SEISMIC VULNERABILITY ASSESSMENT OF THE SEATTLE-TACOMA HIGHWAY CORRIDOR USING HAZUS

Donald Ballantyne[1], Mark Pierepiekarz[2], and Dr. Stephanie Chang[3]

ABSTRACT

The seismic vulnerability of 214 bridges along three highways, I-5, SR-167, and SR-99 between Seattle and Tacoma, Washington, was modeled using HAZUS.

The USGS developed six ground motion scenarios for representative earthquakes from the Cascadia Subduction Zone, the Deep Benioff Zone, and crustal earthquakes. The ground motions were amplified for site response using modified NEHRP amplification factors based on soil classifications developed by the Washington State Department of Natural Resources (DNR). The resulting ground motion maps were input into HAZUS 99. DNR also developed liquefaction mapping for the study area that was input into HAZUS.

Bridge data was provided by the Washington State Department of Transportation (WSDOT), and modified to properly represent bridges had been upgraded. Bridges in the WSDOT database were classified in accordance with the HAZUS bridge types. Some bridge classifications were modified to better represent the year various design standards were implemented in Washington. Pushover analyses were conducted on several representative bridges to check the validity of the fragility curves in HAZUS 99. There was good concurrence.

HAZUS 99 was run, and expected bridge damage states for the six scenarios output and mapped. For the 3 intermediate scenarios, an average of 26 out of 214 bridges were estimated to suffer extensive damage or collapse. In the most severe scenario, 40 bridges were rendered unusable. Based on individual bridge damage states, the probability of each highway segment along the corridor was estimated. Recovery times were estimated by HAZUS 99 and mapped by highway segment indicating the probability of being open immediately following, 3 months, 6 months, and one year following the event. Three scenarios had highway segments that had closures exceeding 6 months, and the most severe scenario, closures exceeding a year.

The regional economic impact due to one of the smaller events was estimated. Over twenty businesses were interviewed to identify the likely effect on their operations, costs, and revenues. Highway outage and recovery times were provided to each business. Based on these results and a regional economic model, impacts were estimated at $3 billion in reduced business income, and a loss of 39,000 jobs in the year following the event.

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[1] Donald Ballantyne, P.E., Senior Consultant, MMI Engineering, Federal Way, WA 98003, dballantyne@MMIEngineering.com

[2] Mark Pierepiekarz, P.E., S.E., MRP Engineering, New Castle, WA

[3] Dr. Stephanie Chang, Associate Professor, University of British Columbia

INTRODUCTION

Washington is the most trade-dependent state in the country, where one in four jobs rely on international trade. The airplane, software, financial, forest product, and biomedical industries are all key to the region's economic success. Two and a half million people (40% of the State population) reside along the north-south corridor supporting these industries. One hundred billion dollars in goods moves through the ports of Seattle and Tacoma annually. Much of the cargo, 60 percent, moves through the region to inland domestic markets. The Puget Sound region accounts for seven percent of the nation's international trade, but is home to only one percent of the population. In the highly competitive import-export shipping business, disruption of service from a disaster could deal a terrible blow to the Puget Sound economy, shifting business to foreign and domestic West Coast ports.

In this region, the I-5 corridor is funneled by the Cascade Mountains to the east, and the Puget Sound to the west, so there is minimal transportation "redundancy" in the event one of the major routes is damaged in an earthquake. The I-5 corridor moves about 200,000 vehicles per day north south between Tacoma and Seattle, where most of region's businesses are located. Parallel routes, including SR-167 and SR-99, have a total capacity about half that of I-5, and are already jammed. Boeing (the nation's largest exporter) is dependent on moving airplane components along the corridor, as part of their manufacturing process. All employers depend on the corridor to get people to work to ship and receive goods, and for access of customers.

In 1998, Washington’s King and Pierce counties combined their Project Impact funding to address regional issues. When they convened a group of public and private sector citizens and asked them to identify their greatest concern following a disaster, the overriding consensus was transportation. Not only is transportation critical to provide emergency response but it provides the lifeblood to maintain the long-term economic vitality of the region. And transportation systems in the Pacific Northwest are already at maximum capacity.

