



## EFFECTS OF SIMULATED M9 EARTHQUAKES ON REINFORCED CONCRETE WALL STRUCTURES IN THE U.S. PACIFIC NORTHWEST

N. A. Marafi<sup>(1)</sup>, M. O. Eberhard<sup>(2)</sup>, J. W. Berman<sup>(3)</sup>

<sup>(1)</sup> Senior Modeler, Risk Management Solution, Inc., [nasser.marafi@rms.com](mailto:nasser.marafi@rms.com); Affiliate Assistant Professor, University of Washington

<sup>(2)</sup> Professor, University of Washington, [eberhard@uw.edu](mailto:eberhard@uw.edu)

<sup>(3)</sup> Professor, University of Washington, [jwberman@uw.edu](mailto:jwberman@uw.edu)

### Abstract

The Cascadia Subduction Zone (CSZ) can produce long-duration, large-magnitude earthquakes, whose ground motions will be modified by the deep sedimentary basins that underlie several cities in the Pacific Northwest (e.g., Portland, Seattle, and Vancouver, BC). The effects of these basins on the characteristics of the ground-motions are poorly understood, because no recordings are available for large-magnitude earthquakes in this region.

To compensate for this paucity of recordings, researchers from the United States Geological Survey and the University of Washington generated ground motions for numerous scenarios of an M9 event. The simulations were generated using deterministic, finite-difference ( $T > 1s$ ) and stochastic ( $T < 1s$ ) approaches and included effects of the deep sedimentary basin underlying Seattle. As a result of this work, basin effects will be included in future versions of the building code for Seattle. This paper discusses the implications of basin effects and long duration shaking on the expected performance of reinforced concrete core-wall structures. Specifically, motions were selected from multiple source mechanisms to probabilistically assess the collapse risk for 36 archetypes, located in Seattle, and ranging from 4- to 24-stories.

The durations of the motions were long, but they were not significantly increased by the basin. The frequency dependent basin amplification increased the spectral accelerations at periods corresponding to that of tall structures and resulted in damaging spectral shapes. Buildings designed to the minimum requirements set by the current U.S. code (ASCE 7-16) resulted in a collapse risk that exceeded the 1% risk of collapse in 50-year target. The 1% target could be achieved by (a) increasing the design lateral forces by 25%, (b) decreasing drift limits from 2.0% to 1.25%, or (c) increasing the deformation capacity of the gravity system to an interstory drift ratio of 9%.

*Keywords: reinforced concrete walls, deep basins, long duration, collapse risk analysis*



## 1. Introduction

Some of the largest metropolitan regions in the Western United States are underlain by sedimentary basins, including the Puget Sound region, as well as parts of the Los Angeles, San Francisco Bay Area, and Salt Lake City regions [6]. Such basins are known to amplify long-period spectral accelerations ranges (e.g., [1]) resulting in more damaging spectral shapes [2], which increase the likelihood of collapse during an earthquake (e.g., [3,4,5]). The National Seismic Hazard Model (NSHM) referenced by building codes did not account for basins until recently. The 2018 version of the NSHM [6] accounts for the effect of basins on spectral acceleration using basin terms derived from ground motion models from NGA-West-2 [7]. The adoption of this new hazard model into current building and bridge seismic provisions would result in large increases in design spectral accelerations for structures located on deep basins.

Current building seismic provisions (ASCE 7-16 [15]) are derived from the 2014 NSHM [8], which does not consider the effects of deep basins. In this paper, the collapse risks for ASCE 7-16 code-compliant building archetypes are investigated for the increased spectral accelerations from the updated 2018 NSHM. These consequences are calculated for a series of previously designed reinforced concrete wall archetypes ranging from four to twenty-four stories [5]. The archetypes were designed for the seismic hazard in Seattle, met the minimum code requirements set by ASCE 7-16, and are referred to as *reference archetypes* throughout this paper. Previous work by the authors [5] showed that, if basin effects were considered, the conditional collapse probability for reference archetypes averaged 21% for an **M**9 event on the Cascadia Subduction Zone with a return period of approximately 526 years [8].

