaduct branch off to the east to connect to the Railroad Way Ramp. To support the widened deck in this area, Bent 121 consists of four columns connected transversely by struts.

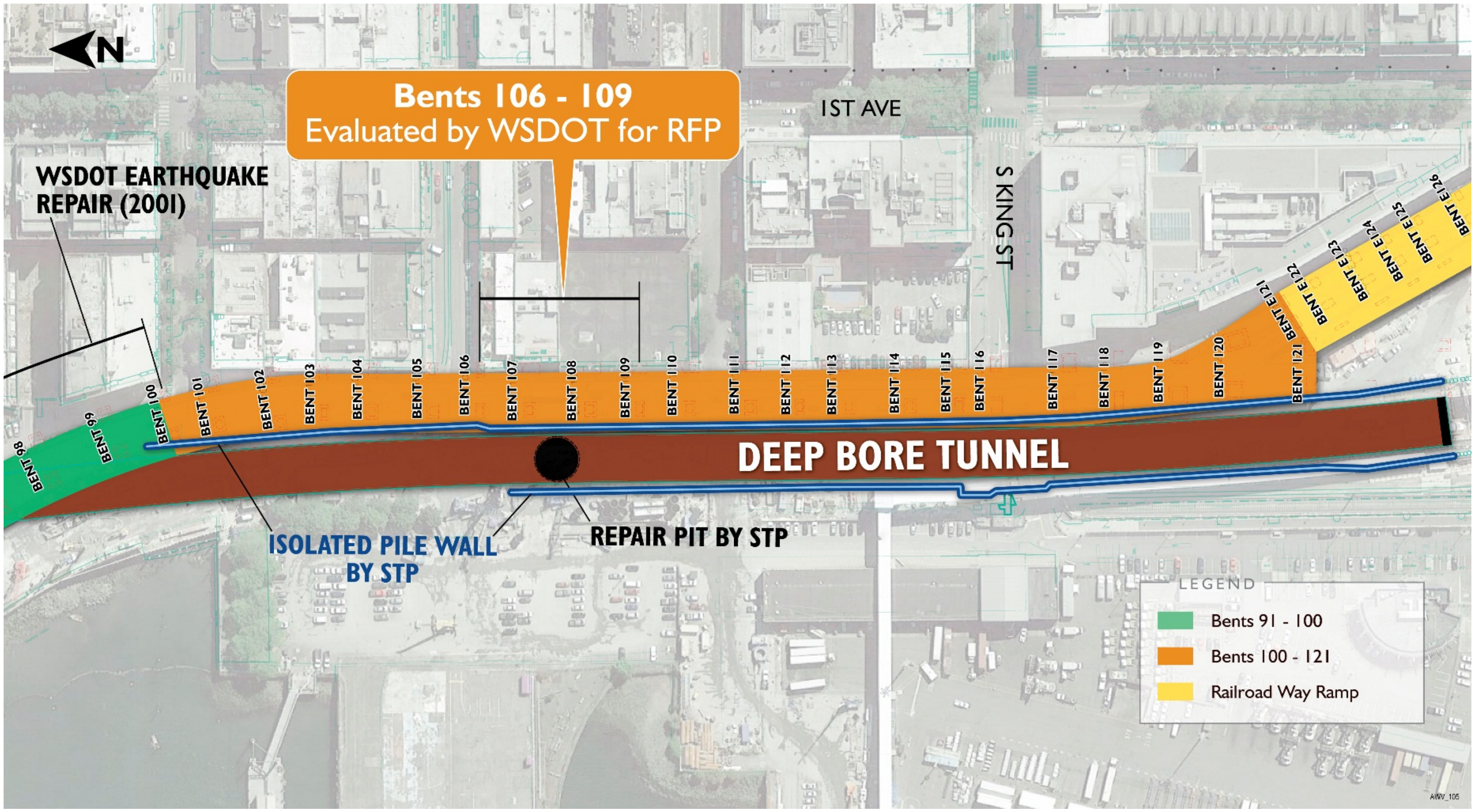

FIGURE 3-6
AWV Mainline Bents 100-121

For the SR99 Bored Tunnel Project RFP, WSDOT retained a consultant to evaluate a typical frame within this portion of the viaduct, between Bents 106 and 109, to assess the impacts to the viaduct caused by potential tunneling settlement. The evaluation suggested that strengthening is required to provide a sufficient safety margin against settlement-induced overstress.

As part of the SR99 Bored Tunnel Project, the design-build contractor, STP, performed settlement mitigation measures in close proximity to this portion of the viaduct. The settlement mitigation measures consisted of constructing a large diameter isolated concrete pile wall west of the viaduct alignment that runs between the bored tunnel and the viaduct. This wall was designed to significantly reduce the structure movement of the viaduct resulting from tunneling operations.

3.2.2 Review Methodology

CH2M HILL reviewed available structure survey data for this portion of the viaduct to evaluate the differential structural settlements observed to date. Past bridge inspection reports, load rating reports, and as-built drawings were reviewed to gain an understanding of the condition of the existing structure. CH2M HILL also reviewed the calculations for the settlement assessment performed by WSDOT's consultant for the structure between Bents 106 to 109. The overall assumptions and approaches of the calculations were checked. The review did not attempt to validate the computer models used in the analysis. Instead, the computer output presented in the calculations was assumed to be generally accurate. The review also consisted of line-by-line checking of representative calculations at selected locations of the structure.

3.2.3 Findings

WSDOT's column survey data for this segment of the viaduct did not start until December 2014, while GEOSCOPE survey data for this segment did not start until mid-2012. So the review was focused on the gutter line survey data. Review of available survey data found that the viaduct structure has experienced low to moderate differential settlement between Bents 100 and 121. The maximum magnitude of the vertical differential settlement approaches 1.5 inches near Bent 119, as shown in Figure 2-6. It should be noted that the reported settlements are from a single source (gutter line survey) and most of the reported differential settlement appears to have occurred prior to April 2001. Settlement values have seen relatively small changes since October 2014. Similar to Bent 91 to 100, the availability of the horizontal survey data is limited. Based on the available data, the magnitude of the horizontal differential movement appears to be small.

