Post-earthquake Prioritization of Bridge Inspections

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Bridge damage reports from the 2001 Nisqually earthquake were correlated with estimates of ground-motion intensity at each bridge site (obtained from ShakeMaps) and with bridge properties listed in the *Washington State Bridge Inventory*. Of the ground-motion parameters considered, the percentage of bridges damaged correlated best with the spectral acceleration at a period of 0.3 s. Bridges constructed before the 1940s, movable bridges, and older trusses were particularly vulnerable. These bridge types were underestimated by the HAZUS procedure, which categorizes movable bridges and older trusses as "other" bridges. An inspection prioritization strategy was developed that combines ShakeMaps, the bridge inventory and newly developed fragility curves. For the Nisqually earthquake, this prioritization strategy would have made it possible to identify 80% of the moderately damaged bridges by inspecting only 481 (14%) of the 3,407 bridges within the boundaries of the ShakeMap. To identify these bridges using a prioritization strategy based solely on epicentral distance, it would have been necessary to inspect 1,447 (42%) bridges. To help the Washington State Department of Transportation (WSDOT) rapidly identify damaged bridges, the prioritization procedure has been incorporated within the Pacific Northwest Seismic Network (PNSN) ground-motion processing and notification software. [DOI: 10.1193/1.2428313]

INTRODUCTION

After an earthquake, city, county, and state agencies with large bridge inventories are expected to rapidly inspect bridge damage in numerous locations, divert traffic from damaged structures, and restore bridges to service. In the past, engineers have often dispatched inspectors based on the reported earthquake magnitude, distance from the earthquake epicenter to the bridge, and field reports of observed damage (Malone et al. 2005). This approach can lead to delays in finding damaged bridges because field reports can be unreliable and the likelihood of damage to a bridge correlates poorly with its epicentral distance and earthquake magnitude (EERI 2001, Ranf et al. 2001, Wald et al. 2003, Dönmez and Pujol 2005).

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Earthquake Spectra, Volume 23, No. 1, pages 131–146, February 2007; © 2007, Earthquake Engineering Research Institute

Recent improvements in seismic networks (USGS 2005a) and processing software (Wald et al. 1999, USGS 2005b) have made it possible to estimate the earthquake intensity at many locations. These estimates can be combined with data contained in bridge databases (e.g., WSDOT 2000) and with fragility relationships (e.g., FEMA 1999, Malone et al. 2005) to rapidly estimate the likelihood of damage to each bridge. This strategy has been incorporated into the PNSN ground-motion processing and notification software to help Washington State Department of Transportation (WSDOT) plan post-earthquake inspections (Malone et al. 2005).

The 2001 Nisqually earthquake provided a unique opportunity to evaluate the effects of a moderate earthquake on a large number of bridges located in the Pacific Northwest. This paper describes the damage that the 2001 Nisqually earthquake caused to bridges, as well as the correlations between the percentage of bridges damaged and the bridge properties and estimated ground-motion intensity at each site. The data made it possible to evaluate the accuracy of the HAZUS relationships and to develop new fragility relationships for bridges with slight damage in the Pacific Northwest.

Similar research to investigate the effects of ground-motion intensity on bridge damage has been conducted for bridges within other regions of the United States, as well as Japan. Basöz et al. (1999) investigated the accuracy of pre-existing fragility curves using peak ground acceleration for various bridge classifications and damage levels using data from the Northridge earthquake. Jernigan and Hwang (2002) developed fragility curves using peak ground acceleration estimates for various types of bridges characteristic of those in the central and eastern United States. Shinozuka et al. (2000b) developed fragility curves using peak ground acceleration estimates and bridge columns that were damaged during the 1995 Kobe earthquake.

This paper introduces a post-earthquake inspection strategy for bridges in the Pacific Northwest and describes practical considerations for implementing this strategy, such as the proximity of the bridges to the inspection team.

BRIDGE DAMAGE CAUSED BY NISQUALLY EARTHQUAKE

The 2001 Nisqually earthquake, which had a moment magnitude of 6.8, shook much of western Washington state. Its epicenter was located approximately 18 km northeast of Olympia and 57 km SW of Seattle, Washington, at a hypocentral depth of 52 km. (EERI 2001). This earthquake damaged 78 bridges, with no collapses (Ranf et al. 2001).

The level of shaking was monitored by the Pacific Northwest Seismograph Network, (PNSN), which is operated and funded through a joint effort by the University of Washington, the University of Oregon, the United States Geological Survey, and the United States Department of Energy. During the Nisqually earthquake, 42 PNSN strong-motion stations recorded ground motions with peak accelerations up to 0.31 g and transmitted this information to the University of Washington in near-real time.

