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Flexural Assessment of Existing Slab Bridges in The Pacific Northwest Region Under Long-Duration Earthquake Effects

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Abstract **-** Previous research has been conducted on the vulnerability of bridges, but there is a gap in assessing the vulnerability of existing bridges, such as slab bridges, when subjected to long-duration earthquakes in regions with high seismic activity. This study provides a unique quantification and assessment of the impacts of an anticipated moment magnitude (MW) 9.0 earthquake event characterized by its long-duration on the incipient collapse risk of slab bridges in the Pacific Northwest (PNW) region. The assessment encompasses the potential for flexural failures in the columns of slab bridges and the risk of collapse. A slab bridge is modeled in OpenSees as case studies to quantify the vulnerability and risk of incipient collapse using fragility analyses and risk-targeted approach per the 2023 AASHTO Guide Specifications for LRFD Seismic Bridge Design. This study highlights the consequences of the lack of strict seismic design standards in older design codes, especially for slab bridges built before the 1990s. In addition, the findings of this research have shown the impact of long-duration earthquakes on their potential to drastically increase collapse risks of aging slab bridges built before the 1990s.
Keywords**:** slab bridge, Pacific Northwest, long-duration, fragility analyses, risk-targeted.

1. Introduction

The Pacific Northwest (PNW) region lies within the Cascadia Subduction Zone (CSZ), and is characterized by producing the world's most powerful Long-duration earthquakes with magnitudes exceeding $\boldsymbol{M}_\mathbf{W}$ 8.5 [1, 2]. Consequently, during such seismic events, bridges in this region, particularly those designed before the 1990s, face a higher risk of damage. This damage can occur through flexure, shear, or a combination of flexural-shear behavior, depending on the reinforcement details. The majority of the interstate highway systems in the PNW region which include both Washington and Oregon states were built in the mid to late 1960s. These bridges were built according to less stringent seismic design standards than those in place today, making them particularly vulnerable to the next significant earthquake or tsunami. Consequently, the focus of this study is to evaluate the flexural assessment and the risk of collapse for slab bridges built before the 1990s in the PNW.

2. Research Objective

The primary objective of the study is to quantify the flexural failure and risk of slab bridges typical in the PNW region in the event of a long-duration using fragility analysis. Furthermore, the effects of location on incipient collapse risk of slab bridges in the PNW region need to be considered, whether they are situated within or outside the basin, using latest site classification definitions outlined in AASHTO, 2023 [3]. This study investigated the effects of outdated seismic design standards (i.e., column displacement ductility) on the slab column capacity. In addition, the new risk-targeted approach per the 2023 AASHTO Guide Specifications for LRFD Seismic Bridge Design [4] for new design is used to evaluate the collapse risk for existing slab bridge. The updated 2023 version of the AASHTO LRFD Bridge Design Specifications has moved to a risk-targeted approach rather than using a uniform seismic hazard approach.

3. Bridge Inventory in the Pacific Northwest (PNW) Region

In this study, the bridges in Washington and Oregon states were considered to represent the PNW region. These two states have close to 9600 bridges with varying ages, and construction styles. Figure 1 illustrates the categorization of bridges in the PNW region according to the design of their main span, as per the FHWA National Bridge Inventory [5-7]. It was discovered that over 32% of the bridges are slab, with 97% of them built utilizing the concrete construction style. Furthermore, figure 2 indicates that 66% of the bridges in the PNW region are rated in fair to poor condition.