The existing settlement assessment performed by WSDOT's consultant between Bents 106 and 109 was based on predicted tunneling settlement alone without taking historic settlement into account. The magnitude of imposed vertical differential settlements used in the assessment were 1-inch in the transverse direction and 0.5-inch in the longitudinal direction and were based on predictions from preliminary settlement analysis. Based on the subsequent settlement analysis performed by STP, which accounted for the mitigating effects of the isolated concrete pile wall, the predicted tunneling settlements were reduced to approximately 0.1-0.2 inches in both longitudinal and transverse directions.

Because tunnel construction has already advanced to the vicinity of Bents 108 and 109, it is reasonable to assume that tunneling settlement has already occurred for a portion of the viaduct within this segment (roughly between Bent 108 and Bent 121). When all sources of settlement are accounted for, differential settlements appear to be within the limits considered in the assessment by WSDOT's consultant, with the possible exception of Bent 119. At Bent 119, the gutter line survey data show a differential transverse settlement of about 1.5 inches. For the rest of the viaduct structure within this segment (Bents 100 to 108), the historic differential settlements are relatively low. When combined with predicted tunneling settlement, the total predicted differential settlement is unlikely to exceed the imposed settlement values used in the analysis.

The analysis by WSDOT's consultant examined flexure and shear strength of the girders, crossbeams, and columns, as well as shear strength of the beam-column joints. The analysis did not include foundations of the viaduct. The assessment concluded that some members of the structure could exceed their elastic capacities under dead and live loads, without including any additional loads caused by differential settlement. These members include the exterior crossbeams and the exterior longitudinal girders. For exterior girders, the demand-to-capacity (D/C) ratio for shear is 2.2 when settlement is considered. The assessment also suggested that strengthening would be required to provide a sufficient safety margin against settlement-induced overstress.

CH2M HILL generally agrees with the approaches and conclusions of the assessment by WSDOT's consultant. Overall, the calculations appear to be conservative. Relatively low (and conservative) material strengths were used in the assessment. In addition, live loads used in the analysis were higher than the vehicular live loads that are currently permitted by the load posting for the viaduct. Furthermore, the assessment was based on elastic analysis and did not take advantage of any internal force redistribution after member yielding occurs. As a result, the conclusions of the assessment are likely to be conservative.

It is our understanding that STP did not perform a structural settlement evaluation or strengthening for this portion of the viaduct. The reason for this decision appears to be the minimal predicted differential settlement caused by tunneling activities in this area. Given the aforementioned observed historical settlement in this area and the member capacity deficiencies identified in the assessment by WSDOT's consultant, it is reasonable to expect that some members of the viaduct structure may be experiencing overstress that is beyond their elastic capacity.

Structural members can typically withstand demands exceeding their elastic capacity to a certain extent because of their innate ductility and the inherent conservative nature of structure design. Based on the observed performance of the viaduct structure between Bents 91-100, the structural members at Bents 91 to 100 appear to have sufficient ductility to accommodate significant settlement-induced flexural overstress, sometimes well beyond the elastic range. Considering the similar detailing between the structures at Bents 100-121 and Bents 91-100, it is reasonable to expect that the structure at Bents 100-121 can also tolerate a certain amount of distress beyond the elastic range, especially for flexure action. Furthermore, WSDOT inspection of this portion of the viaduct has yet to report any signs of significant structure distress. However, the high demand-to-capacity (D/C) ratios, especially those reported for the shear capacities of crossbeams and girders that are more brittle in nature, do raise some concerns. Even after accounting for all the conservatism in the assessment performed by WSDOT's consultant, it appears that some members are likely experiencing demands exceeding their elastic shear capacities. In view of this, as well as the possibility of continued future settlement in the area, further refinement of the settlement evaluation for this segment of the viaduct is recommended to better define the safety margin between structural capacities and demands.

3.3 Railroad Way Ramp

3.3.1 Introduction

South of Bent 121, the original mainline viaduct structure was removed. All traffic on the viaduct is being routed onto the Railroad Way Ramp, which veers to the east of the viaduct mainline alignment and touches down at First Avenue, as shown in Figure 3-7. Between Bent E121 to the north and E130 to the south, the Railroad Way Ramp consist of three two-level, three-span, semi-independent rigid reinforced concrete frames. Each frame consist of two parallel decks at different heights with a length of approximately 138’. At each bent location, the frame consists of three columns connected by transverse crossbeams and struts at upper and lower deck level, as shown in Figure 3-8. Bents within a frame are connected longitudinally by a series of longitudinal girders. The deck slabs at the upper and lower deck level are supported by the longitudinal girders and a number of small transverse stringers. Each frame is separated from the adjacent frames with expansion joints. The columns of the adjacent frames at the expansion joint share a common footing. Split columns are used at several expansion joints.

South of Bent E130, the Railroad Way Ramp splits into two separate parallel structures, as shown in Figure 3-9. The original East Ramp was removed and a temporary ramp consisting of simple-span precast concrete deck slabs and steel substructure was constructed as part of WSDOT’s SR99 S. Holgate Street to S. King Street Viaduct Replacement Stage 2 Project. This temporary structure is not included in the scope of this study. The original West Ramp, between Bents W130 and W141, remains in operation. This portion of the structure consists of one 138’-6” three span rigid frame unit and one 110’ eight-span unit. Each bent of the three-span rigid frame consists of two columns connected by a transverse crossbeam. Longitudinal girders connect adjacent bents and support the deck. The eight-span unit consists of a continuous reinforced concrete beam-and-slab structure enclosed by curtain walls.

As part of the SR99 Bored Tunnel Project RFP, WSDOT’s consultant evaluated two 3-span frames within this portion of the viaduct, between Bents E121 and E127, to assess the impacts of settlement caused by excavation from the South Portal construction. It should be noted that Bents E121-E130 are within the mandatory settlement mitigation zone required by the design-build RFP. However, no known settlement evaluation or strengthening was performed for this part of the viaduct structure by STP.