With that direction the counties developed a project to evaluate the post-earthquake reliability of a key section of the regional transportation system, and if it were not operational, to estimate the regional economic impact. Consulting with their partners, the Counties defined the study area as the “Port to Port” Corridor connecting the nation’s fifth and sixth busiest container ports: Seattle and Tacoma. Ultimately, the counties are planning to use the project results to help spur development and implementation of effective mitigation strategies.

Based on the background presented above, the project team established the following five project objectives that were used to formulate the project approach, and as guidance throughout the project.

1. Engage business and government participation.
2. Evaluate post-earthquake transportation system survivability.
3. Develop an emergency response and recovery plan.
4. Estimate the economic impact of transportation system outage.
5. Promote mitigation of high-risk bridges on critical lifeline corridors.

The project carried out a four-step evaluation process to estimate the earthquake risk associated with the transportation corridor.

1. Hazard assessment - quantifying hazards, including ground motions and liquefaction.

2. Loss estimation - evaluating individual bridge vulnerability/reliability, route reliability, and recovery time.
3. Economic analysis - estimating the regional economic impact if the corridor is disrupted.
4. Contingency planning – developing plans to detour around key collapsed bridges.

HAZUS was used as the platform to integrate the hazards and individual reliabilities. HAZUS 99 is an earthquake loss estimation software developed and funded by FEMA to help communities to prepare, plan, and build stronger and safer communities. Among many HAZUS 99 uses are analysis of disaster-related damages; identification of vulnerable areas; assessment of vulnerability of housing, essential facilities and lifelines; estimation of potential losses; and aid in development of response and recovery plans.

Highway transportation systems generally consist of roadways, bridges, and tunnels. Road damage occurs due to surface fault ruptures or extreme soil failure. Bridge damage can occur due to extreme ground shaking and or site soil failure. Loss of bridge function usually results in significant disruption to the transportation network, and thus is a key component to reliability of these lifelines. The project focused on the loss estimation methodology used in HAZUS 99 for bridges.

The reliability of individual bridge structures was estimated based on the local earthquake hazards, the bridge structural design characteristics, and performance of similar structures in previous earthquakes. Most of the bridges along the I-5 corridor were constructed before the mid-1970s, when more rigorous seismic design codes were initiated.

The reliability of the transportation corridor "system" was estimated by combining the reliabilities of the individual bridge structures. The reliability of each bridge in a linear system such as I-5 has a dramatic impact on the overall route reliability. In the Puget Sound region, there are limited redundant routes compared to the grid, or network of highways that were available in Los Angeles following the Northridge Earthquake.

The potential regional economic impact was estimated considering the likely bridge/highway segment outage time, associated increased travel times, and the resulting impact on a cross section of the region's employers.

Contingency planning was developed by stakeholders with interests in each county including the counties (public works and sheriffs), cities, the WSDOT, and the State Police.

HAZARDS ASSESSMENT

A hazard assessment was performed for six earthquake scenarios. Ground motion assumptions were developed, site amplification estimates applied, and liquefaction susceptibility mapping prepared.

Ground motions were developed independently due to the limitations of HAZUS generated scenarios. HAZUS does not allow site amplification of user supplied ground motions within the program, so “amplified” ground motions were input into HAZUS.

The scenario ground motion approach was selected rather than using probabilistic ground motions. The premise of probabilistic ground motions is that they will not be exceeded over the associated return period. This may result in overestimating the impact as several different earthquakes may contribute to those ground motions. Ground motions for the scenarios were used to better approximate what may occur for a single event. The scenarios modeled included:

- Seattle Fault M6.5 (shallow crustal)
- Seattle Fault M7.0 (shallow crustal)
- Tacoma Fault, M6.7 (shallow crustal)
- Cascadia Subduction M9.0
- Deep Benioff zone M6.5
- Deep Benioff zone M7.1

The expected return period for the scenarios is: Deep Benioff – 50 to 100 years; Cascadia Subduction, Tacoma or Seattle M6.5 – 300 to 1,000 years; and Seattle M7.0, over 1,500 years.

Site amplification for peak ground acceleration and 1-second spectral acceleration were taken as developed in NEHRP, and applied in HAZUS. The amplification values were renormalized to better represent the their original basis.