Following the Nisqually earthquake, the PNSN developed maps of earthquake intensity (ShakeMaps) by interpolating data between the stations and accounting for geologic conditions (Wald et al. 1999, PNSN 2001). These maps provided approximate values for

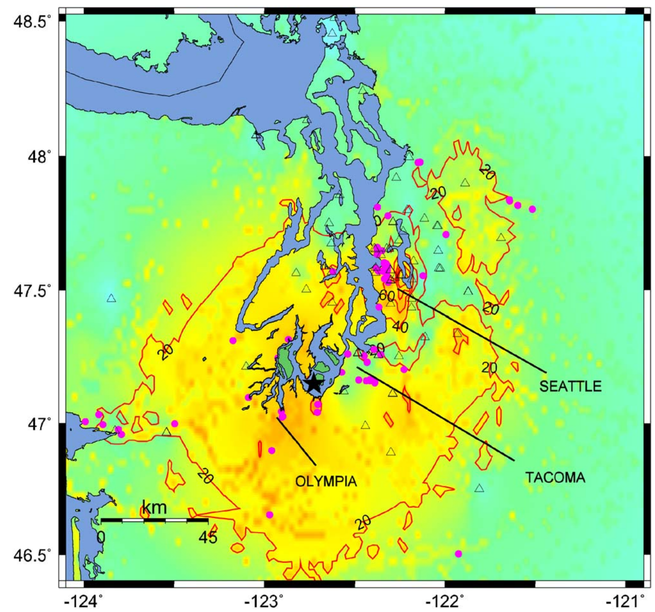

Figure 1. ShakeMap showing estimated spectral acceleration at T = 0.3 s (PNSN 2001b).

the peak ground acceleration and the spectral accelerations (for a damping ratio of 5%) at periods of 0.3, 1.0, and 3.0 s. Figure 1 shows a map generated for the 2001 Nisqually earthquake, detailing estimations of the spectral accelerations at a period of 0.3 s (PNSN 2001). Seventy-one of the damaged bridges are within the range of this ShakeMap. The empty triangles in Figure 1 identify the locations of the seismic instruments, and the circles identify the locations of each damaged bridge.

The extent of bridge damage was documented by the Washington State Department of Transportation (WSDOT), city and county agencies, and the Nisqually Earthquake Information Clearinghouse (Ranf et al. 2001). The Nisqually earthquake damaged 78 bridges, of which 46 belonged to the WSDOT, and 19 belonged to the city of Seattle.

Figure 2 shows photographs of typical damage. Damaged bridges were categorized by whether the bridge was movable (e.g., bascule bridge), whether it was a steel truss, and by the material used for the main span, as follows:

- Movable bridges (6)
- Steel truss bridges (11)
- Reinforced-concrete (RC) bridges (33)
- Prestressed-concrete (PSC) bridges (20)
- Other steel bridges (8)

The damage to the 6 movable bridges was classified separately because these bridges suffered unique types of damage, including misalignment, dislodging of counterweights,

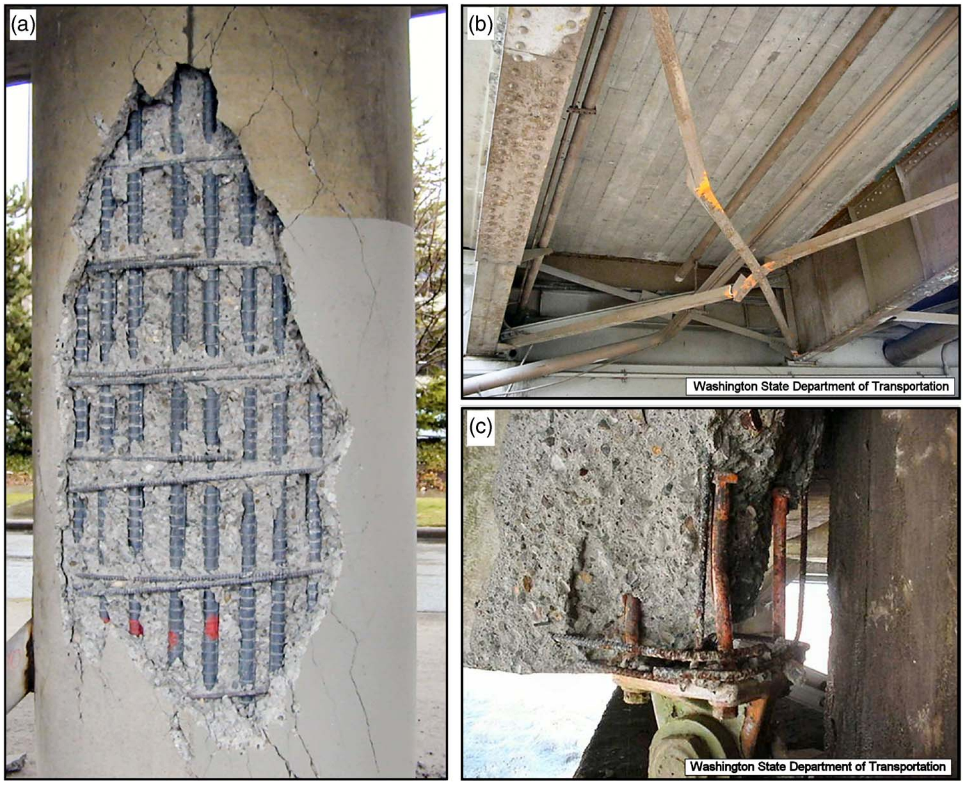

Figure 2. Typical damage: (a) concrete spalling, (b) buckling of steel cross-bracing, and (c) rocker bearing damage.