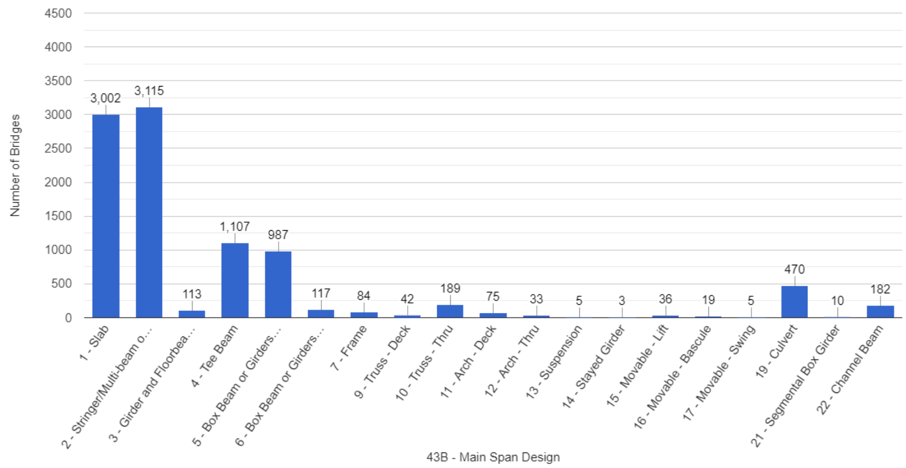

Fig.1: Bridge classes inventory in PNW region by national bridge inventory, 2023, based on main span design.

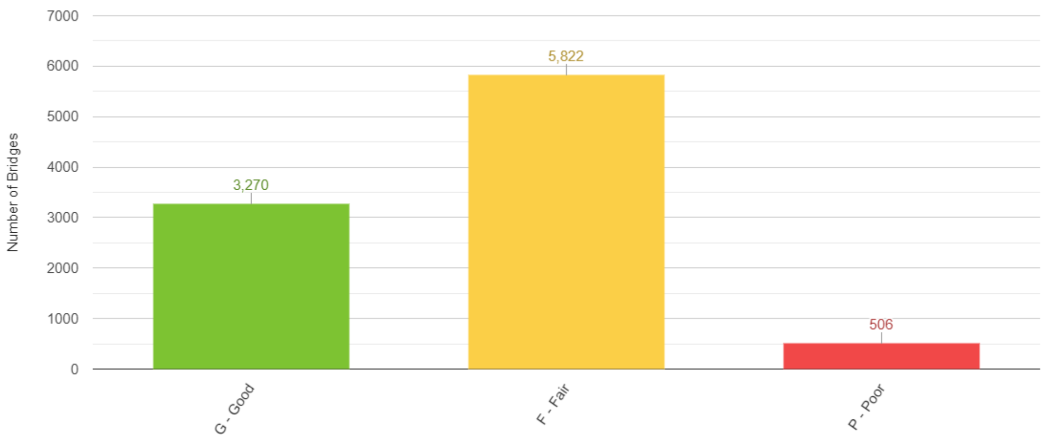

Fig. 2: Bridge condition by national bridge inventory, 2023.

4. Methodology

4.1. Selection of Ground Motions for the PNW Region

This study aims to investigate the previously mentioned objective under the long-duration earthquake. Because there is a limited number of long-duration records available in the PNW region, simulated ground motions of M_W 9.0 earthquakes in the PNW region are utilized for this purpose. Eight representative locations across the PNW region were identified and listed in Table 1, depicted in figure 3. The locations are classified into two groups: coastal and inland, based on their proximity to the fault, Z2.5 values (representing the depth to a shear-wave velocity of 2500 m/s), and numerical intensity measure (IM) that describe their content. For each location, 30 different earthquake rupture scenarios were selected, resulting in a total of 240 simulated ground motions across the eight locations. The coastal areas include Brooking, Florence, Ocean Shores, and Forks, while the inland regions consist of Abbotsford, Vancouver, Bremerton, and Port Angeles. These classifications are roughly aligned with those utilized by Kortum et al., 2022 [8, 9]. The peak ground accelerations (PGAs) for the simulated ground motions range from 0.14 to 1.84 g. Ground motion data for the eight locations were sourced from the nearest monitoring station to each city, with the station IDs provided in table 1, column 1.

Table 1: Representative locations across the PNW region selected for the study.

