Alaskan Way Viaduct
Summary – Safety and Service Limitations of the Alaskan Way Viaduct

Background:

The Alaskan Way Viaduct is a 2.1 mile long double-decked, reinforced concrete Viaduct carrying State Route 99 along the shoreline of Elliott Bay past downtown Seattle. It is a vital part of Washington's highway system through Seattle, carrying approximately 110,000 vehicles per day. The Viaduct was constructed in two major phases. The first was designed by the Seattle Engineering Department, and built in 1952. The second section, to the south, was designed by the Washington State Department of Transportation (WSDOT), and built in 1956. The design details for the two sections differ, however neither section meets modern standards for earthquake resistant design.

The Viaduct was designed and constructed of reinforced concrete using the technology of the 1950's. Engineering materials and design standards have advanced significantly since that day, including those related to earthquake design. The Puget Sound region is prone to major earthquakes, with a recurrence interval for significant events in the range of 20 to 25 years. Limited segments along the Viaduct are exposed to additional seismic risks related to the Seattle seawall structure, which in the event of major soil liquefaction in an earthquake may allow lateral spreading of the soil that provides support to the pile foundations on the Viaduct.

On February 28, 2001 the Nisqually earthquake struck the Puget Sound region of Washington State. The epicenter of this magnitude M_w=6.8 earthquake was located in the Nisqually Delta about 12 miles northeast of Olympia, WA and about 35 miles south of Seattle, WA. The Viaduct sustained significant damage in the earthquake, but continued to be serviceable soon after the event, and on to this day. Post-earthquake evaluations were quickly commissioned by WSDOT, and included a review of the Viaduct by a Blue Ribbon Panel of structural engineering experts. This "Structural Sufficiency Review Committee" investigated the post-earthquake damage, conducted independent evaluations of the viaduct design and construction, and authored a report to WSDOT in June of 2001. [1] The report recommended that the Viaduct be replaced, rather than retrofitted.

Limitations of Design and Construction:

The period of design and construction of the Viaduct preceded a time of significant changes in the design methodology for reinforced concrete. The transition from working stress design to ultimate

strength design was another decade in coming to the bridge design field. The design methods of the day were based on the expected performance under normal loads for a structure in like-new condition, without any particular reference to the maximum strength of the structure for extreme loads such as earthquakes. In addition, materials of the day were produced consistent with the demands of design. Since breaking strength was not the focus of designers or constructors, the performance of materials at the extremes of service were not investigated.

There are three particular aspects of the 1950's technology that relate closely to the limitations of the Viaduct to serve the modern traffic needs of the corridor, irrespective of major earthquakes.

> Design Shear Strength: Since design codes did not address loadings beyond normal service level, the code did not consider what might happen to concrete beam members once they cracked in shear due to overloads. The shear design provisions did not require the extent of reinforcing required today – often about half as much steel reinforcing as today. As a result, with larger trucks and environmental overloads (see below), shear design of the viaduct does not provide the level of safety required for transportation structures today.
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> Reinforcing Steel Design: The 1950's was in a period of transition in the manufacturing of reinforcing steel for concrete structures. Earlier steel reinforcing was little more than steel billet bars, bent at their ends as a hook anchor into concrete. By the 1950's, these bars generally included deformations to improve the bond of reinforcing to concrete, and provide more of a composite member that was possible with plain reinforcing. But the design of deformed bar had not advanced to modern standards, in part due to the focus on only service level design, which does not evidence the same demands on reinforcing design as does ultimate strength design. The bond capacity of 1950's steel is thus considerably less than that of today, both due to the square bar shape of some reinforcing, and due to the less develop deformation pattern rolled into the bars.
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> Material Certifications: Part of the current limitation with reinforcing steel that relates to the 1950's design is the material itself. At the time of Viaduct construction, reinforcing steel was not a specialized material item. Virtually any steel scrap would be made into reinforcing bar, without much regard for the particular material chemistry of the steel. As a result, there was a wide disparity in the quality, chemical composition, and weldability of reinforcing steel from this era. This is particularly significant when considering some of the connection details used for the Viaduct. The major portal bents that support the Viaduct have very large moment and shear demands on the "knee joints" (those joints that connect the columns to the massive transverse support beams). Contemporary standards include design rules for effecting the transition of large forces in reinforcing within a detail such as this. But at the time of Viaduct construction, this transition was accomplished by welding reinforcing bars within this critical detail. Welding itself was not well developed in the early 1950's, and the combination of reinforcing bar steel that was not conducive to welding, and welding procedures that did not yet account for high carbon steel or moisture within weld metal resulted in details like that which ruptured in the Nisqually Earthquake.