and jamming of centerlocks. The 11 truss bridges, mostly built in the first half of the twentieth century, were also classified separately. Such bridges typically sustained damage at the movement joints or to the cross-bracing. The remaining 61 reinforced-concrete, prestressed-concrete, and steel bridges had damage of the following types:

- concrete damage (42)
- steel damage (2)
- bearing, restrainer, or expansion joint damage (11)
- settlement damage (6)

The damage reports were further categorized according to their estimated repair costs: below \$30,000, \$30,000–\$100,000, and above \$100,000. In cases where bridge agencies did not provide a cost estimate but where the level of damage was apparent, the researchers estimated the repair costs based on similar cases of damage. The number of damaged bridges in each category was as follows:

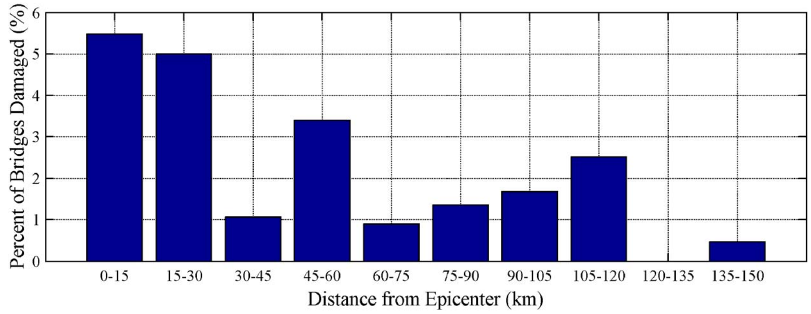

Figure 3. Effect of epicentral distance on the percentage of damaged bridges.

- Below $30,000 (51 bridges)
- $30,000–$100,000 (16 bridges)
- Above $100,000 (11 bridges)

Considering the 6.8 magnitude of the earthquake, these statistics show that the damage sustained by bridges during the Nisqually earthquake was light. This low level of damage may have been attributable to the large depth (52 km) of the hypocenter (EERI 2001).

EFFECT OF GROUND-MOTION INTENSITY

The vulnerability of the bridges in western Washington state was investigated by correlating reports of bridge damage with several measures of ground-motion intensity (epicentral distance, estimated peak acceleration, and spectral accelerations at periods of 0.3, 1.0, and 3.0 s). Ground-motion characteristics for 7 of the damaged bridges could not be estimated reliably because the boundaries of the ShakeMap did not include all of western Washington state (Figure 1). Within the boundaries of the ShakeMap, 71 of 3,407 bridges were damaged, resulting in an overall damage percentage of 2.1%.

Epicentral distance can be used as a simple proxy for the ground-motion intensity. For each bridge, the epicentral distance was calculated as the arc length on the earth's surface connecting the epicenter and the bridge location (Ranf et al. 2001). Figure 3 presents a histogram of the percentage of bridges damaged as a function of epicentral distance. The percentage of bridges damaged within each bin was calculated by dividing the total number of damaged bridges by the total number of bridges in the Washington State Bridge Inventory (WSBI) (WSDOT 2001). As expected, the percentage of damaged bridges was largest near the epicenter. However, the damage percentage did not decrease consistently as the epicentral distance increased. The largest percentage of damaged bridges fell within the ranges of 0–30 km and 45–60 km, which correspond to the distances to Olympia and Seattle, respectively. The range of 30–45 km corresponds to the distance from the epicenter to Tacoma, which suffered very little damage

Table 1. Correlation coefficients for various measures of ground-motion intensity

Measure of Ground Motion	Correlation Coefficient
Epicentral Distance	−0.744
Peak Ground Acceleration	0.613
Spectral Acceleration (T=0.3 s)	0.892
Spectral Acceleration (T=1.0 s)	0.716
Spectral Acceleration (T=3.0 s)	0.308

during the earthquake. The ShakeMap presented in Figure 1 also shows that the attenuation of ground motion was not uniform with epicentral distance.

Table 1 provides the correlation coefficients between the percentage of bridges suffering slight damage and several measures of ground-motion intensity. As expected, the percentage of bridges that were damaged decreased with increasing epicentral distance, resulting in a correlation coefficient of −0.744.