3.3.2 Review Methodology

No structure survey data was available from WSDOT for this portion of the viaduct and review of settlement data was based on available GEOSCOPE survey data provided by STP. Past bridge inspection reports, load rating reports, and as-built drawings were reviewed to gain an understanding of the condition of the existing structure. CH2M HILL reviewed the calculations supporting the settlement assessment performed by WSDOT’s consultant for the structure between Bents E121 and E127. The review checked the overall assumptions and approaches of the calculations for reasonableness. The review did not attempt to validate the computer models used in the analysis as detailed computer input files were not available. Rather, the computer output presented in the calculations was assumed to be generally accurate. The review also consisted of line-by-line checking of representative calculations for selected locations of the structure.

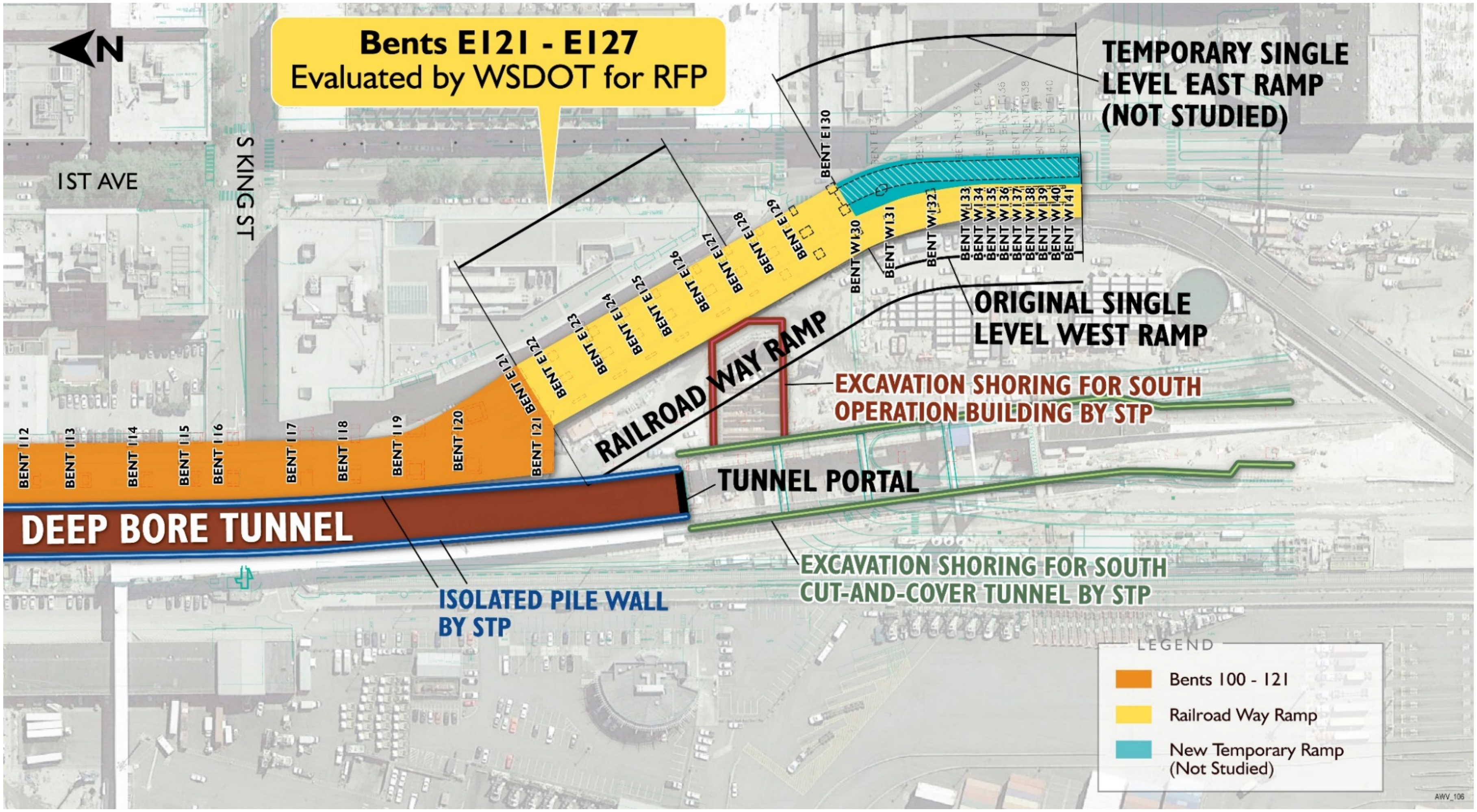

FIGURE 3-7
Railroad Way Ramp Bents E121-W141

FIGURE 3-8
Railroad Way Ramp

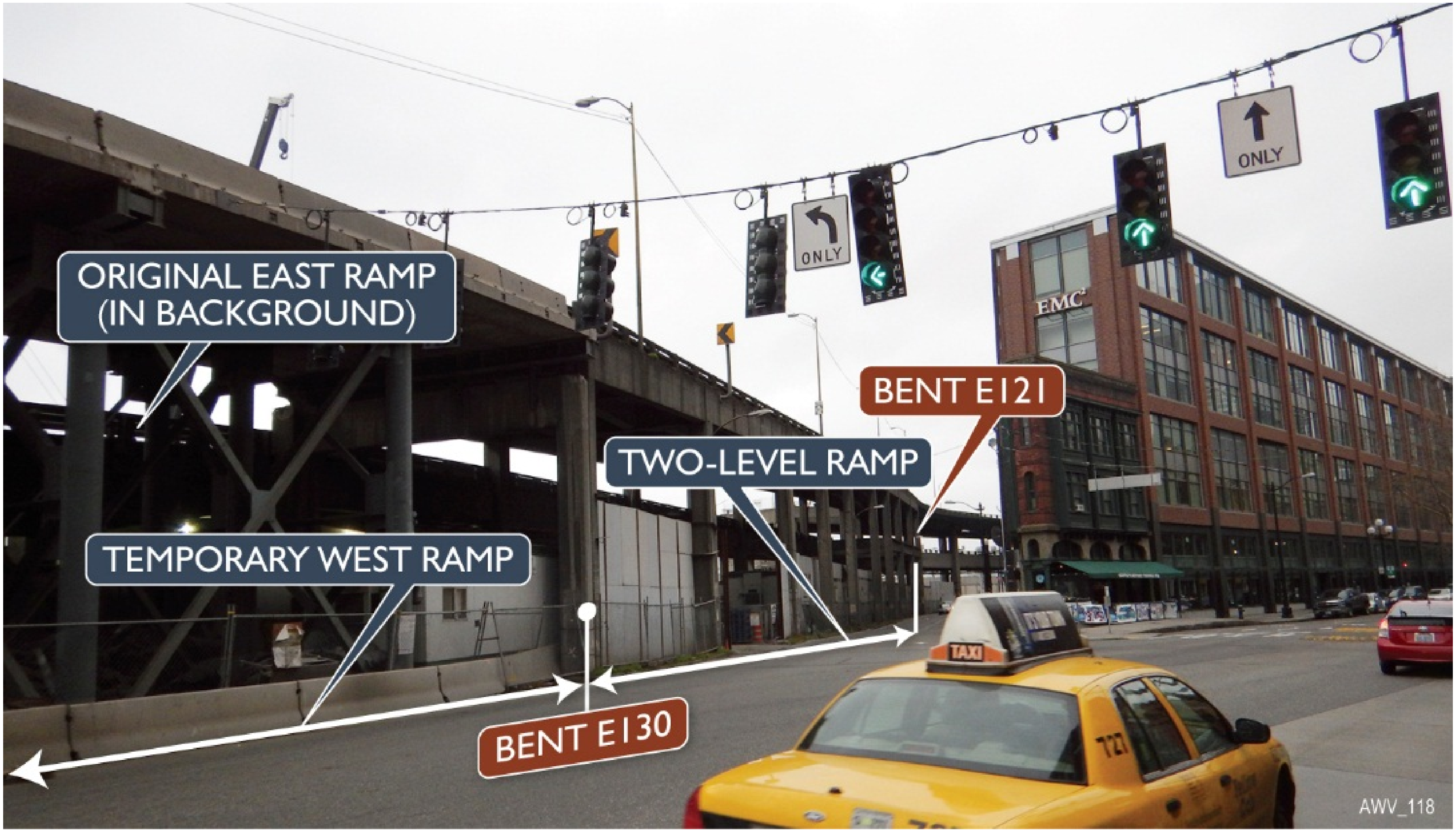

FIGURE 3-9
Railroad Way Ramp

3.3.3 Findings

GEOSCOPE survey data of the Railroad Way Ramp were only available from about July 2012 to 2015. Although historical settlement data prior to 2012 do not exist, the settlements appear to be small since there is no mention of significant structure settlements in the bridge inspection reports. The available GEOSCOPE data appear to contain measurements for the west and middle columns of each bent only, with no data present for the east columns. The maximum observed transverse vertical differential settlement is approximately 0.5 inches between the west and middle columns of Bent 126. The maximum longitudinal vertical differential settlement is about 0.3 inches between the west columns of Bents 125 and 126 and between Bents 126 and 127. The magnitude of horizontal differential movement appears to be small.

The structural assessment performed by WSDOT's consultant was based on a set of hypothetical differential settlements. The magnitude of the transverse differential settlements was 0.5-inch in the vertical direction and 0.5-inch in the horizontal direction. No longitudinal differential settlements were used in the analysis. The reason for not considering longitudinal differential settlement appears to be due to the fact that differential settlements were anticipated to be primarily in the transverse direction, resulting from excavation of the adjacent South Operation Building and South Portal (see Figure 3-7).

The assessment by WSDOT's consultant concluded that the columns and crossbeams perform adequately under these imposed transverse differential movements. Although the analysis approach appears to be reasonable, CH2M HILL's review identified several discrepancies. Of the various members of the structure, only crossbeams and columns were assessed for their structural capacity. In some cases, the reported demand-capacity ratios were not the maximum (controlling) values for a given member. Rather, a lower value was reported. However, in all cases, the unreported maximum demand-capacity ratios are still under 1.0.