Fracture at Knee Joint

Cracking at Knee Joint

Age and Deterioration:

The Viaduct has served as a primary artery for Seattle area transportation for over 50 years. Until recently the design life assumed for design and construction codes for bridges in the US was 50 years. However, that projection of design life did not include consideration of the extreme events of earthquakes, nor did it consider the limitations of design and material technology noted above. In addition, the Viaduct carries a significant volume of truck traffic. Trucks of today have larger axle weights and larger total weights, and these larger vehicles have increased the rate of wear on the viaduct in recent years. The acceleration of deterioration from traffic is quite evident since the Nisqually Earthquake as explained below.

Effects of the Nisqually Earthquake:

The Nisqually Earthquake of February 28, 2001, cause significant structural damage to the Viaduct. The most severe damage occurred at Bent 100, near Washington Street. The Viaduct alignment curves in this region, and complex response of the structure at this turn amplified demand on the structure. The post-earthquake review by the Structural Sufficiency Review Committee[1] determined that a longer duration of ground shaking would likely have caused liquefaction of the supporting soils as well as extensive structural collapse along the Viaduct.

The particular damage to the Viaduct from the earthquake is documented elsewhere.[1 2] What is of major concern is the accelerated deterioration of the Viaduct since the earthquake. WSDOT has continually monitored the Viaduct after the earthquake, tracking local deterioration as evidenced by increasing cracks and crack widths, as well as foundation settlements. [3]

The traffic loading today is similar to that before the earthquake; with some truck weight restrictions imposed due to the condition of the structure that lower demand from pre-earthquake conditions. So it is somewhat unexpected to see ongoing foundation settlement and structural deterioration continue so long after the earthquake. The accelerated deterioration can be attributed to a combination of age and destructive effects of the earthquake. The latter is what heightens the need for immediate action to replace the viaduct.

The earthquake imposed extreme loads on the viaduct, in some local conditions to the point of failure. But the general conditions throughout the viaduct involved load excursions well beyond the service level loads for which it was designed. There are at least two consequences of that extreme loading that affect the structural behavior we see now.

Destruction of reinforcing steel bond: As described above, the reinforcing steel in the viaduct is not the same as that used today. At the working level loads envisioned for the 1950's design, the reinforcing acts through a combination of adhesion between steel and concrete paste and mechanical bond with deformations on the bars. Due to the limited spacing of deformations, lack of length for development of details, and the rectangular shape of many bars, the mechanical bond is not sufficient to restrain slippage of the reinforcing steel within the concrete matrix. Prior to the earthquake, the combination of adhesive bond and mechanical bond worked to resist the loads imparted to the bridge. However, the extreme loads of the earthquake in many cases destroyed the adhesive bond to the reinforcing bars, leaving only the mechanical bond to work alone. Where adhesive bond was destroyed, increased cracking is observed, some of it very significant. This condition also leads to "working" cracks – cracks that change under load due to slip along the reinforcing bars that cross the crack. Continued deterioration of the structure will continue to occur at these locations at an accelerated rate.

Changes in the ground support conditions: Soil mechanics for foundation design is somewhat complex on a mechanistic level. Foundation engineering is empirical as a result, and that was especially true at the time of design in the 1950's. Most of the Viaduct is supported on piles, which in turn are supported by a combination of end bearing and friction along the pile length. The pile capacities were proven during construction by the process of pile driving, which reflected the soil conditions under the foundations at that time.

