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Seismic Vulnerability of the Alaskan Way Viaduct Phase II

SEISMIC VULNERABILITY OF THE ALASKAN WAY VIADUCT: SUMMARY REPORT

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16. ABSTRACT

University of Washington researchers studied the structural and geotechnical aspects of the seismic vulnerability of the Alaskan Way Viaduct. A design-level earthquake would strongly shake the viaduct and cause widespread liquefaction of the underlying loose, saturated soils. The liquefaction would likely cause the foundations to settle and to move laterally. The Alaskan Way Viaduct's reinforcing details make the viaduct particularly vulnerable to strong shaking and to foundation movements induced by liquefaction. In a design level earthquake, the Alaskan Way viaduct would be severely damaged and multiple sections could collapse.

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SEISMIC VULNERABILITY OF THE ALASKAN WAY VIADUCT: FINAL SUMMARY REPORT

S.L. Kramer and M.O. Eberhard

University of Washington

The Alaskan Way Viaduct, which carries an average of 86,000 vehicles per day, is one of only two north-south highways through downtown Seattle. It is one of a number of major highway bridges identified by the Washington State Department of Transportation (WSDOT) as requiring special analysis to evaluate their vulnerability to earthquakes (Lwin and Henley, 1993). This report summarizes a detailed investigation of the seismic vulnerability of the Alaskan Way Viaduct.

Following the collapse of the Cypress Viaduct in Oakland, California, during the 1989 Loma Prieta earthquake, WSDOT initiated a series of analyses of the seismic vulnerability of the Alaskan Way Viaduct. The results of a preliminary, in-house investigation conducted by engineers in the WSDOT Bridge & Structures office shortly after the Loma Prieta earthquake were described by Dodson et al. (1990). That in-house investigation was then independently reviewed (Brown et al., 1992) by a team of researchers from the University of Washington (UW). The UW team generally concurred with the findings of the WSDOT preliminary investigation and recommended that a more detailed investigation be undertaken. The detailed investigation was to include both structural and geotechnical engineering aspects of the vulnerability of the viaduct.

This report summarizes both the structural and geotechnical engineering aspects of the seismic vulnerability of the Alaskan Way Viaduct (Eberhard et al., 1995, Knaebel et al., 1995, and Kramer et al., 1995) and presents the conclusions of the researchers who performed the investigation. WSDOT is planning a subsequent study to develop strategies and cost estimates for mitigating deficiencies identified in this study.

BACKGROUND

The seismic vulnerability of the Alaskan Way Viaduct is influenced by many factors, including its location, age, and construction. The performance of the Alaskan Way Viaduct and other viaducts in previous earthquakes also provides information regarding the Alaskan Way Viaduct's seismic vulnerability. Background information on these important factors is presented in the following sections.

Geologic Setting

From the standpoint of geological/geotechnical conditions, the Alaskan Way Viaduct site is dominated by thick deposits of loose, saturated soil. Most of the loose soils were placed as fill during reclamation of the area's tideflats and extension of the waterfront toward Elliot Bay in the late 1800s and early 1900s. Some of the loose soils, particularly those south of about Yesler Way, are natural tideflat soils. The loose soils are underlain by very dense natural soils. The thicknesses of these loose soils vary along the length of the viaduct, as illustrated in Figure 1.

The natural shoreline of Elliot Bay actually lies to the east of all but the very northern portion of the viaduct; in other words, the current location of the Alaskan Way Viaduct was part of Elliot Bay a century ago. The filling operations that extended the waterfront to its current position were typical of those used around the world at that time. The fill soils either were mixed with water and pumped to the site or were dumped through the waters of Elliot Bay. To retain the fill in a manner that would allow large ships to berth, the City of Seattle designed and constructed a timber-and-concrete sea wall that runs parallel to much of the current alignment of the viaduct. The sea wall, constructed in the early 1930s with four different types of walls, was designed according to the procedures that were accepted at that time.