The paper evaluates the effectiveness of implementing four strategies to redesign the reference archetypes to reduce the seismic collapse risk for the 2018 NSHM demands. The strategies are: (1) increasing the seismic response coefficient ( $C_s$ ) in ASCE 7-16 by 25% or by 50%, (2) reducing the design drift limits prescribed in ASCE 7-16 from 2.0% to 1.5% or 1.25%, and (3) increasing the drift capacity of the gravity system.

## 2. National Seismic Hazard Model

The 2018 update of the National Seismic Hazard Model [6], denoted here as 2018 NSHM, accounts for the effects of the basins in Western United States. Figure 1 shows the uniform hazard spectra (UHS) in the orientation corresponding to median spectral acceleration values for Seattle for a 2% probability of exceedance in 50 years for Site Class C. This value, often denoted as  $S_{a,ROT50}$ , will be referred to as  $S_a$  throughout the paper. As shown in Figure 1, the increases between the 2014 and 2018 NSHM occur over a wide range of periods. The increases are on average approximately 25% for short periods ( $< 0.45$  s), and the average increase is approximately 50% for periods ranging from 0.5 to 1.7 s. This period range corresponds approximately to typical periods of 4- to 24-story reinforced concrete wall buildings designed as per ASCE 7-16 [5]. The increase is largest at a period of 4 s, where  $S_a$  increases from 0.13 g to 0.22 g, corresponding to an increase of 72%. However, at this period, the design base shear is typically (ASCE 7-16) governed by the minimum base-shear requirements.

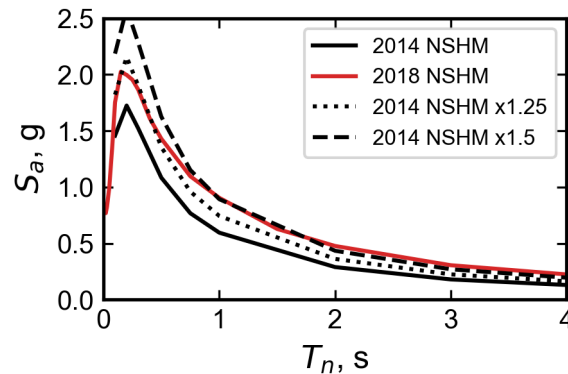


Figure 1. Uniform hazard spectra for a 2% probability of exceedance in 50 years in the direction corresponding to median spectral acceleration (RotD50) for Seattle computed using the USGS (2019) probabilistic seismic hazard analysis code.

## Archetype Designs

Modern mid- and high-rise reinforced concrete core-wall archetypal residential buildings, ranging from 4 to 24 stories were evaluated between the 2014 and 2018 versions of the USGS hazard models (Figure 1). To reflect current practice in Seattle, all of the archetypes were (1) designed and detailed as special reinforced concrete shear walls (ACI 318-14), (2) used a seismic force-reduction factor,  $R$ , of 6, (3) developed with extensive input from design professionals (refer to [5]). Buildings with a height above 73 m (240 ft) are not considered in this paper, because the design of such buildings in Seattle is subject to extensive peer review, which accounts for the effects of the Seattle basin.

All archetypes had a floor plate that was 30.5 m (100 ft.) long by 30.5 m (100 ft.) wide with three, 9.15-m (30-ft.) bays of slab-column gravity framing in each orthogonal direction. The 4-story archetypes had two planar walls in each orthogonal direction. Archetypes with 8 stories or more used a central core-wall archetype that was symmetrical in both directions, in which one direction used two uncoupled C-shaped walls, whereas the other direction used coupled C-shaped walls. As is typical for residential buildings, the 4- and 8-story archetypes included two and three basement levels, respectively, and the taller archetypes had four basement levels. The basements were assumed to have plan dimensions of 48.8 m x 48.8 m (160 ft x 160 ft). The floor-to-floor heights for all stories (basement levels included) were 3.05 m (10 ft). Further information related to the design of the structure can be found in Marafi et al. [5].