The occurrence of significant settlement[3] after the earthquake is adding greatly to the demands on the Viaduct structure, and WSDOT has developed contingency plans for emergency replacement of sections that appear most likely to fail due to settlement. The cause of post-earthquake settlement is due to one or a combination of causes that were triggered by the earthquake. There may have been local failures of the foundation piles during the earthquake. It is possible that partial failures occurred that allowed subsequent settlement, however this type of event would typically have shown considerable initial settlement during the earthquake, which was not observed. A more likely cause of delayed settlement is a remolding of the soil during the earthquake. This would occur during the ground shaking, but would be manifest after the earthquake in the form of soil consolidation or load transfer within the changed foundation matrix. Soil behavior would be also affected by a change in groundwater conditions as a result of the earthquake. We know that at certain stations along the viaduct that the ground was perilously close to experiencing soil liquefaction. [1] Even in locations where piles were designed as end bearing, the presence of soil friction along the length of the pile as originally installed would limit settlement. Loss of this incidental friction component of pile resistance would be expected during the earthquake, resulting in additional loading being applied to the end bearing condition. This loss of friction is conceptually similar to that described above for the adhesive component of reinforcing in the structure. Once it is lost, deterioration of structural performance accelerates, even though subsequent loads are the same as before the earthquake.

Implications for Service of the Viaduct:

The age and associated load rating of the Alaskan Way Viaduct is alone a basis for programming replacement. However, the acute and latent damages caused by the Nisqually earthquake change the need from normal programming to an emergency status. Structural details are replicated throughout the length of the Viaduct, and those that have failed differ from the remainder only in the variance of original construction tolerances – a razor thin margin. The accelerated deterioration of the Viaduct is approaching the point of a zipper effect; subsequent failures of similar details can be expected with future events. Future earthquakes

notwithstanding, the accelerated deterioration since the Nisqually earthquake handicaps the serviceability of the Viaduct. From the risks of falling concrete spalls, to the structural deterioration due to bond loss and increased foundation settlement, the current condition of the viaduct is not reliable. As a result, regular closures are required for extensive structural inspections, just to assure that additional latent defects do not unduly compromise public safety. And when the risk of future earthquakes is considered, the Viaduct fails precipitously according to any modern engineering standards.

A Perilously Frayed Lifeline:

The Alaskan Way Viaduct and SR99 carry approximately 25% of the north-south traffic through the City of Seattle. Much of this traffic is essential commercial traffic from West Seattle northward. The closure of the Viaduct after the Nisqually Earthquake revealed the degree to which Seattle relies on the Viaduct for essential transportation and commerce.

The Viaduct was deteriorating due to age and the demands of extensive commercial traffic many times more than the Viaduct was designed for. However, the Nisqually earthquake changed the complexion of transportation planning related to the Viaduct. The earthquake not only caused direct and immediate damage to the Viaduct, but it also created latent deterioration throughout the structure. This condition greatly heightens the need for replacement, future earthquakes not withstanding.

Our national transportation system has some unflattering examples of inaction and neglect that have caused disruptions of service inconsistent with our progressive transportation policies. From the Silver Bridge, to the Cyprus Viaduct to the West Side Expressway in Manhattan, sudden disruption of vital transportation structures have crippled local economies and compromised public safety. The State of Washington is determined to avoid such an event with the Alaskan Way Viaduct. The duration required for planning and constructing a new facility is approaching the recurrence interval for another significant earthquake event in the Puget Sound Region – an event that could have catastrophic consequences for traffic using the Viaduct. We have taken proactive measures to monitor and control utilization of this crippled component of our transportation infrastructure. We have worked in concert with the City of Seattle and the Federal Highway Administration to clarify the critical need for immediately proceeding with replacement of the Viaduct, and we are anxious to work with Congress to meet the funding needs to assure reliable and safe service for this vital transportation asset.