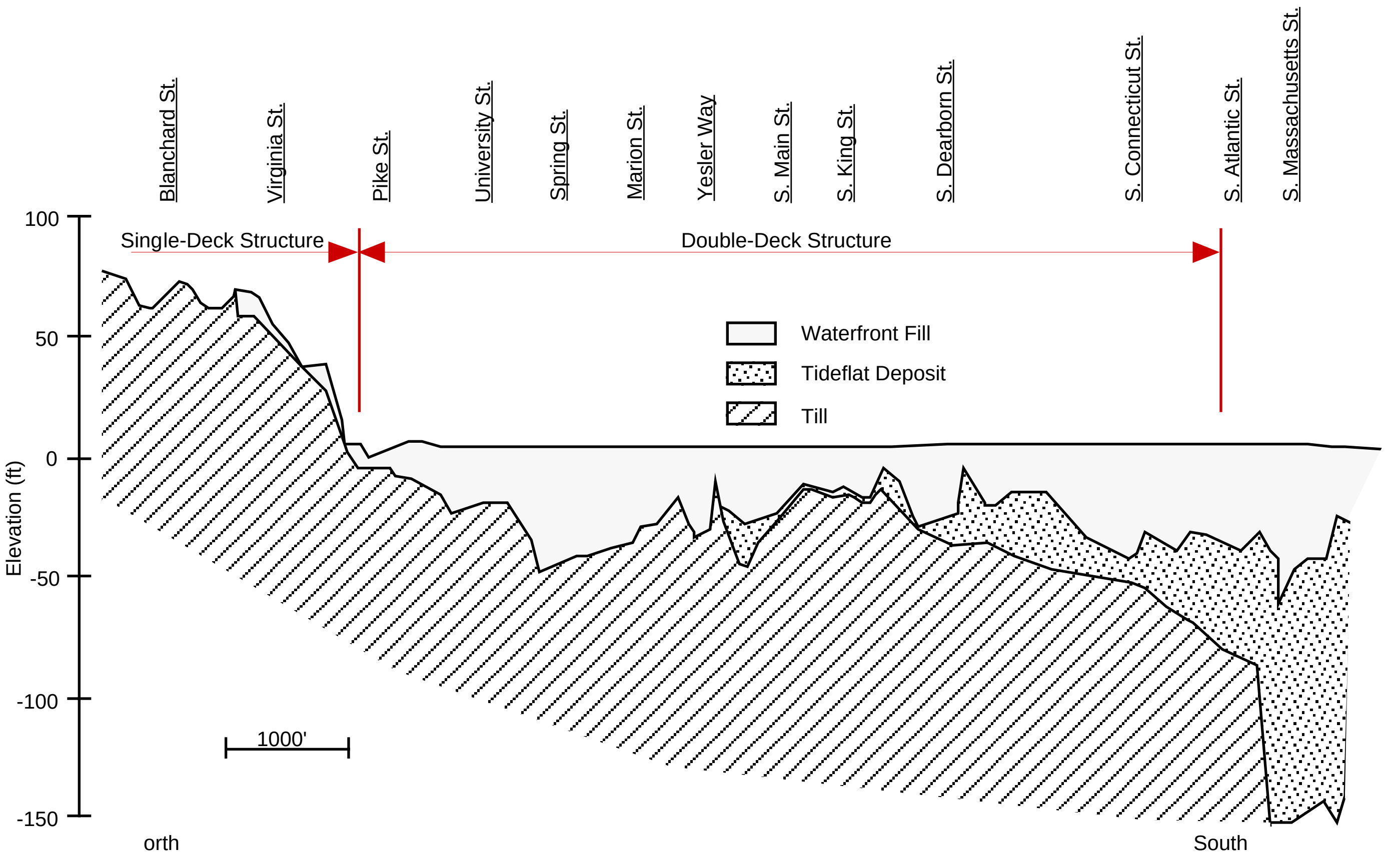

Figure 1. Soil Profile along the Length of the Alaskan Way Viaduct

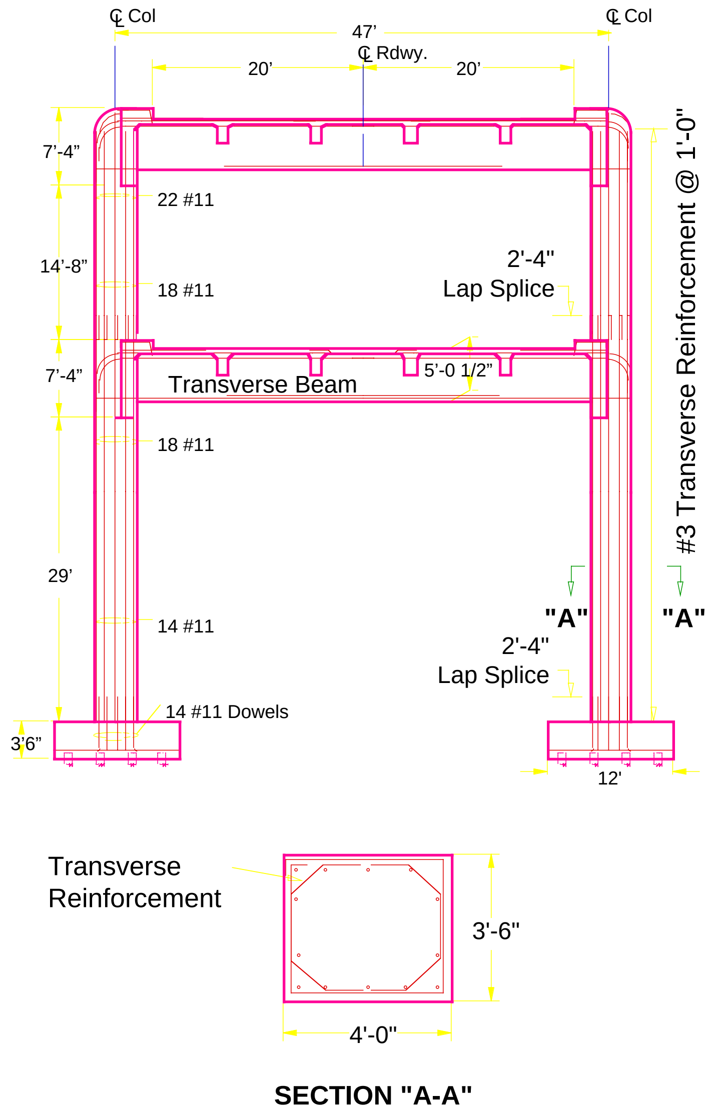

Figure 2. Elevation of Typical Interior Transverse Frame

Viaduct Construction

The Alaskan Way Viaduct was constructed from 1949 to 1953 in three main sections. The northern third of the viaduct consists of two side-by-side, single-deck structures, which were designed by the City of Seattle. Near Pike Place Market, the viaduct transitions to a double-deck configuration, which is maintained over the remainder of the viaduct. The middle third of the viaduct was also designed by the City of Seattle, while the southern third was designed by the Washington State Department of Transportation. The two agencies selected different member geometries and reinforcement details.

Despite variations to accommodate off-ramps, superelevations and curves, the double-deck portion of the viaduct consists mainly of three-span units that are separated from adjacent units by 2-inch expansion joints. The two decks are supported by beams that run in the transverse direction (perpendicular to traffic) and deep girders that run in the longitudinal direction (parallel to traffic). Unlike many other bridges, the beams and girders frame directly into the columns. In the transverse direction, the beams and columns form four frames that provide the lateral-force resistance of the three-span unit (Fig. 2). The girders and columns form two frames that provide the unit's longitudinal lateral-force resistance (Fig. 3).

The viaduct is supported on pile foundations that extend through the waterfront fill and tideflat deposits to the underlying dense soil. Each column of the viaduct is supported by a group of piles connected by a buried footing. The number and arrangement of piles in each group vary along the length of the viaduct and between interior and exterior columns, and the sizes of the footings vary to accommodate the various pile groups. Available pile driving records indicate that most of the piles were driven only a short distance into the dense soil; consequently, pile bearing support is derived from the top few feet of the dense soil.