DNR provided liquefaction mapping. Liquefaction and lateral spread can have a dramatic impact on bridge foundations and highways segments. The Puget Sound region has a higher potential for liquefaction than many other areas, because of high water tables in river valleys with young geologic deposits, such as in the Green and Duwamish river valleys. Liquefaction can result in loss of bearing, and lateral movement (spread) can occur, measured in meters.

HAZUS uses liquefaction susceptibility map data in determining a conditional liquefaction probability used in subsequent damage-state calculations. The program translates a relative liquefaction susceptibility (ranging from very high to none) into a conditional liquefaction probability. The conditional probabilities are adjusted for earthquake magnitude (duration) effects and variation in the depth to groundwater. These probabilities are then used to calculate the expected permanent ground displacement both from lateral spreading and settlement. The permanent ground displacements then modify direct damage estimates.

BRIDGE VULNERABILITY EVALUATION

General Model and Preliminary Screening

Earthquake damage can be estimated for various transportation components based on anticipated ground accelerations and ground deformation. The required data to estimate bridge damage includes:

- Geographical location/longitude and latitude
- Bridge classification (structure type)
- Site spectral accelerations at 0.3 seconds and 1.0 seconds
- Permanent-ground deformation (PGD)
- Peak-ground acceleration (for PGD-related calculations)

HAZUS 99 classifies bridges into 28 categories based on the following structural characteristics:

- Seismic design
- Number of spans
- Structure type and material
- Pier type
- Abutment type
- Span continuity

General bridges with good seismic design features can accommodate relatively higher seismic input and allowable drift limits. The general fragility curves for each of the 28 bridge classes can be further refined in HAZUS 99 using bridge specific data such as: bridge length/span length/number of spans, bridge width, and skew. The effects of these parameters for several bridge types were investigated using sensitivity spreadsheet analyses. The bridge inventory was divided into the 28 categories as shown in Table I. More detailed analysis focused on the bridge categories with the least lateral capacity, HWB 12 and HWB 17.

TABLE I. SUMMARY OF BRIDGE CLASSES AND ASSOCIATED CAPACITIES

Bridge Class	Number/ Percent of Total		Lateral Capacity (g)	PGD Capacity (in)	Bridge Type
HWB10	76	36%	1.05	3.9	Continuous Concrete
HWB17	68	32%	0.44	3.9	Multi-Col. Bent, Simple Support-P/T Concrete
HWB23	23	11%	1.05	3.9	Continuous - Prestressed Concrete
HWB22	12	6%	1.05	3.9	Continuous - Prestressed Concrete
HWB11	11	5%	1.05	23.6	Continuous Concrete
HWB3	9	4%	1.1	3.9	Single Span
HWB4	4	2%	1.1	3.9	Single Span
HWB12	4	2%	0.44	3.9	Multi-Col. Bent, Simple Support- Steel
HWB15	3	1%	0.76	3.9	Continuous Steel
Other	4	2%	varies		
Total	214				

Definition of Damage States

HAZUS 99 defines four bridge damage states (as modified by WSDOT) plus no damage, that are related to the damage ratio (i.e. the repair-to-replacement cost) for evaluation of direct economic loss:

- Slight damage - minor cracking or spalling to concrete bridge elements. Bridge remains structurally sound.
- Moderate damage – Any column experiencing moderate cracks but remaining structurally sound, moderate superstructure displacement (< 2 inches), any damaged connections, bearing failure or moderate (< 6 inches) settlement of approach. Requires temporary repair and/or capacity or functionality reduction.
- Extensive damage – Any columns degrading without collapse – shear failure (column structurally unsafe), significant permanent displacement at connectors or major settlement (6 inches or greater) of an approach, or differential structural alignment.
- Complete damage – Any column collapsing or span losing all bearing support that may lead to imminent span collapse, tilting of structure due to foundation failure.

Damage Algorithms for Bridges

The HAZUS 28 primary bridge classes are defined for the above damage states as a function of ground motion and ground displacement. The assumptions in the development of these damage algorithms were reviewed and verified for applicability in this project. The verification focused on the most vulnerable bridge types that generally consist of simple-span bridge structures lacking modern seismic design features. A typical plot of a family of highway bridge fragility curves as the function of spectral acceleration is presented in Figure 1. For ground deformation, HAZUS considers incipient unseating and collapse as the possible types of damage due to ground failure. Initial damage to bearings, which correspond to slight damage from ground failure, is not considered.