CH2M HILL's review also found several gaps in the analysis. No assessment was performed for the longitudinal girders, foundations, column-beam joints, and shear capacity of columns. The analysis was also based on hypothetical differential movements in the transverse direction only. Based on available settlement data, longitudinal differential movements may also need to be considered. For the south end of the structure, between Bents E127 and E130, and W131 and W141, no assessment was performed by WSDOT. In view of the possibility of continued future settlement in this area, it is recommended that further settlement assessment be performed for this part of the viaduct to address these gaps.

3.4 Columbia and Seneca Street Ramps

3.4.1 Introduction

The Columbia and Seneca Street Ramps are shown in Figures 3-10 and 3-11. The Columbia Street Ramp consists of a six-span precast prestressed concrete girder structure supported mostly on single column bents. The superstructure is simply-supported between the bents. The west-most bent, Bent 6, is a straddle bent consisting of two columns connected transversely by a crossbeam, as shown in Figure 3-11. The Seneca Street Ramp consists of a seven-span precast prestressed concrete girder structure supported mainly on single column bents. Like the Columbia Street Ramp, the superstructure is simply-supported between the bents. The two west-most bents, Bents 6 and 7, are straddle bents consisting of two columns connected transversely by a crossbeam, as shown in Figure 3-11.

As part of the SR99 Bored Tunnel Project RFP, WSDOT's consultant assessed the impacts of predicted tunneling settlements on these two structures. The assessment concluded that, while the predicted settlement may result in damage to the existing bearing pads, no significant damage was expected for the columns, girders, crossbeams, and footings of the two structures.

The Columbia Street and Seneca Street Ramps are outside the mandatory settlement mitigation zone required by the SR99 Bored Tunnel Project RFP.

3.4.2 Review Methodology

No structure survey data of the Columbia Street Ramp and the Seneca Ramp was available for review. CH2M HILL reviewed the calculations for the settlement assessment performed by WSDOT's consultant for the two structures. The review checked the overall assumptions and approaches of the calculation for reasonableness. The review did not attempt to validate the computer models used in the analysis as computer input files were not available. Rather, the computer output presented in the calculations was assumed to be generally accurate. The review also consisted of line-by-line checking of representative calculations for selected locations of the structure. Past bridge inspection reports, load rating reports, and as-built drawings were also reviewed to gain an understanding of the condition of the existing structure.