Station Name	City Name	PGA (g)	Category	City Name Abbr.
D00414	Abbotsford	0.14	Inland Outside of Basin	Abb.
C03853	Vancouver	0.43	Inland Outside of Basin	Van.
A11120	Bremerton	0.49	Inland Deep Basin	Bre.
Y0FRE	Florence	0.99	Coastal Outside of Basin	Flo.
B01192	Forks	1.07	Coastal Outside of Basin	For.
B01052	Ocean Shores	1.29	Coastal Outside of Basin	Oce.
Z0XANG	Port Angeles	1.55	Inland Shallow Basin	Por.
Z0XCRC	Brookings	1.84	Coastal Outside of Basin	Bro.

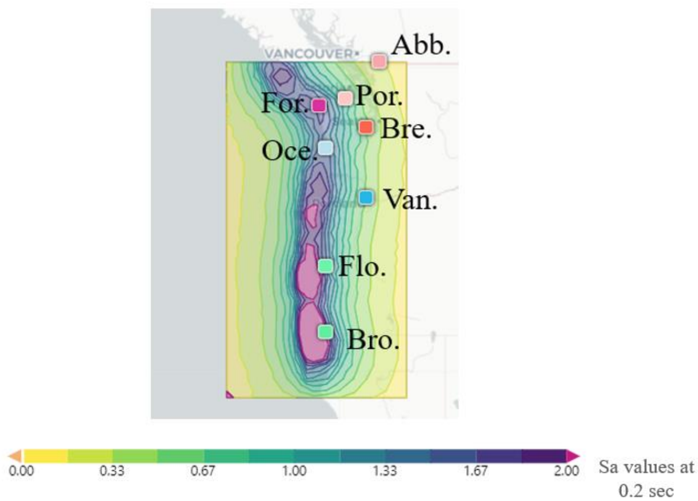

Fig. 3: Representative locations across PNW region selected for study (source: $\boldsymbol{M}_{\mathrm{W}}$ 9.0 Data Visualizations, [10]).

4.2. OpenSees Model Development

A three-span slab bridge in the PNW region was modeled using the OpenSees software [11] to assess the flexural behavior of its reinforced concrete (RC) columns. Various element types were utilized during the modeling process to accommodate the nonlinearities within the bridge components. The superstructure consists of an RC deck slab with spans of 56 ft, 69.5 ft, and 59.5 ft, respectively. At each end span, there are four integral columns positioned at 56 ft and 125 ft. Figure 4 illustrates the materials and element types utilized in the OpenSees model for the bridge components. For the columns, Concrete04 was utilized to model the uniaxial core concrete material, accounting for degraded linear unloading/reloading stiffness. Concrete01 was used to model the cover concrete (2 in), with this material type considering zero tensile strength. The reinforcement was modeled using a uniaxial hysteretic material available in the OpenSees library.