For each of these six archetypes, the impacts of adopting three design strategies were studied. As part of Design Strategy #1, archetypes were redesigned for lateral loads that are 25% or 50% larger than  $S_{a,MCE}$  computed using the 2014 NSHM. As part of Design Strategy #2, archetypes were redesigned to meet a stricter story drift target of 1.5% or 1.25%, as opposed to the current ASCE 7-16 value of 2.0%. Design Strategy #3 assumed no changes to the reference designs of the seismic force resisting system, but it assumed that the gravity system could be redesigned to have a larger drift capacity.

## Archetype Modelling

The six archetypes and their design strategy variations were analyzed using 2D nonlinear models in *OpenSees* [9] to assess the seismic performance. These analyses were performed with the help of the



computational resources provided by *DesignSafe-CI* [10]. The nonlinear behavior of the wall was modeled using a methodology that is summarized in Marafi et al. [5], which uses displacement-based, beam-column elements with lumped-plasticity fiber sections to capture the axial and flexural nonlinear responses of the RC walls. The stress-strain behavior of the steel fibers includes cyclic strength degradation [11] to account for strength deterioration expected with long-duration shaking.

### Multiple Stripe Analysis

The performance of each archetype was assessed using a multiple stripe analysis [12], in which the collapse probability was quantified at multiple intensity measure levels, each corresponding to a particular return period. The intensity stripes used in the MSA had return periods of 100, 475, 975, 2,475, and 4,975 years. The variety in return periods made it possible to account for the performance of a structure during low-intensity events that occur more frequently (i.e., lower return period) and high-intensity events that occur less frequently (i.e., longer return period). The probability of collapse results from each intensity level and corresponding earthquake return period was then integrated over the overall  $S_a(T_1)$  hazard curve to estimate the probability of building collapse over a period of 50 years. It should be noted that collapse was defined using the story drift of a structure under intense ground shaking. Haselton et al. [13] define collapse as an increase in lateral drift without bounds due to global P-Delta instability. A building may also collapse (or partially collapse) due to the failure of components of the gravity system. Based on the work of Zhou and Hueste [14], the median interstory drift ratio at collapse was assumed to be 5.9%. Both failure mechanisms were considered in this study.

### Collapse Risk for 2014 and 2018 NSHM

Seismic provisions in ASCE 7-16 target a uniform 1% likelihood of collapse during a 50-year period. To compute the collapse risk, the annual rate of collapse ( $\lambda_{collapse}$ ), considering the full range of expected shaking intensities from all earthquake sources that contribute to the seismic hazard was computed. Figure 2 shows the probability of collapse for the 8-story, 16-story, and 24-story archetypes with respect to earthquake return period, for the 2014 NSHM (Figure 2a) and 2018 NSHM (Figure 2b). The figure also shows smooth curves that represent a fitted lognormal distribution of the data points.

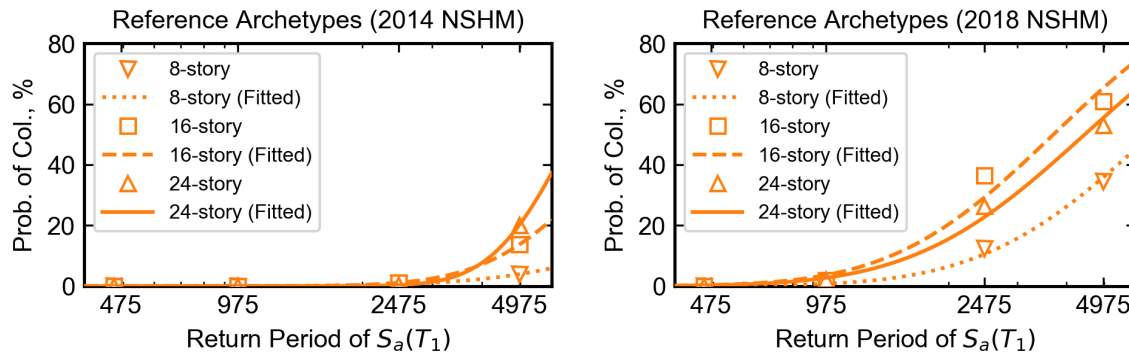


Figure 2. Probability of collapse with respect to earthquake return period for the 8-story, 16-story, and 24-story ASCE 7-16 archetypes evaluated using the (a) 2014 National Seismic Hazard Model and (b) 2018 National Seismic Hazard Model.