3.4.3 Findings

CH2M HILL's review found that settlement assessments performed by WSDOT's consultant for both structures were based on predicted tunneling settlement. No historic settlement was taken into account except for at Bent 6 of the Columbia Street Ramp. The settlement assessments concluded that the simply-supported, single column structures that represent most of the two ramps are relatively insensitive to differential settlement and no life-safety concerns would arise from predicted tunneling settlements. This conclusion appears to be reasonable.

The straddle bents at the western end of the ramp structures are more sensitive to transverse differential settlement because at these locations the ramp is supported by a rigid frame. The settlement assessment by WSDOT's consultant for Bent 6 of the Columbia Street Ramp included consideration for 4 inches of historical vertical differential settlement, which is evidenced by the small downward settlement at mainline Bent 92, which shares the foundation with the north column of Bent 6 of the Columbia Street Ramp, and the much larger settlement at Bent 93, which is adjacent to the south column of Bent 6. These settlements are shown in Figure 2-6 and are corroborated by inspection reports.

CH2M HILL generally agrees with the approach used in the settlement assessment of Bent 6 but notes that the analysis did not include evaluation of the foundations nor several potential critical shear locations in the crossbeam. A cursory check of these critical locations seemed to suggest that the controlling demand-capacity ratios due to the historical differential settlement could slightly exceed 1.0 when using nominal material properties. When taking into account the actual material properties, it is likely these demand-capacity ratios would be less than 1.0, which is generally considered as the upper limit for adequate capacity. It appears that the structure has sufficient capacity to resist the demand resulting from settlement observed to date. Furthermore, WSDOT inspects the condition of this bent on a regular basis and has not reported any significant signs of distress or cracking.

The predicted tunneling settlement at Bent 6 is relatively small compared with the historical settlement and does not appear to be a significant concern. It is recommended that this bent to be actively monitored. Should the differential settlement at Bent 6 continue to increase, further evaluation may be necessary.

WSDOT's consultant did not perform a structural assessment of the two straddle bents at the Seneca Street Ramp. There was reported historic settlement in the vicinity although the magnitude of such settlement is unknown. No report of significant structure distress or cracking was found in the inspection reports. Moreover, due to the distance of the west end of the ramp from the proposed tunnel alignment, this portion of the ramp is located outside the zone of influence for tunnel-induced settlement. It is recommended that the settlement at Bents 6 and 7 of the Seneca Street Ramp to be actively monitored. Further evaluation may be required if the magnitude of the differential settlement becomes significant.