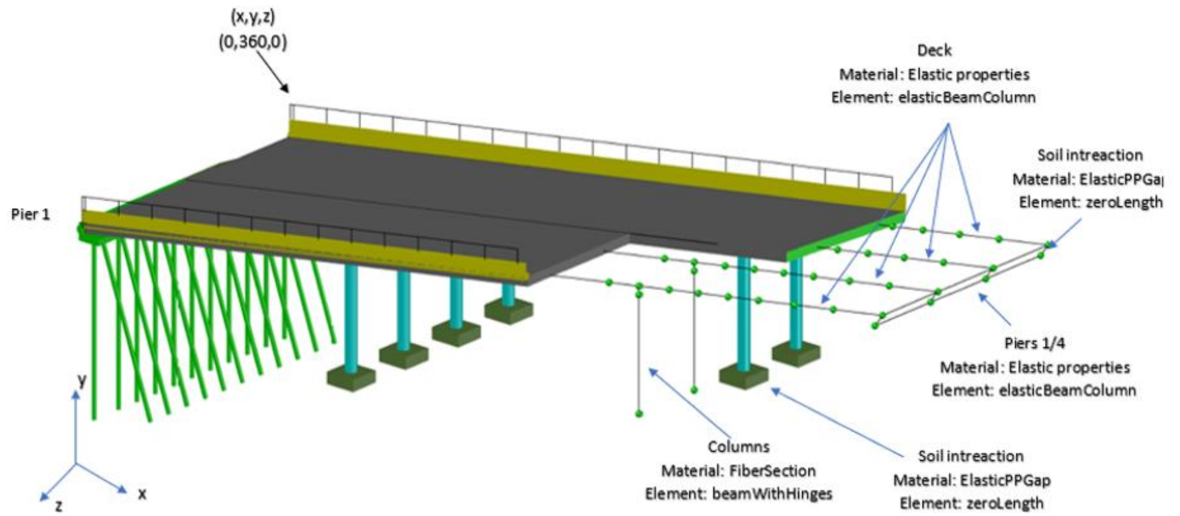

Fig. 4: OpenSees slab bridge model (material and element types of the bridge components).

4.3. Fragility Analysis for Flexural Assessment

A seismic demand model and damage states capacity need to be conducted in order to develop the fragility analysis, where the seismic demand model could be quantified by developing the Probabilistic Seismic Demand Model (PSDM). PSDM characterizes how earthquakes may affect a structure by relating an Intensity Measure (IM) to an Engineering Demand Parameter (EDP). The IM used for flexural assessment is PGA, while the EDP is represented by the column displacement ductility. The damage states capacity (DSs) outlines the probable damage incurred by structures at the demand level experienced during an earthquake. Four damage states, slight, moderate, significant, and complete damage are considered, comparable to those found in HAZUS-MH [12]. In the analysis, the column demand from Nonlinear Time History (NLTH) analysis and the IM data from ground motions are subjected to a regression analysis to determine the parameters of the PSDM. The column displacement ductility is the EDP considered for the flexural assessment and is defined as follows:

$$\mu_{\Delta} = \frac{\mu_{max}}{\mu_{yield}} \tag{1}$$

where μ_{max} is the maximum displacement and μ_{yield} is the displacement when the vertical reinforcements reach the steel yield strength at the first time; which is the displacement of the column at first yield.

4.4 Risk Assessment Approach

Seismic hazard analysis is the process of predicting strong motion for specific sites to design a safe structure. The risk of collapse is a function of the overlap between the developing fragility curve which is a response damage function of a structure and the hazard curve which is the likelihood of observing ground motions of different intensities at the site being exceeded in a time frame (AASHTO, 2023a). In this study, the individual effect of $\boldsymbol{M}_{\mathbf{W}}$ 9.0 simulated ground motions using AASHTO Guide Specifications for LRFD Seismic Bridge Design (2023a) approach on calculating the collapse risk is discussed and compared to specification limit per AASHTO Guide Specifications for LRFD Seismic Bridge Design (2023) and AASHTO LRFD bridge design specifications (2020). The design target ground motions for AASHTO Guide Specifications for LRFD Seismic Bridge Design (2023a) is 1.5% in 75 years, but 7% in 75 years for AASHTO LRFD Bridge Design Specifications (2020). In the PNW region, the risk of collapse is calculated and assessed using fragility curves derived from an extensive Nonlinear Time History (NLTH) analysis for the slab bridge and a recently updated 2018 seismic hazard map. Fragility curves for the DS4, representing complete damage, for slab bridges in both inland and coastal locations, considering the seismic activity level in the PNW region. Spectral displacement at short periods (0.2 sec) is used to assess the risk posed by seismic loads from simulated ground motions of $\boldsymbol{M}_{\mathrm{W}}$ 9.0 earthquakes. For inland sites, the hazard curve for Port Angeles is utilized, whereas Ocean Shores is chosen for coastal locations, as both cities experience a higher annual frequency of exceedance.

5. Results

The study examines flexural failure in existing slab bridges located in the state of Washington within the PNW region, particularly under long-duration earthquakes. Fragility curves are created using the Intensity Measure (IM) of PGA and the Engineering Demand Parameter (EDP) of column displacement ductility for a selected slab bridge in the PNW region built before the 1990s. The analyses aim to demonstrate the impacts of older bridge designs and their seismic vulnerability, particularly when evaluating column displacement ductility in columns with low confinement. This assessment is then compared with the current specification limit by AASHTO Guide Specifications for LRFD Seismic Bridge Design (2023), which adopts a risk-targeted approach.