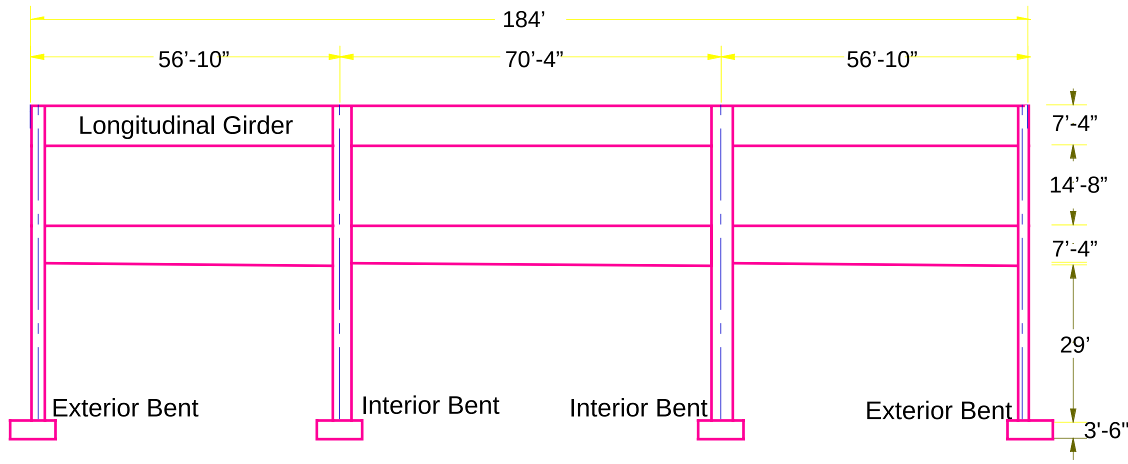

Figure 3. Elevation of Typical Longitudinal Frame

The construction details of the viaduct are typical of reinforced concrete bridges built before the 1971 San Fernando Earthquake. The viaduct is relatively stiff and strong, but its reinforcement details differ greatly from those required by current national seismic codes. The most significant difference between the Alaskan Way Viaduct and modern bridges is the viaduct's shortage of transverse reinforcement (Fig. 2, Section A-A). Transverse reinforcement increases the shear strength of the columns and beams, and the confinement that the transverse reinforcement provides is essential in preserving the integrity of the concrete columns and joints during an earthquake. The need for sufficient transverse reinforcement is one of the most important lessons engineers have learned from earthquakes in the past 25 years.

Another difference between the Alaskan Way Viaduct and modern construction is the presence of longitudinal column reinforcement splices at the column bases and directly above the first deck (Fig. 2). The lap splices are much shorter than those required by current standards, are enclosed by inadequate transverse reinforcement, and are located in regions that are likely to undergo large flexural demands during an earthquake. Other significant differences between the viaduct and new construction are that the bottom transverse beam and longitudinal girder reinforcement extends into the columns only a short distance, and the footings have no top reinforcement.

Performance of the Alaskan Way Viaduct in Past Earthquakes

Since its completion, the Alaskan Way Viaduct has been subjected to significant earthquake shaking only once — during the 1965 Seattle earthquake. This earthquake, which had a magnitude of 6.5 and an epicenter some 15 miles from the viaduct, produced a modest level of shaking at the bridge site. Inspection of the viaduct following the 1965 earthquake revealed no apparent signs of distress in the structure.

Some evidence of soil liquefaction was observed near the site of the Alaskan Way Viaduct following both a 1949 earthquake and the 1965 earthquake. Liquefaction is a phenomenon in which soil loses a large portion of its strength during an earthquake. Liquefaction has been responsible for tremendous damage to waterfront facilities in earthquakes around the world. The liquefaction that occurred in 1949 and 1965 was not extensive, but it did produce damage at Pier 66, Pier 36, east of the viaduct at 177 SW Massachusetts, and just north of the viaduct along Elliot Avenue. Following the 1965 earthquake, breaks in underground water supply mains were observed near Piers 64 through 66. The effects of liquefaction near the Alaskan Way Viaduct site following the 1949 and 1965 earthquakes were modest, but the levels of shaking in both earthquakes were relatively low. The triggering of liquefaction by these relatively weak motions indicates that the loose, saturated soil near the viaduct is highly susceptible to liquefaction. If either earthquake had produced stronger shaking, or if the duration of shaking of either had been longer, more liquefaction-induced damage would have occurred.

Comparison with Oakland and San Francisco Viaducts

Comparison of the Alaskan Way Viaduct with the Oakland Cypress Viaduct and the San Francisco viaducts is inevitable. All these viaducts have two decks, have reinforcement details typical of pre-1971 construction, and provide vital transportation links in urban areas. Portions of the Cypress Structure collapsed during the 1989 Loma Prieta earthquake, and the San Francisco viaducts were so heavily damaged that they had to be either demolished or subjected to a costly rehabilitation program.

Although the viaducts are similar, extrapolation from one structure to another is difficult because each viaduct's deficiencies are not identical. The Cypress Viaduct had inadequately-reinforced column hinges just above the first deck. At this location, the Alaskan Way Viaduct does not have structural hinges but instead has short lap splices. Unlike the Alaskan Way Viaduct, the San Francisco viaducts did not have longitudinal girders that frame directly into the columns. Most importantly, the geotechnical conditions differ for all of the viaducts.