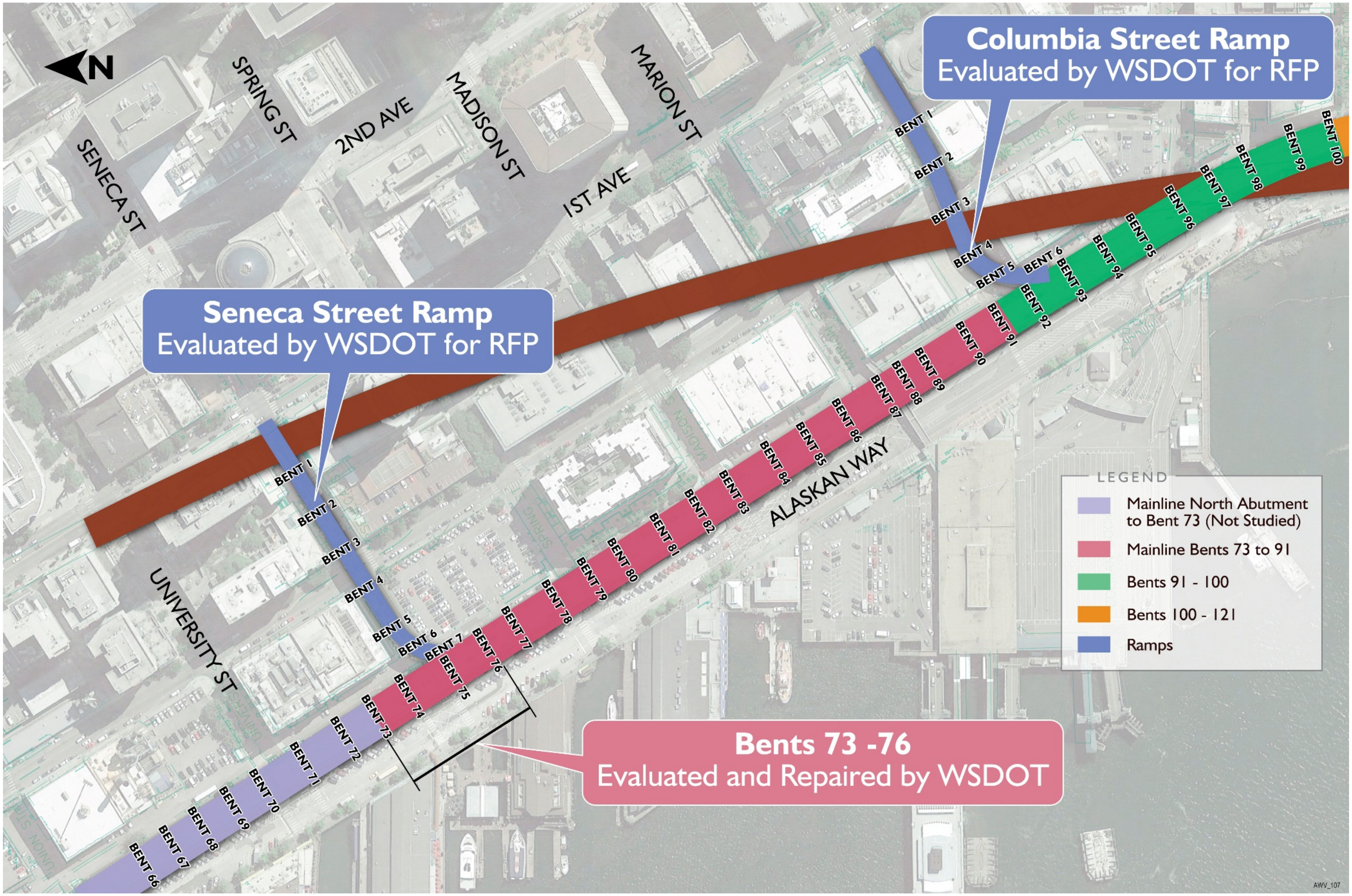

FIGURE 3-10

Columbia and Seneca Street Ramps and Mainline Bents 73-91

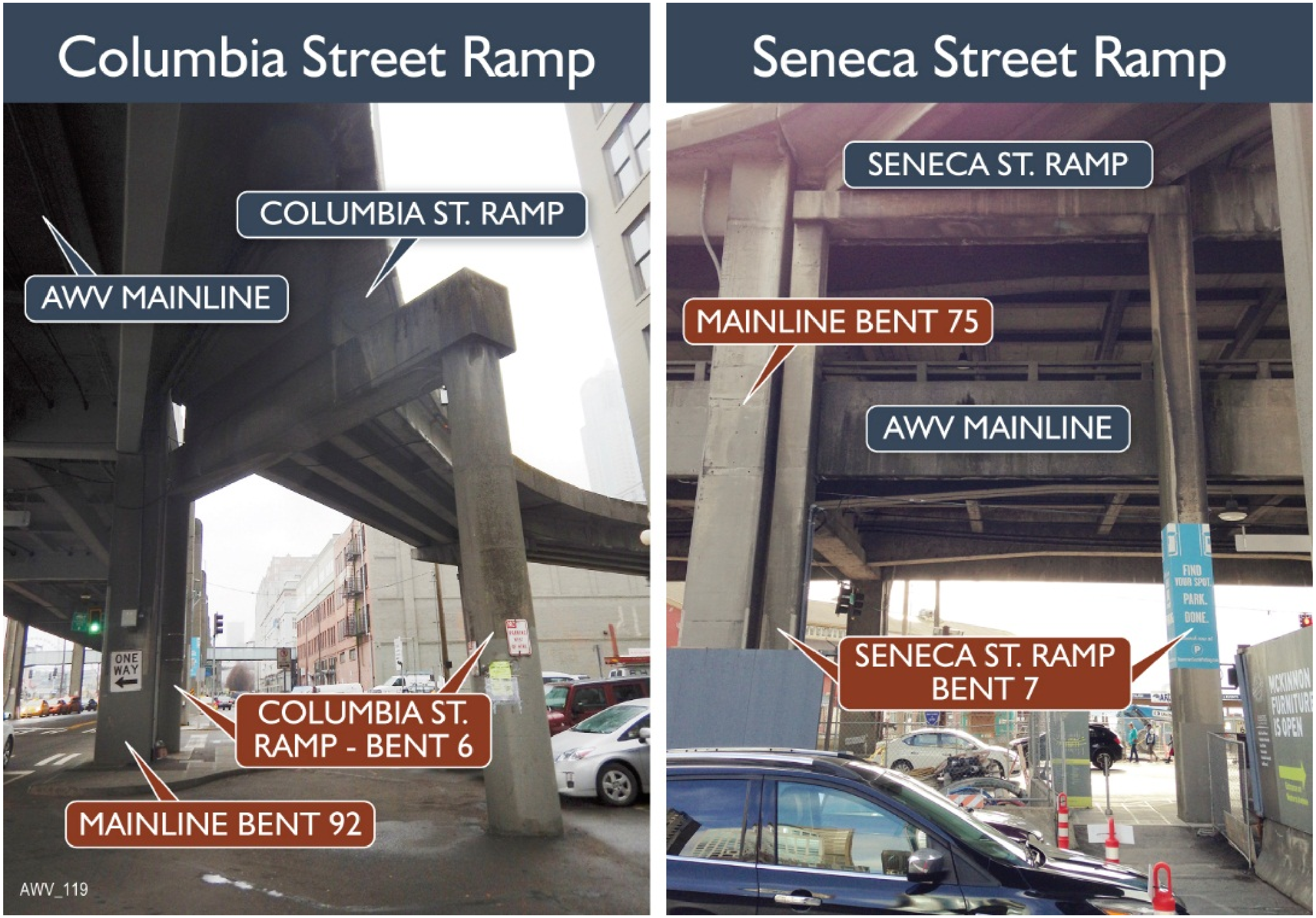

FIGURE 3-11
Columbia and Seneca Street Ramps

3.5 Mainline Bents 73-91

3.5.1 Introduction

The viaduct mainline structure between Bents 73-91 is similar in configuration to the viaduct structure between Bents 91-100. This portion of the viaduct consists of four 222’ three-span frames, one 165’ two-span frame, and one 230’ three-span frame, as shown in Figure 3-10.

Significant historical settlement has been observed near Bents 75 and 76, as Figure 3-12 shows. Specifically, it was reported by WSDOT that the east footing of Bent 76 appeared to have settled 2.7 inches, while the east footing of Bent 75 appeared to have settled 1.8 inches. WSDOT also reported that the east footing of Bent 79 had settled 1.3 inches. It is understood that cracks were discovered in the upper west column of Bent 76 during a recent WSDOT inspection in March 2014. As a result, WSDOT performed a structural settlement analysis for the three span frame between Bents 73 and 76. Based on the results of the analysis, WSDOT repaired the upper west column of Bent 76 in 2014 using epoxy injection.

It should be noted that this portion of the viaduct is outside the mandatory settlement mitigation zone required by the SR99 Bored Tunnel Project RFP.

3.5.2 Review Methodology

CH2M HILL reviewed available structure survey data for this portion of the viaduct to determine the differential vertical structural settlements that have been observed to date. Horizontal survey data do not exist. Past bridge inspection reports, load rating reports, and as-built drawings were reviewed to gain an understanding of the condition of the existing structure.