Restrainers do not have a significant effect on the shape of the fragility curve for ground motion but will modify the expected performance of bridges when subjected to liquefaction/lateral spread.

The “extensive” and “complete” damage states were of primary interest since they result in loss of functionality. Figure 1 shows probabilities that a given bridge structure will not be extensively damaged.

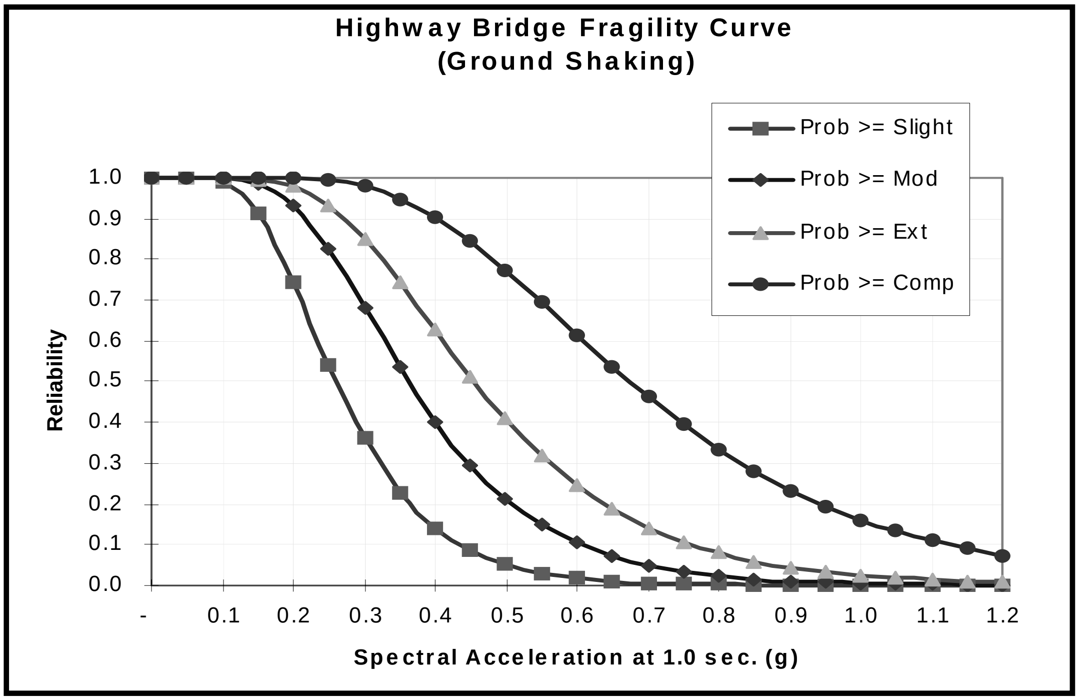

Figure 1. Highway Bridge Fragility - Prestressed Concrete Bridge Multi-Column Bent, Simple Support

Evaluation Inventory Considerations and Verification

The important questions to ask when applying HAZUS-based bridge vulnerability functions to Project Impact port-to-port corridor study are the following:

1. Is the bridge data currently in HAZUS database accurate relative to bridge location, physical characteristics, and key descriptors important for seismic performance?
2. Do damage functions, particularly for the most vulnerable bridges, accurately reflect Washington State bridge stock and design practice?
3. What modifications need to be made to appropriately model corridor bridges and assess the vulnerability of the lifeline network?

First, the existing HAZUS geographic database for the port-to-port corridor was examined to see whether bridges are accurately located. Second, the HAZUS database and WSDOT bridge database fields were mapped against each other to verify consistency of the key descriptors such as bridge type, bridge length, span length, number of spans, construction date, etc. Bridges with data discrepancies were discussed with WSDOT staff to establish an accurate input data for those structures. Furthermore, new structures, retrofitted bridges, and bridges with unique seismic features were also discussed to appropriately classify these within the available 28 HAZUS bridge classes.