The effect of ground-motion intensity was also investigated using estimated values of peak ground acceleration, and spectral accelerations at periods of 0.3 s, 1.0 s, and 3.0 s. The relationship between peak ground acceleration and percentage of damaged bridges is shown in Figure 4. The correlation is weak, and only one acceleration range (0.20−0.25 g) differs significantly from the other ranges. As shown in Table 1, the correlations were also weak for the estimated spectral acceleration at a period of 3.0 s. The correlation was better for the estimated spectral acceleration at a period of 1.0 s, with a correlation coefficient of 0.716. However, this correlation was still worse than the correlation between the percentage of damaged bridges and epicentral distance. Of the intensity measures considered, the damage percentage correlated best with the spectral acceleration at a period of 0.3 s (Figure 5), for which the correlation coefficient was 0.892. The correlation coefficient for this case was 0.176 larger than the correlation coefficient for the spectral acceleration at a period of 1.0 s. As shown in Figure 5, damage percent-

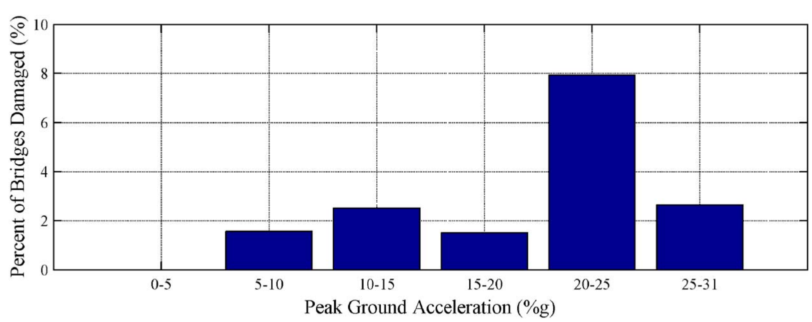

Figure 4. Effect of peak ground acceleration on the percentage of damaged bridges.

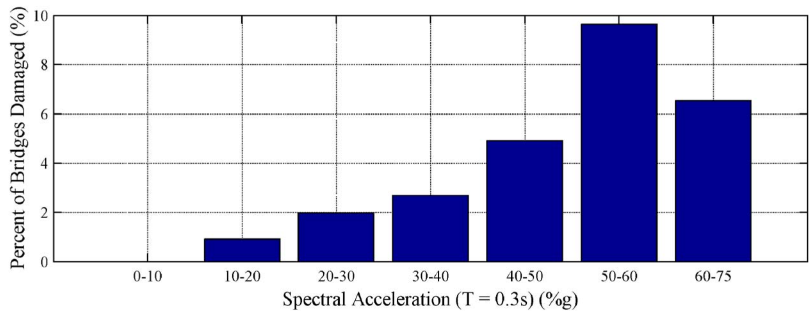

Figure 5. Effect of spectral acceleration (T=0.3 s) on the percentage of damaged bridges.

age increased consistently with spectral acceleration at 0.3 s. The exception to this trend occurred in the highest acceleration range, which had the second highest damage percentage. This anomaly is likely attributable to the small number of bridges in the highest-acceleration category (7 damaged out of 110) and the small number of instruments that recorded the strong motions.

The importance of the spectral acceleration at 0.3 s (as opposed to higher periods) is consistent with the percentage of short bridges in the inventory. Of the 3,407 bridges within the boundaries of the ShakeMap, 2,934 (86%) had lengths shorter than 400 ft (122 m). Such bridges would be expected to have low fundamental periods. For example, Douglas and Reid (1982) found that the first two modal periods for a 400-ft (122 m) long bridge were 0.37 s and 0.27 s.

EFFECTS OF BRIDGE PROPERTIES

Damage progression in a bridge during an earthquake is a complex process that depends on details of the bridge that are not commonly available in bridge databases. For example, the WSBI does not provide heights for the columns along the bridge length, nor does it provide reinforcing details. For this reason, many researchers in the past have classified bridges based on characteristics common to bridge inventories. For example, Basöz et al. (1999) found (from the results of regression analyses) that the most important bridge characteristics for classifying bridge vulnerability were peak ground acceleration, abutment type, skew, span length, and span continuity.

For slight/minor damage (as was the case for the majority of the bridges damaged from the Nisqually earthquake), HAZUS defines bridge classifications based on the age of the bridge, superstructure type, span length, and span continuity. Within this methodology, bridge age, span length, and span continuity acted as binary switches, with the threshold year for bridges outside of California being 1990 and the threshold span length being 492 ft (150 m).