CH2M HILL also reviewed the calculations for the settlement assessment performed by WSDOT for the three-span structure between Bents 73 to 76. The review checked the overall assumptions and the calculations for reasonableness. The review did not attempt to validate the computer models used in the analysis as computer input files were not available. Rather, the computer output presented in the calculations was assumed to be generally accurate. The review also consisted of line-by-line checking of representative calculations.

3.5.3 Findings

CH2M HILL’s review of available survey data found that the viaduct structure experienced significant differential settlement in the area between Bents 74 and 76. The maximum magnitude of vertical differential settlement appears to be in excess of 3 inches according to gutter line survey. This magnitude matches relatively well with the settlement reported by WSDOT (2.7 inches). The magnitude of horizontal differential settlement could not be determined as no horizontal survey data were available.

WSDOT’s settlement analysis focused on the upper west column at Bent 76, since this is the location where the most significant cracking was observed. The analysis computed capacity-to-demand ratios for flexure and shear in the column and the results suggest that the column has adequate capacity to resist settlement-induced stress. The lowest capacity-to-demand ratio reported was 1.22, with 1.0 usually considered as the minimum for adequate capacity. CH2M HILL’s review found the overall analysis approach to be reasonable and the calculations appear to be conservative. However, the analysis did not explain why the column exhibited significant signs of cracking at these relatively low demand levels. Moreover, the analysis did not examine the effect of settlement on rest of the members in the frame.

Considering the magnitude of observed differential settlement in this area, it is recommended that this portion of the viaduct be actively monitored. The settlement assessment should also be expanded to include structural members other than columns. At a minimum, exterior longitudinal girders and crossbeams, which appear to be the most vulnerable members based on the analysis performed for similar frames between Bents 91-100, should be examined to establish their safety margin.

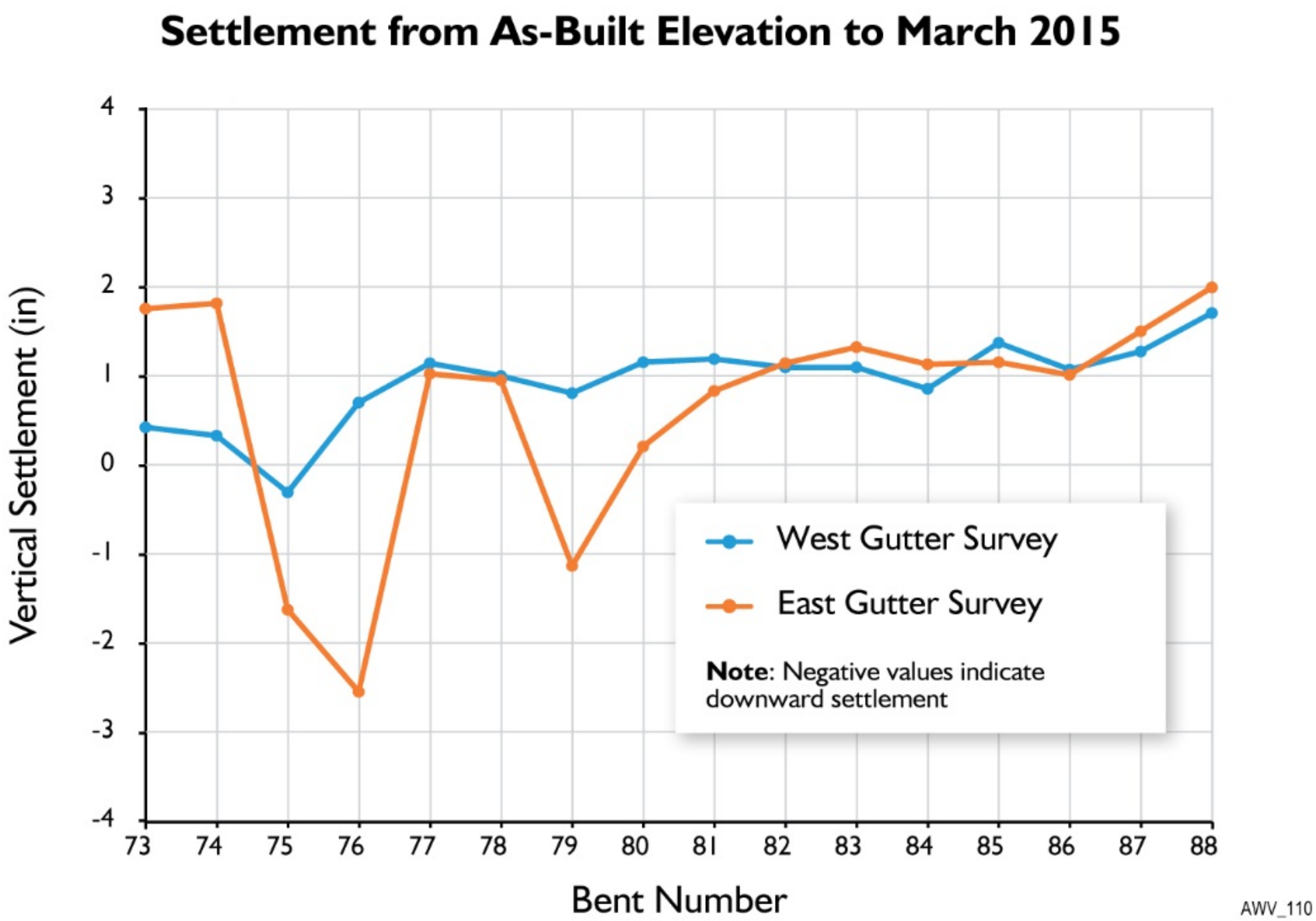

FIGURE 3-12
Structural Settlement – Bents 73 to 88 (From As-Built Elevation to March 2015)

4 Summary of Findings

4.1 Summary of Findings

At the request of the Seattle Department of Transportation, CH2M HILL performed a technical review of existing structure settlement assessments, analyses, and strengthening design calculations prepared by WSDOT, WSDOT's SR99 Bored Tunnel design-build contractor, STP, and their consultants. The goal of this review was to evaluate the effects of observed structure settlement on the structural capacity of the Alaskan Way Viaduct. The area for this study consists of the south end of the existing Alaskan Way Viaduct between Bents 73 and 121, the Railroad Way Ramp, and the Columbia Street and Seneca Street Ramps. The findings from this technical review are summarized below.