Based on our discussions with WSDOT Bridge and Structures engineers, it is apparent that WSDOT has closely followed California DOT (Caltrans) seismic design practice. Consequently, for this the bridge categories were modified to use of these three curves as follows:

1. "Seismic design" category will be applied to all Washington State bridges built during or after 1982. WSDOT adopted ATC-6 provisions at that time.
2. The second category, originally intended to correspond to pre-1975 construction in California, will be applied to WSDOT bridges built between 1973 and 1982 according to AASHTO 1973 provisions.
3. The third category, intended for those bridges that lacked key seismic features or were designed to very low seismic forces, will be applied to WSDOT bridges built in Washington State prior to 1973.

The date of construction of the WSDOT bridge inventory is compared with the dates when the applicable design codes were in place. The plot, shown in Figure 2, shows that a significant number of the state bridges were built prior to the advent if adequate seismic codes.

Pushover Analysis

A nonlinear static pushover analysis for typical transverse bridge bents for selected bridges along State Route 167 was performed. This was of interest since column behavior governs WSDOT bridge response for simple span bridges. A pushover analysis is used to determine the load-deformation behavior of a structure prior to failure. Failure is defined as that point at which the structure becomes unstable resulting in collapse. The analysis was performed using a two-dimensional finite element model of a transverse bridge bent. The lateral force can

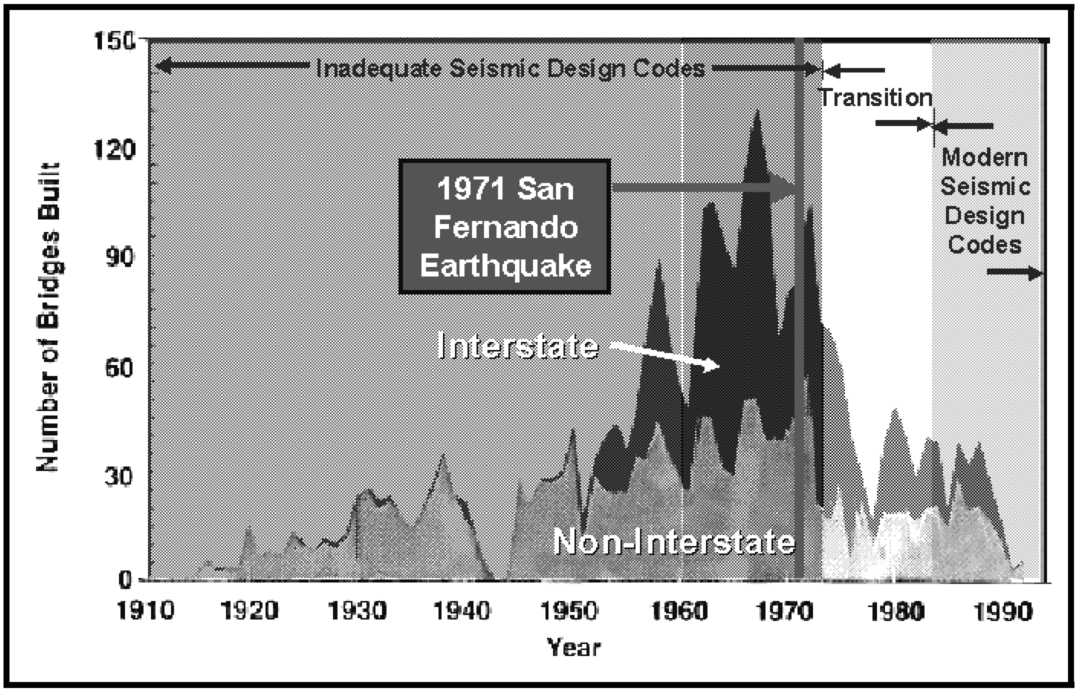

Figure 2. Construction of Washington State Bridges and the Relevant Seismic Codes.

be related to the spectral acceleration, and further normalized to spectral acceleration at one-second period to compare with existing HAZUS bridge fragility models.