For each bridge, the WSBI (WSDOT 2001) provided the following characteristics, among others:

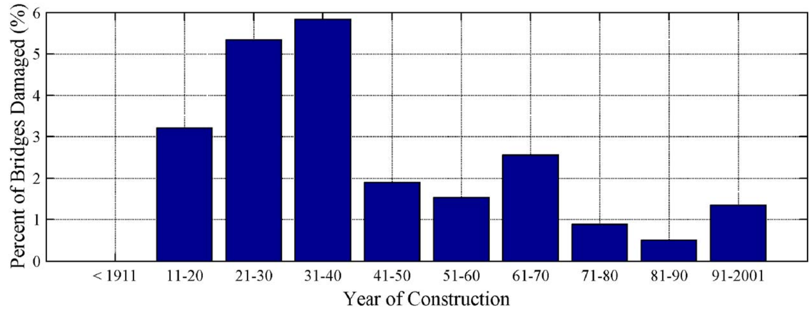

Figure 6. Effect of the year of construction on the percentage of damaged bridges.

- year of construction
- span length
- bridge length
- latitude and longitude
- structural system (e.g., movable, truss, simply supported, continuous)
- material used for the main span (reinforced concrete, prestressed concrete, or steel)

For the analysis of the damage data from the Nisqually earthquake, the year of construction of the bridge was used to account indirectly for variations in design methodologies and details. Figure 6 shows the percentage of bridges damaged as a function of the decade of construction. The percentage of damaged bridges was largest before 1941 and smallest after 1970. The importance of year of construction is also apparent when this factor is considered in combination with spectral acceleration, as shown in Figure 7.

From similar analyses it was determined that span continuity did not significantly affect the vulnerability of bridges at these low levels of damage. It is possible that the

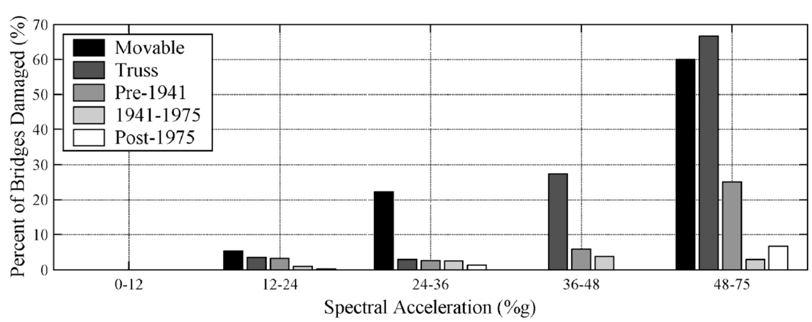

Figure 7. Effects of spectral acceleration (T = 0.3 s) and year of construction.

effect of span continuity is more important at higher levels of deformation, at which point a continuous span redistributes forces to the end abutments. Although span length may also influence damage, the influence could not be evaluated with the Nisqually data. Only 2 of the 18 bridges with spans longer than 492 ft (150 m) were damaged within the boundaries of the ShakeMap.

The characteristics that most influenced the vulnerability of bridges during the Nisqually earthquake were the estimated spectral acceleration (T=0.3 s), the age of the bridge, and the bridge type. Fixed (nonmovable) bridges built after 1975 were the least likely to suffer damage, probably as a result of code changes adopted following the 1971 San Fernando earthquake. The fixed bridges that were built before 1941 had higher damage percentages than bridges built after. The cause of the large damage percentage for these older bridges is unclear. It is possible that the 1949 Olympia earthquake damaged some of these bridges.

Movable bridges and steel trusses were particularly vulnerable (Figure 7). In particular, 6 of the 43 movable bridges and 8 of the 106 trusses within the boundaries of the ShakeMap were damaged, resulting in overall damage percentages of 14% and 8%, respectively. Three of the 15 movable bridges (20%) and 5 of 14 trusses (36%) with a spectral acceleration above 0.36 g suffered damage.

EVALUATION OF HAZUS FRAGILITY RELATIONSHIPS

Bridge fragility relationships are important elements of loss-estimation methodologies for natural disasters such as earthquakes. Among others, Mander (1999), Shinozuka et al. (2000a, b), and Jernigan and Hwang (2002) have developed seismic damage fragility relationships for bridges. Mander (1999) developed fragility relationships for highway bridges and evaluated them using damage data from the 1989 Loma Prieta earthquake. Mander's methodology relies on the bridge properties listed in the National Bridge Inventory (USDOT 2005) and the spectral acceleration at a period of 1.0 s. Shinozuka et al. developed fragility relationships based on empirical data from the 1995 Kobe earthquake in combination with the estimated peak ground accelerations at each site. To complement their empirical model, they developed fragility curves based on nonlinear dynamic analyses. Jernigan and Hwang conducted analytical studies of typical bridges in the central United States.