5.1. Flexural Assessment Results

Fragility curve analysis is utilized to assess the flexural failure of the slab bridge column. A total of 240 ground motion records were generated and paired with the analytical model, resulting in 240 model outcomes. For each ground motion, a complete nonlinear time-history analysis, capturing the maximum demand on the bridge. Subsequently, the bridge demands were correlated with the PGA of the ground motion responsible for the demand. Given that the columns of the bridges were anticipated to be the primary failure source, the column demand was then plotted against the PGA of the ground motion. These datasets are subjected to regression analysis to estimate the parameters of the PSDM. Figure 5 illustrates the PSDM, depicting the correlation between PGA and displacement ductility of slab bridge columns in both inland and coastal cities. Notably, there is a considerable difference in column demand between inland and coastal cities, with a higher demand observed in bridge columns located in coastal cities. This disparity is anticipated due to the closer proximity of coastal cities to active faults, resulting in higher PGAs (approximately exceeding 1g).

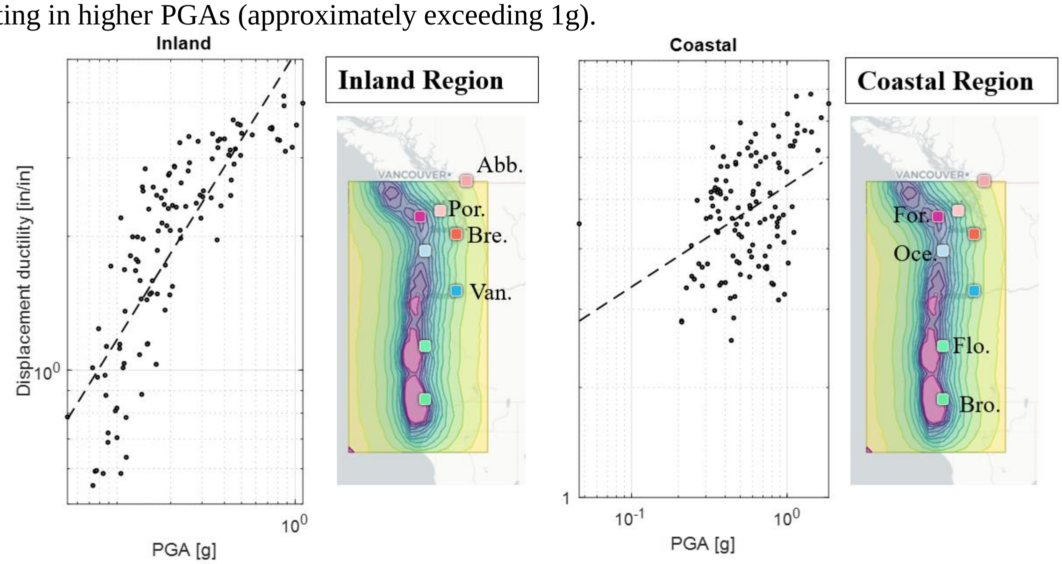

Fig. 5: PSDM for inland region and coastal regions for slab bridge [10].

Fragility curves for slab bridges under seismic loads are plotted to evaluate their vulnerability to earthquake- induced damage. Figure 6 shows these fragility curves for the slab bridge for the four limit states relative to PGA. Notably, there are significant variations in the fragility curves between the two groups of sites, influenced in part by their proximity to active faults. The fragility curves illustrate how a slab bridge might respond if it were located in various cities subjected to specific ground motions. Based on these curves, it is evident that if slab bridges were located near coastal cities, they would ideally experience higher demands due to the specific ground motions in those areas.