Pushover analysis included the following assumptions:

- Model transverse bridge bent.
- Use cracked concrete section properties.
- Include “widened” section properties.
- Include gravity “deck” loads.
- Model soil stiffness (linear springs).
- Failure of bridge bent controlled by column plastic moment capacity (Mp) – verified.

Pushover analysis procedure includes:

- Increase lateral load until Mp is developed at column.
- Determine bent stiffness based on load and deflection prior to failure.
- Calculate spectral acceleration (Sa) at failure given bent stiffness and the weight of the structure.
- Compare to HAZUS bridge fragility curves for non-ductile detailing (pre-1973 WSDOT bridges).

The maximum calculated displacements for sample bridges range from 2.2” to 3.7” (this is just prior to the last hinge forming. At this displacement level, a bridge is extensively damaged, but has not yet failed. The corresponding HAZUS value is 3.9", which is in reasonable agreement. The "failure" displacement of HAZUS is 13.9" – i.e., the bridge can probably accommodate additional displacement after the full hinge mechanism is formed. This corresponds to some reduced moment capacity (i.e. non-zero moment strength) in the columns, after the hinges have formed.

Vulnerability to Long-Duration Earthquakes

It is important to consider long-duration earthquakes, such as those originating on the Cascadia Subduction zone, and their effects on bridge performance. Long-duration effects apply at 0.23 g lateral force representing the median value for onset of cracking in bridge columns. Bridge vulnerabilities are based on: 90% probability of failure is at 0.40 g and 90% probability of cracking is at 0.28 g. Thus, if a bridge responds in the "plastic" range (above 0.28 g), in a long duration event, then it could degrade and fail. Therefore, the vulnerability of bridges under these conditions is reduced by a factor of 1.4 (0.4 g/0.28 g).

RESULTING BRIDGE DAMAGE AND HIGHWAY SEGMENT RELIABILITIES

The estimated number of bridges damaged (extensive or complete) for each of the six scenarios is shown in Table II.

TABLE II. REGIONAL BRIDGE DAMAGE ESTIMATES (EXTENSIVE/ COMPLETE DAMAGE)

Earthquake Scenario	Project Area Bridges Damaged	Regional Impact Multiplier	Regional Bridges Damaged	Damage Category	Additional Soft Soil/ Lique-faction	Additional area affected by shaking
Benioff M6.5	6	1	6	Low	No	Limited
Benioff M7.1	13	1.25	16	Low	No	Limited
Tacoma M6.7	23	1.5	35	Moderate	Nisqually	I-5 south to Olympia, SR-16 (competent soils), I-705, SR-509, SR-410, SR-18.
Seattle M6.5	28	1.5	42	Moderate	Limited	I-5, I-405 and SR-99 north to Snohomish County Line (-). I-90, SR-520, SR-522.
Seattle M7.0	40	2	80	High	Limited	I-5, I-405 and SR-99 north to Snohomish County Line (+). I-90, SR-520, SR-522
Cascadia Subduction M9.0	29	3	87	High	Significant	Entire state west of the Cascades. All alluvial valleys along I-5 corridor. All state routes west of I-5.

Highway segment reliabilities immediately following the earthquake were calculated by multiplying together the reliabilities of individual bridges in the segment. The results on shown on the project web site. Bridge reliabilities are combined using this approach immediately after the earthquake because the probabilities of failure of each bridge are not influenced by restoration management decisions. The reliability of highway segments after restoration is based on the restoration of the individual bridge that HAZUS estimates has the longest restoration time.

Restoration time will be influenced by the availability of resources. The general approach assumes that for “low” damage category earthquakes, there will be adequate resources to pursue restoration of all bridges immediately following the earthquake. For “moderate” and “large” damage category earthquakes (refer to Table II), it is assumed that bridge restoration will be delayed for lower priority bridges.

The HAZUS restoration curve shows that on the “average” bridge will be about 67 percent restored within 3 months. It is assumed that many of the resources that would be used in the initial stages of bridge restoration would be freed up after 3 months, and could be applied to other bridges. For high damage category earthquakes, bridges are divided into 3 priorities for restoration, with delays for starting restoration of 3 and 6 months respectively for 2nd and 3rd priority highway segment bridges.