SEISMIC VULNERABILITY EVALUATION

Evaluation of the seismic vulnerability of the Alaskan Way Viaduct involved determining design-level ground motions along the length of the viaduct, evaluating the potential for liquefaction of the soil beneath the viaduct, and estimating the structural response.

Design-Level Ground Motion

The seismic vulnerability of any structure depends on the strength of ground shaking to which it is subjected. Modern earthquake engineering procedures evaluate seismic vulnerability in relation to a design-level ground motion. Engineers determine this design-level ground motion by considering all known and postulated earthquake sources, the historical activity of each of the sources, and the effects of earthquakes of various sizes from each of the sources.

Given the uncertainties in the locations, frequency, and effects of earthquakes of various sizes, design-level motions can be computed for different levels of risk. Current national design codes for buildings and bridges recommend the use of design-level motions with a 10 percent probability of exceedance for an exposure period of 50 years. Such motions are likely to be exceeded about once every 475 years. Of course, earthquakes do not occur at regular intervals, so the elapsed time between design-level motions will vary. This "10 percent in 50 years" risk level was used to develop design-level motions for seismic vulnerability evaluation of the Alaskan Way Viaduct. The design-level ground motion with a 10 percent probability of exceedance in a 50-year period represents a strong level of shaking at the Alaskan Way Viaduct site. The peak ground acceleration produced by the design-level motion would be about three times higher than the peak acceleration that occurred at the viaduct during the 1965 earthquake.

Ground Response

The level of ground shaking at a given site is strongly influenced by the soil conditions at that site. Because soil conditions vary along the length of the Alaskan Way Viaduct, various portions of the viaduct will be subjected to various levels of ground shaking. The viaduct's acceleration levels will likely be highest at locations underlain by 10 to 20 feet of fill; most of these locations are north of about Dearborn Street. South of Dearborn Street, acceleration levels will generally be lower, but larger ground displacements are likely to occur. The variation of the acceleration response for four soil profiles along the length of the viaduct is illustrated in Figure 4.

Liquefaction Hazards

Historical accounts of the placement of the waterfront fills, observations of their performance in the 1949 and 1965 earthquakes, and the results of the subsurface investigations suggested that the liquefaction potential of the waterfront fills and tideflat deposits could be high. Consequently, a great deal of effort was devoted to evaluating