The combination of estimates of ground-motion intensities (ShakeMaps), damage reports, and bridge properties provided the opportunity to evaluate the default fragility curves incorporated in HAZUS for slight damage (FEMA 2002). One of the functions of HAZUS is to assess the likelihood of disrupted lifelines by, among other things, determining each of the bridges' probability of damage. HAZUS estimates the fragility relationship for each bridge based on a classification that depends on the year of construction, material type, span continuity, and span length. For each category, HAZUS assesses the probability of damage based on a lognormal cumulative distribution function with a log standard deviation equal to 0.6, and a median that varies with the bridge classification and the expected level of damage. Because most of the damage from the Nisqually

Table 2. Comparison of HAZUS predictions with observed damage

				# of Damaged Bridges		
Bridge Type	Continuity	Year of Construction	Bridge Classification	HAZUS Prediction	Actual	Ratio
Long span	All	⩽1975	HWB1	0.7	1	0.7
		>1975	HWB2	0.0	0	N/A
RC	Simply supported	⩽1975	HWB5	66	7	9.4
		>1975	HWB7	2.0	1	2.0
	Continuous	⩽1975	HWB10	18	17	1.1
		>1975	HWB11	1.0	2	0.5
Steel	Simply supported	⩽1975	HWB12	19	6	3.2
		>1975	HWB14	1.0	0	N/A
	Continuous	⩽1975	HWB15	0.4	1	0.4
		>1975	HWB16	0.3	0	N/A
	Short span	⩽1975	HWB17	6.5	1	6.5
		>1975	HWB19	0.0	0	N/A
PSC	Simply supported	⩽1975	HWB22	54	6	9.0
		>1975	HWB23	6.9	1	6.9
	Continuous	⩽1975	HWB24	4.6	4	1.2
		>1975	HWB26	1.3	3	0.4
Other	All	All	HWB27	3.8	21	0.2
			Σ	186	71	2.6

earthquake fell into the HAZUS slight/mild damage category, the accuracy of the default HAZUS fragility relationships was evaluated only for that level of damage.

For bridges constructed outside of California, HAZUS classifies bridges according to whether they were built before or after 1990, with those built after 1990 being modeled as less vulnerable. The resulting default HAZUS estimate of 216 damaged bridges greatly exceeds the observed number of damaged bridges (71) within the boundaries of the ShakeMap. To improve the accuracy of the HAZUS estimates, the threshold year for classifying new and old bridges was changed to 1975. Seismic codes were improved in Washington state around this time, and the damage data (Figure 6) suggests that the mid-seventies is a critical period. Although using 1975 as the critical year (vs. 1990) slightly improved the accuracy of the damage estimates (Table 2), the HAZUS fragility relationships still overestimated the total number of damaged bridges (186 estimated vs. 71 observed).

The accuracy of the default HAZUS damage estimates varied greatly according to the bridge classification (Table 2). For example, the HAZUS methodology assumes that simply supported bridges are much more vulnerable than continuous bridges. For reinforced-concrete bridges, HAZUS uses median spectral accelerations of 0.25 g and 0.60 g for slightly damaged simply supported and continuous bridges, respectively. The HAZUS fragility relationships accurately estimated the number of continuous bridges

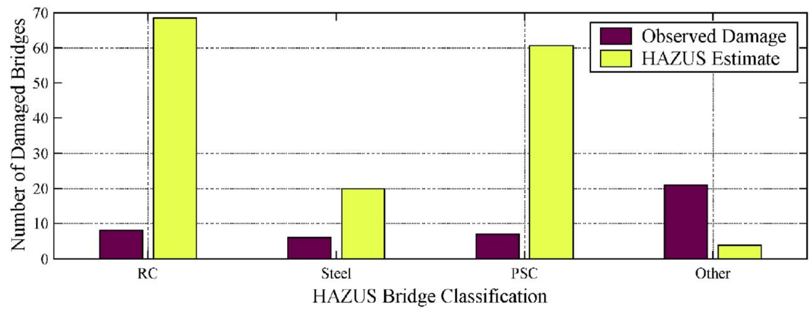

Figure 8. Observed and estimated number of damaged bridges in simply supported and "other" categories.

that were damaged (26 estimated vs. 27 observed). In contrast, the number of damaged simply supported bridges was greatly overestimated (149 estimated vs. 22 observed). Within the boundaries of the ShakeMap, 1.5% of simply supported bridges suffered damage, whereas 2.2% of continuous bridges were damaged. Although lack of continuity may make simply supported bridges particularly vulnerable at higher levels of damage, the data suggests that continuity may not play such a large role at the lowest level of damage. Figure 8 compares the HAZUS estimates and the observed damage for simply supported bridges and for the "other" category.

As Figure 8 shows, the default HAZUS fragility relationships greatly underestimated the damage for the bridges classified as "other" (3 estimated vs. 21 observed). This category includes movable bridges (6 damaged), arch bridges (4), truss bridges (8), and bridges for which the main span design was not classified by the WSBI (3).