In order to establish the bridge damage categories in Table II, bridge damage results are used to estimate the total number of bridges across the state that will have at least extensive damage. This done by multiplying the average probability of being in the damage state times the total number of bridges. This approach is applied to main line bridges, as those are the bridges required to resume near full traffic volumes. The estimated number of bridges with at least extensive damage is shown in Table II for each earthquake scenario.

The study area only encompasses a portion of the interstate bridge system that would likely be impacted by an earthquake. The WSDOT would be responsible for restoration of all state owned bridges. Therefore an order of magnitude estimate is provided of the total number of interstate bridges that would be damaged as shown in Table II. This estimate takes into account the location, type, and expected distribution of ground motions of each earthquake, and the location of bridges in areas with significant site amplification and liquefaction susceptibility. In general, the study area encompasses the largest liquefiable areas in the region. To the north, the next large liquefiable area is the Snohomish River valley/delta just north of Everett. To the south, the next significant liquefiable are is the Nisqually River valley/delta. Each earthquake scenario affects bridges differently. Those affects are described in Table II. The result is the total number of bridges with at least extensive damage for the entire region, as shown in Table II.

The six earthquake scenarios are subdivided into 3 groups for low, moderate, and high levels of earthquake bridge damage, based on the total number of bridges with at least extensive damage. High levels of damage are expected for the Cascadia Subduction M9.0 earthquake and the Seattle M7.0 earthquake. Moderate levels of damage are expected for the Seattle M6.5 and the Tacoma M6.7 events. Low levels of damage are expected for the Benioff earthquakes. For the high level of damage category, it is assumed that bridges will be restored in 3 priorities: 1) I-5, 2) SR-167 north of SR-18 to I-405, and SR-518, and 3) all other highways. For moderate levels of damage, 2 priorities are identified: 1) I-5, and 2) all others. For low levels of damage, it is assumed that restoration will start on all bridges at the same time.

ECONOMIC IMPACT

The economic impact analysis evaluated only one earthquake scenario, the M7.1 deep Benioff earthquake centered under the City of SeaTac. This therefore should not be considered a worst-case scenario. However, the projected economic impact is severe. The earthquake's transportation related effects could mean:

- Reduced business revenues of $3 billion.
- Loss of 39,000 jobs costing over $1 billion in income.
- Tax losses to local government of $72 million.

Trucking firms, port related businesses, "just-in-time" manufacturers and retailers depending on customer access to stores could be hard hit. Small businesses without financial reserves could face bankruptcy. Furthermore, these estimates of economic loss are based only on the study area, and not the entire region.

CONTINGENCY PLANNING

The contingency planning efforts by both counties revealed significant challenges in redirecting up to 200,000 cars per day (I-5) onto surface streets. Simultaneous route outages could bring traffic to a standstill, with few arterial substitutes to carry daily traffic. Earthquake damage to multiple bridges would disable entire routes for up to three to six months. One of the major benefits of this multi-jurisdictional contingency planning was that it brought together transportation planners for the first time to address these types of issues.

FINDINGS AND CONCLUSIONS

For earthquakes with ground motions that are expected to be exceeded in the order of every 50 to 100 years, the maximum probability of failure of any single bridge is less than 35 percent, and overall may result in loss of use of about 3 to 6 percent (6 to 13 bridges) of the 214 bridges in the study area. However, for earthquakes that produce ground motions that are expected every 300 to 1,000 years, 10 to 15 percent of the bridges (23 – 29 bridges) are fail functionally, with nearly 20 percent (40 bridges) failing in an M7.0 earthquake on the Seattle fault.

Restoration of these bridges following the 300 – 1,000 year event will exceed six months, and be over a year for the larger event.

With failure of only six bridges in the deep Benioff M6.5 event (the smallest modeled event), the region is expected to lose $3 billion in business revenues, and lose 39,000 jobs due to the impact on the regional transportation system, including effects on Boeing, and the ports of Seattle and Tacoma.

REFERENCES

King and Pierce County Project Impact, Port-to-Port Transportation Corridor Earthquake Vulnerability Project Report, prepared by ABS Consulting, 2000.

HAZUS Loss Estimation Software and Technical Manuals developed by the National Institute of Building Sciences with funding from the Federal Emergency Management Agency.