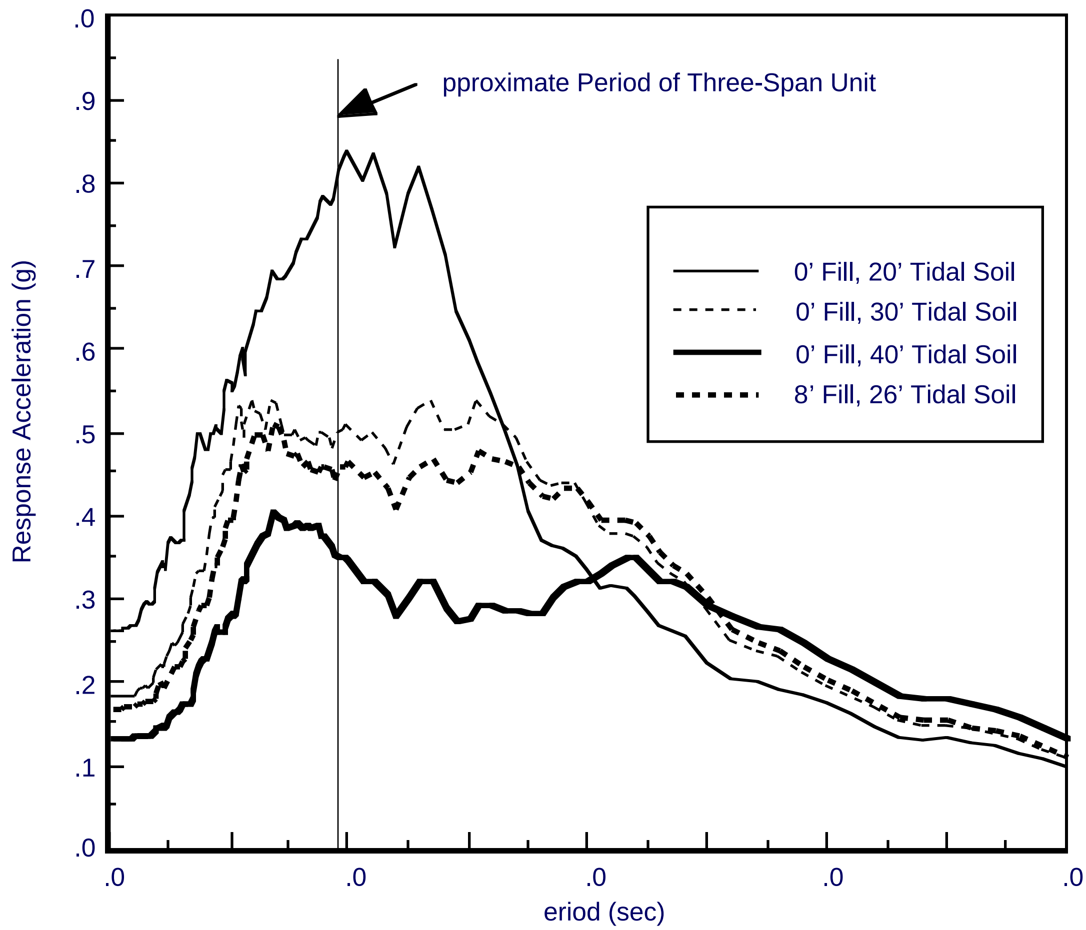

Figure 4. cceleration Response Spectra

liquefaction hazards. Previously available subsurface soil data were supplemented by data from additional tests performed as part of this investigation. The liquefaction resistance of the soils beneath the viaduct was evaluated in three different, independent ways; each was used to evaluate liquefaction potential. Additionally, the same procedures were used to evaluate the level of liquefaction that would have been expected in the 1965 earthquake. The potential effects of liquefaction were also evaluated; this effort required consideration of the response of the sea wall that runs along the waterfront.

The manner in which the waterfront fills beneath the Alaskan Way Viaduct were placed is a virtual recipe for creating a liquefiable soil deposit. Other soil deposits placed in the same way have liquefied and caused extensive damage in earthquakes around the world. These techniques are no longer used in seismically active areas. In the present investigation, three independent analyses indicated that widespread liquefaction of the loose, saturated soils beneath the Alaskan Way Viaduct is expected to occur in a design-level ground motion. Furthermore, the investigation indicated that widespread liquefaction could also be caused by a lower (and consequently more likely) level of motion. The same liquefaction evaluation procedures were repeated using the 1965 earthquake motion. The results, which indicated that modest liquefaction should have occurred, were consistent with observations following that earthquake.

The effects of liquefaction on the seismic vulnerability of the viaduct are likely to be severe. Widespread liquefaction is expected to cause vertical settlement of the viaduct foundations ranging from 0 to 24 inches. These settlements, which will begin during the earthquake and continue for several minutes afterward, will be highly irregular and will induce large vertical differential foundation settlements. These vertical settlements could lead to collapse of multiple sections of the viaduct.

Widespread liquefaction is also expected to cause lateral movement of the waterfront fill toward Elliot Bay. The amount of movement will be strongly influenced by the seismic performance of the sea wall. Sea walls retaining similar liquefiable soils have failed with large lateral movements in past earthquakes. These lateral soil movements would occur in an irregular pattern and could induce large differential movements of the viaduct's foundations. These lateral foundation movements could cause multiple sections of the viaduct to collapse.

The amount of lateral movement of the sea wall is difficult to predict. Rough calculations for a particular section with a particular wall type indicate that lateral movements will be on the order of 3 to 4 feet. The movements at other sections and with other wall types may be smaller or larger. A detailed investigation of the seismic performance of the sea wall was not within the scope of this study. Such a study should be performed to more accurately evaluate its effect on the Alaskan Way Viaduct.

Structural Performance

All evaluations of earthquake vulnerability include uncertainty. The soil, concrete, and steel properties vary; the placement of the reinforcement can differ somewhat from that specified on the structural plans; and the evaluation procedures involve approximations. Most importantly, the level of shaking at a site varies greatly from one earthquake to the next. Despite this uncertainty, it is clear that the Alaskan Way Viaduct does not meet current design standards for earthquake resistance.

To investigate the likelihood and consequences of various failure modes, the research team implemented widely used guidelines written by consulting engineers, researchers, and state and federal highway engineers (Applied Technology Council, 1983). The viaduct was evaluated also with assessment procedures that were developed recently by researchers at the University of California, San Diego (Priestley et al., 1992), and at the University of California, Berkeley (Moehle et al., 1994). These are the most up-to-date assessment procedures available to the structural engineering profession.