The review included an evaluation of observed structure settlement to date. The settlement data were assembled from multiple sources, including WSDOT's gutter line and column surveys, as well as survey data provided by STP. The temporal and spatial coverage of settlement data vary significantly between the different sources. There are also noticeable discrepancies between the different data sets. An attempt was made to address these discrepancies by comparing data from different sources, but the findings were inconclusive. Nevertheless, data from all sources appear to indicate that there has been moderate to significant structure settlement at several locations within the study area.

The gutter line survey, which is the only data source that goes back to the time prior to 2010, also shows significant historical settlement in several locations. Reported differential settlement, which is of main concern for the structure, is most pronounced between Bents 91-100, near Bent 119, near Bents 75 and 76, and at Bent 6 of the Columbia Street Ramp (see Figures 2-6 and 3-12). The maximum magnitude of vertical differential settlement is approximately 5-6 inches between Bent 91 to 100, approximately 1.5 inches near Bent 119, approximately 3 inches near Bents 75 and 76, and approximately 4 inches at Bent 6 of the Columbia Street Ramp. It should be noted that the majority of the aforementioned settlement appears to have occurred prior to 2011, with only a minor portion attributed to the timeframe between 2011 and present time.

The review also included several existing settlement assessments, prepared for different portions of the viaduct by either WSDOT, WSDOT's consultants, or STP. The findings from the review are summarized below:

- **Mainline Bents 91 to 100:** Settlement assessment and strengthening design were performed by STP for mainline Bents 91 to 100. CH2M HILL's review identified some issues regarding the structural modeling methods used in STP's calculations. The impact of these potential discrepancies is being studied and is not yet clear. The review also identified a gap in the accounting of structure settlement. Differential structure settlements that have occurred since 2011 have not been included in STP's structural analysis. The additional settlement has likely reduced the safety allowance of the strengthening design, but may not necessarily pose a safety concern. This safety allowance should be reevaluated. It is also recommended that this portion of the viaduct be actively monitored for both settlement and signs of structure distress. If the magnitude of the differential settlement continues to increase, or if certain signs of structure distress (such as increased cracking in the members) start to develop, remedial action may become necessary.
- **Mainline Bents 100 to 121:** A settlement assessment was performed by WSDOT's consultant for a typical three-span frame between Bents 106 to 109. CH2M HILL generally agrees with the approaches and conclusions of the settlement assessment. Overall, the calculations appear to be

conservative. The review found that current observed settlement appears to have slightly exceeded the settlement considered in the analysis at Bent 119. Given the member capacity deficiencies identified by WSDOT's consultant, it is reasonable to expect that some members, especially exterior longitudinal girders and crossbeams, are likely experiencing overstress that is beyond their elastic shear capacity. Considering the similarity in detailing between the structures at Bents 100-121 and Bents 91-100, it is reasonable to expect that the structure at Bents 100-121 can tolerate a certain amount of distress beyond the elastic range, especially for flexure action. WSDOT's inspection of this portion of the viaduct has not reported any signs of severe structure distress. However, given the brittle nature of shear behavior, as well as the possibility of continued future settlement in the area, further refinement of the settlement evaluation for this segment of the viaduct is recommended to better define the safety margin between structural capacities and demands.

- **Railroad Way Ramp:** WSDOT's consultant performed a structural evaluation of a portion of the ramp for a hypothetical set of transverse differential movements and concluded that the columns and crossbeams performed adequately under these movements. CH2M HILL's review found the analysis approach to be reasonable and only identified minor discrepancies in the analysis that do not affect the final conclusions. The review also found several gaps in the analysis. No assessment was performed for the longitudinal girders, foundations, column-beam joints, and shear capacity of columns. It is recommended that further settlement assessment be performed for this part of the viaduct to address these gaps.
- **Columbia and Seneca Street Ramps:** Settlement effects for the Columbia Street and Seneca Street Ramps were assessed by WSDOT's consultants as part of the SR99 Bored Tunnel Project RFP. CH2M HILL's review found that the settlement assessments for both structures are reasonable and only contain minor discrepancies. For the Columbia Street Ramp, it appears that the structure has sufficient capacity to resist the demand resulting from settlement observed to date. If the differential settlement at Bent 6 continues to increase, further evaluation may be necessary. For the Seneca Street Ramp, no settlement assessment was performed for the two straddle bents and the magnitude of differential settlement is unknown. No report of significant structure distress or cracking was found in the inspection reports. It is recommended that the settlement at Bents 6 and 7 of the Seneca Street Ramp to be actively monitored. Further evaluation may be required if the magnitude of differential settlement becomes significant.
- **Mainline Bents 73 to 91:** WSDOT performed a settlement analysis for the frame between Bents 73 and 76 after discovering significant differential settlement at some of the bents and cracking at one of the columns. WSDOT's settlement analysis focused on the upper west column at Bent 76 and found the column capacity to be adequate. CH2M HILL's review found the overall analysis approach to be reasonable and the calculations appear to be conservative. However, the analysis did not examine the effect of settlement on the rest of the members in the frame. It is recommended that this portion of the viaduct be actively monitored. Considering the magnitude of differential settlement, it is recommended that the settlement assessment be expanded to include other structural members such as exterior longitudinal girders and transverse crossbeams.

4.2 Recommendations for Further Evaluation

Given the current condition of the viaduct structure and the magnitude of the observed settlements, the viaduct should be actively monitored for any additional differential settlement as well as any signs of distress. As discussed in the previous section, it is recommended that refinements to the existing settlement assessment be performed for several portions of the viaduct structure (between Bents 100 to 121, the Railroad Way Ramp, and between Bents 73 to 91) to address any gaps in the existing assessment. For the portion of the viaduct between Bents 91-100, the safety margin of the strengthening design should be re-evaluated taking into consideration the observed differential structure settlements since 2011. Further evaluation may also need to be carried out for the structure between Bents 91 to 100 to resolve any remaining issues raised during this review.