DEVELOPMENT OF FRAGILITY RELATIONSHIPS

The Nisqually data made it possible to develop new fragility relationships that better correspond to the observed damage for the Pacific Northwest. The preceding analysis of earthquake damage indicated that fragility curves for most bridges should be based on the spectral acceleration at a period of 0.3 s, the year of construction, and the bridge type. The amount of data available is insufficient to calibrate a model that considers each of the HAZUS categories individually, so instead, bridges are categorized by their year of construction and their type (movable, steel truss). Based on the damage data from the Nisqually earthquake, fragility relationships were developed using a lognormal distribution (Equation 1):

$$P_d = \Phi\left[\frac{1}{\zeta}\ln\left(\frac{S_a}{A}\right)\right] \tag{1}$$

where P_d is the bridge damage probability, $\Phi[\ ]$ represents the standard normal cumulative distribution function, S_a is the estimated spectral acceleration (in g), and A and ζ

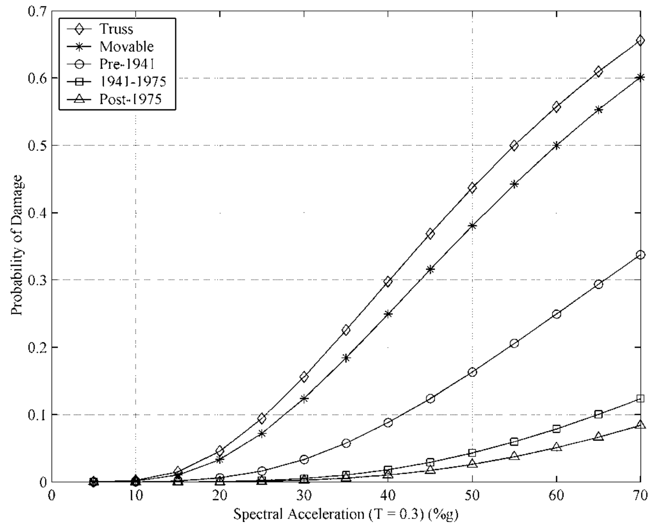

Figure 9. Fragility curves for mild/moderate damage accounting for bridge age and type.

are the median and the log standard deviations of the fragility curves, respectively. The median spectral accelerations were determined to be

$$A = \begin{cases} 0.55 & (\mathit{pre}\text{-}1976\ \mathit{truss}) \\ 0.6 & (\mathit{movable}) \\ 0.9 & (\mathit{pre}\text{-}1941) \\ 1.4 & (1941\text{–}1975) \\ 1.6 & (\mathit{post}\text{-}1975) \end{cases}$$

The values for the log standard deviations of each of the categories were set at 0.60 to mirror those used in HAZUS. The resulting fragility curves are plotted in Figure 9. For the Nisqually earthquake, these curves provide more accurate estimates of the damage probability for each of the bridge categories.

EFFICIENCY OF INSPECTION PRIORITIZATION

Increasing the efficiency of post-earthquake inspections can reduce inspection costs and traffic disruption. In the past, the WSDOT has prioritized bridge inspections based loosely on epicentral distance. The efficiency of this methodology might increase by prioritizing bridge inspections based on the bridge's probability of damage, determined by combining ShakeMap spectral ordinates, the bridge inventory, and the fragility relationships expressed by Equation 1. Figure 10 summarizes the effects of adopting this strategy using data from the Nisqually earthquake, and compares it with strategies based on epicentral distance alone and spectral acceleration alone.

Considering all bridges within the boundary of the ShakeMap for which there was

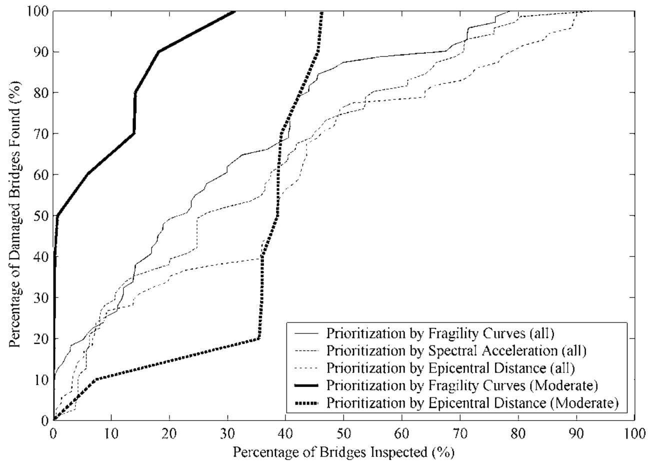

Figure 10. Effectiveness of various prioritization strategies.

ground motion data, the proposed strategy identified damaged bridges nearly twice as quickly as an epicentral distance strategy. For example, to identify 50% of the damaged bridges, it would have been necessary to inspect 784 (23%) bridges using the proposed strategy and 1,240 (39%) bridges using epicentral distance alone. The benefits of using Equation 1 are even more apparent if one considers only the 10 moderately damaged bridges within the ShakeMap boundaries. Eight of these bridges would have been found after inspecting 481 (14%) bridges within the ShakeMap boundary. In contrast, it would have been necessary to inspect 1,447 (42%) bridges if inspections had been prioritized by epicentral distance.