The general assessment that resulted from implementing the older procedure and the newly developed procedures was the same. The evaluations indicated that the viaduct is vulnerable to a design-level earthquake because the design motion would strongly excite the viaduct, and the viaduct's structural details make it brittle. The evaluations identified the following structural deficiencies.

- The lap splices at the bases of the WSDOT-section first-story columns would almost certainly lose their flexural strength during the design motion. Loss of flexural strength would lead to increased damage in other parts of the structure. The splices could fail in shear. If the splices failed in shear, the columns would not be able to support the decks.

- The beam-to-column joints at the lower-level joints would be vulnerable in a design-level motion. Although the likelihood of joint failure is less than the likelihood of failure of the lower-level splices, the consequence of joint failure would be catastrophic. Complete joint failure would lead to collapse of the viaduct. The upper-story splices increase the risk of failure in the joint area because the transverse reinforcement is inadequate.

- Most of the viaduct's columns have inadequate shear strength because their transverse reinforcement is too sparse. Shear failures must be avoided because many bridge collapses during past earthquakes (for example, the 1994 Northridge Earthquake and 1995 Kobe Earthquake) were caused by this type of failure.

- Though the footings are not as vulnerable as the splices, joints, and shear-critical columns, the pile-supported footings were also found to be vulnerable. The consequence and likelihood of footing failure are uncertain because few such failures have been observed during past earthquakes.

- Liquefaction-induced vertical settlement and lateral spreading would damage the piles and pile-footing connections, and could cause the viaduct to collapse.

Peer Review

The University of Washington study was reviewed by eminent structural and geotechnical engineering experts who are active in assessing the seismic vulnerability of bridges. The UW structural evaluation of the WSDOT unit was reviewed by Professor Jack Moehle and Dr. Andrew Whittaker at the University of California, Berkeley, and by Professor Frieder Seible at the University of California, San Diego. The peer reviewers agreed that the UW study had identified the most likely weaknesses in the viaduct. They agreed also that the Alaskan Way Viaduct structural vulnerabilities are probably less severe than those of the San Francisco viaducts, but that the viaduct is vulnerable. All three reviewers stressed that the level of retrofit that is needed (and the associated costs) will vary greatly according to the performance criteria. The geotechnical engineering aspects of the seismic vulnerability investigation were reviewed by Professor Geoffrey R. Martin of the University of Southern California. Professor Martin agreed that liquefaction poses a severe hazard to the viaduct and surrounding area.

CONCLUSIONS

Evaluation of the seismic vulnerability of older structures is a complicated task. Earthquake shaking levels are difficult to predict, and estimates of liquefaction and structural response include significant uncertainty. Nevertheless, the engineering profession has developed vulnerability criteria that are consistent with past experience and with the results of research. Using the most up-to-date of these criteria, this study found that the Alaskan Way Viaduct is clearly vulnerable to severe damage and possible collapse in a design-level earthquake. In particular, the results of the detailed evaluation of the seismic vulnerability of the Alaskan Way Viaduct have led the investigators to the following conclusions:

1. The design-level ground motion represents considerably stronger earthquake shaking than the viaduct has been subjected to in the past. The design-level motion would produce peak ground accelerations about three times larger than those produced by the 1965 earthquake.

2. The geotechnical characteristics of the site make strong excitation of the Alaskan Way Viaduct highly likely during a design-level earthquake. The design-level motion would likely cause heavy damage or collapse because the viaduct's structural elements lack adequate ductility. Significant damage is likely even if the motion is considerably less intense, and hence more likely, than the design-level earthquake motion.

3. Widespread liquefaction is expected to occur in a design-level ground motion and could cause multiple sections of the viaduct to collapse. This collapse could take place either during or shortly after the earthquake. Significant liquefaction is likely even if the motion is considerably less intense than the design-level earthquake motion.

4. Liquefaction hazards extend throughout the waterfront fill. Major damage to Alaskan Way, the sea wall, piers, and lifelines along the Seattle waterfront could occur in a design-level ground motion.

5. Failure of the sea wall would increase lateral spreading displacements and could cause the viaduct to collapse. A detailed investigation should be undertaken to evaluate the seismic performance of the sea wall.

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