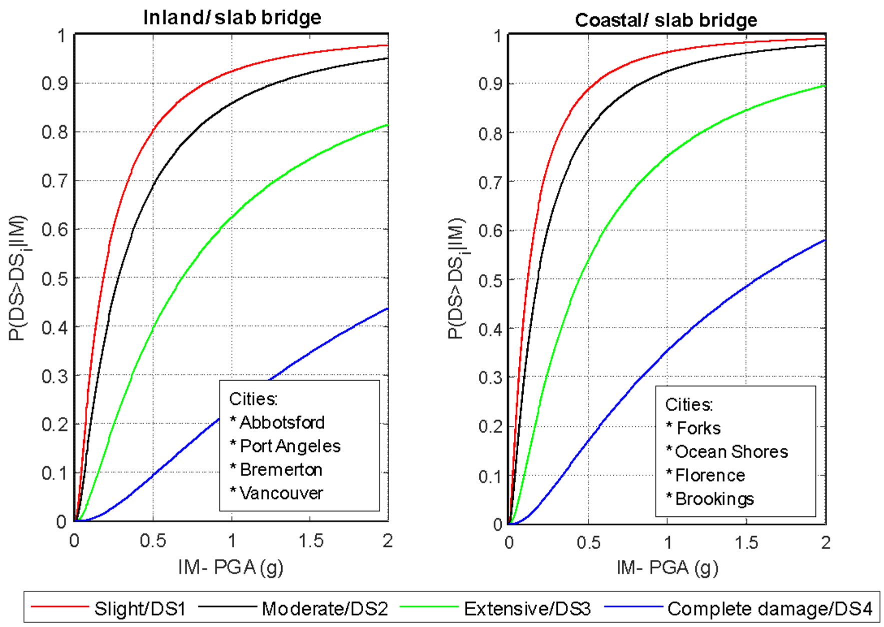

Fig. 6: Fragility Curves for Slab Bridge for Column Displacement Using PGA.

5.2. Seismic Risk Assessment Results

In this section, the impact of M_W 9.0 simulated ground motions on calculating the targeted collapse risk for the slab bridge is assessed. Following the methodology outlined in section 4.4, the 75-year probability of collapse for Port Angeles is determined to be 8.25%, whereas for Ocean Shores is 5.25% using M_W 9.0 simulated ground motion for slab bridge evaluation. The collapse risk over 75 years for all inland regions was found to be higher than that of the coastal regions, and both risks significantly surpass the target 1.5% probability of collapse in 75 years proposed by the AASHTO Guide Specifications for LRFD Seismic Bridge Design, 2023 [4].

Additionally, as stated by AASHTO (2020), a 7% probability of exceedance in 75 years could lead to substantial damage and disruption to bridges, emphasizing the need for designing bridges with a low probability of collapse. In summary, the anticipated MW 9.0 ground motion in the future has the potential to cause significant damage and service disruptions, particularly for aging slab bridges in the PNW region [4]. The geographical location plays a crucial role in risk assessment; for instance, the Inland region exhibits a higher hazard curve compared to the coastal region, posing a greater risk to structures with limited seismic resilience, such as slab bridges.

6. Conclusion

This study involved modeling and evaluating existing slab bridges located in the state of Washington within the PNW region under the effect of long-duration earthquakes through fragility analysis. Furthermore, the collapse risk for the slab bridge was assessed using M_W 9.0 simulated ground motions following the approach outlined in the 2023 AASHTO Guide Specifications for LRFD Seismic Bridge Design. The bridges examined in the PNW region were built before the 1990s and thus lack the risk considerations incorporated in the current 2023 risk-targeted approaches. The ground motions utilized in this study accounted for site classifications and local site effects.

Insights obtained from the flexural assessment of these slab bridges provided crucial information about their performance under various ground motion scenarios. Notably, fragility curves generated using PGA indicated notable regional differences, with coastal cities showing a higher probability of failure for slab bridges compared to inland cities in the PNW region.

The updated risk-targeted methodology introduced in the AASHTO Guide Specifications for LRFD Seismic Bridge Design, 2023 was used to evaluate the vulnerability of older bridges constructed prior to the 1990s. The assessment revealed that M_W 9.0 simulated ground motions, in particular, lead to increased damage and significantly heightened the risk in this area. Moreover, there were observable discrepancies in collapse risk across the different set versions, suggesting the varied effects of earthquake source mechanisms on different regions.

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