IMPLEMENTATION CONSIDERATIONS

The proposed methodology has been implemented within the Pacific Northwest Seismic Network ground-motion processing and notification software for the WSDOT. Shortly after each earthquake that exceeds the magnitude threshold (which depends on epicentral location), e-mail and pager alert messages are sent to WSDOT personnel notifying them of the preliminary earthquake magnitude and epicenter. ShakeMaps and lists of bridges (ranked by likelihood of bridge damage calculated with Equation 1) are available on a Web server at the University of Washington and are pushed to a WSDOT FTP site to be downloaded for post-earthquake response planning (Malone et al. 2005). The California Department of Transportation has implemented a similar system (Wald et al. 2003), which has recently become operational (Wald 2005).

It is important to exercise judgment in interpreting the information provided by the automated software. For example, one anomalous recording can bias the distribution of shaking (Rojahn et al. 2004). None of the available fragility curves have been calibrated with data from numerous, relevant earthquakes and bridge inventories. For this reason, the user can also sort the bridge lists provided according to the probability of damage calculated by the HAZUS procedure or by the level of estimated spectral acceleration.

Although the damage probabilities will help the WSDOT prioritize immediate bridge inspections, it would be inefficient to inspect bridges based solely on their estimated probabilities of damage. For example, it would not make sense for inspectors to bypass bridges based on small differences in estimated probability of damage. In addition, many jurisdictions are organized into districts with local inspection teams whose location must also be considered in developing post-earthquake response. When time becomes available, most districts will want to inspect the remaining bridges within their jurisdiction.

No damaging earthquakes have occurred since the new prioritization software has been operational. Nonetheless, following small earthquakes, WSDOT personnel have used the new information products to confirm that it was not necessary to dispatch inspectors (Coffman 2005).

CONCLUSIONS

The 2001 Nisqually earthquake provided the opportunity to evaluate the influence of ground motion and bridge properties on the likelihood of a bridge's suffering damage during an earthquake in the Pacific Northwest. The Nisqually earthquake damaged 78 bridges, of which 67 had slight or mild damage (based on the estimated repair costs), and 11 had moderate damage. For each damaged and undamaged bridge, several measures of ground-motion intensity were estimated with ShakeMaps. Bridge properties were extracted from the Washington State Bridge Inventory (2000).

The percentage of bridges damaged correlated best with the estimated spectral acceleration at a period of 0.3 s, the year of construction, and whether the bridge was movable or an older steel truss. The mechanical components of movable bridges make them particularly vulnerable. Older truss bridges suffered a disproportional amount of damage to their movement joints and vulnerable bracing members.

The Nisqually data also made it possible to evaluate the accuracy of the HAZUS fragility relationships for slight/mild damage. For Washington state, seismic vulnerability correlated better with whether the bridge was constructed before or after 1975, as opposed to 1990, the year used by HAZUS to identify seismically resistant bridges outside of California. Using this modified date, the default HAZUS fragility relationships accurately estimated the number of continuous bridges that were damaged during the Nisqually earthquake. In contrast, the default HAZUS relationships greatly overestimated the number of damaged simply supported bridges (149 estimated vs. 21 observed). The data suggests that simply supported bridges are not more vulnerable than continuous bridges at this lowest level of damage. In addition, HAZUS greatly underestimated the number of bridges damaged in the category "other" (4 estimated vs. 21 observed), which includes movable bridges and trusses. The data suggests that the high vulnerability of these bridges needs to be included in vulnerability estimates.

Lognormal cumulative distribution functions (Equation 1) were used to model the fragilities of the bridges based on the year of construction, and whether the bridge is movable or an older truss. These relationships, combined with ShakeMaps, can be used to plan post-earthquake inspections. If this method had been used following the Nisqually earthquake, it would have been possible to identify 50% of the damaged bridges by inspecting only 23% of the bridges within the boundary of the ShakeMap. Moderately damaged bridges could have been identified even more efficiently. For example, 8 of the 10 moderately damaged bridges within the ShakeMap could have been identified after inspecting only 481 (14%) bridges. Using a prioritization strategy based on epicentral distance, it would have been necessary to inspect 1,447 (42%) bridges to identify the same amount of damage.

The proposed methodology has been implemented within the Pacific Northwest Seismic Network software to help WSDOT plan post-earthquake recovery operations.

ACKNOWLEDGMENTS

The authors would like to thank the many engineers who contributed damage reports to this study, including Harvey Coffman (WSDOT) and John Buswell (City of Seattle). John Perry of the Federal Emergency Management Agency provided essential GIS support. The Pacific Earthquake Engineering Research Center (PEER) financially supported data gathering and analysis through the Earthquake Engineering Research Centers Program of the National Science Foundation (NSF) under Award Number EEC-9701568, and through the NSF Research Experience for Undergraduates Program. The implementation of the post-earthquake prioritization strategy was supported by the Washington State Department of Transportation.

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(Received 12 December 2005; accepted 8 May 2006)