The annual rate of collapse was computed by integrating the collapse fragility derived in Figure 2 for each archetype. To compute the 1% target in 50-years set in the current provisions, the collapse risk in 50 years for each archetype was computed assuming a Poisson distribution (i.e.,  $1 - e^{-\lambda_{collapse} t}$ , where  $t$  was taken as 50 years). Figure 3 shows the 50-year collapse risk for all the reference archetypes using both the 2014 NSHM (squares) and 2018 NSHM (triangles). For all archetypes, the average 50-year collapse risk computed using the 2014 and 2018 NSHM were on average equal to 0.8% and 2.1%, respectively. This difference in collapse risk between the NSHM versions indicates that the inclusion of basin effects is critical and results in large increases in collapse risk.

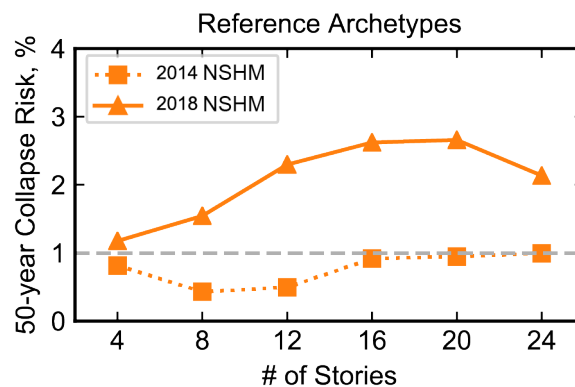


Figure 3. 50-year collapse risk with respect to archetype number of stories using the 2014 and 2018 National Seismic Hazard Models.

### Design Strategies to Reduce Collapse Risk

Engineers could adopt a variety of design strategies to account for the increase in hazard represented from the 2014 to 2018 NSHM, and reduce the 50-year collapse risk to less than 1%.



### **Design Strategy #1. Increasing Design Lateral Forces**

One strategy for reducing collapse risk is to increase the seismic design lateral force of the structure (i.e., structure's strength). Figure 4a shows the 50-year collapse risk for the reference archetypes redesigned using a 25% increase in ASCE 7-16 design loads and a 50% increase in design loads. Increasing the design loads by 25% resulted in a reduction in the average 50-year collapse risk from 2.1% (reference archetypes) to 0.90%. A 50% increase in design loads further reduced the mean collapse risk to 0.77%. This result is consistent with the increase in spectral acceleration values observed in the uniform hazard spectrum (UHS) derived from the 2018 NSHM (Figure 2), which was on average equal to 50% for the period ranges of the buildings.

### **Design Strategy #2. Decreasing Allowable Drift**

Increasing the stiffness of the walls is another strategy to reduce the likelihood of collapse. This increase is achievable by designing archetypes to meet a lower drift limit while maintaining similar design lateral forces to the reference archetypes. Figure 4b shows the collapse risks for reference archetypes (originally designed to meet a 2% limit) that were redesigned to meet a lower drift limit of 1.5% or 1.25%. As expected, reducing the drift limit reduced the average 50-year collapse risk from 2.1% (reference) to 1.27% and 0.90% for the 1.5% and 1.25% drift limit designs, respectively.

### **Design Strategy #3. Increasing Drift Capacity of Gravity System**

To reduce the collapse risk associated with slab-column failures, engineers could increase the rotational drift capacity of the slab-column connection. Zhou and Hueste [14] summarized various slab-column experiments and found that the drift capacity can be increased by: (1) increasing the shear-stress capacity (2) increasing the length of the shear-stud rails, (3) increasing the concentration of top flexural reinforcement, and/or (4) increasing the nominal concrete compressive strength. Figure 4c recomputes the 50-year collapse risk for a series of assumptions for the slab-column connection drift capacity. As expected, increasing the drift capacity reduced the collapse risk for all archetypes. For example, increasing the drift capacity from 5.9% (reference archetype) to 9% (solid line in Figure c) decreased the 50-year collapse risk from and average (for all archetypes) of 2.1% to 1.0%.

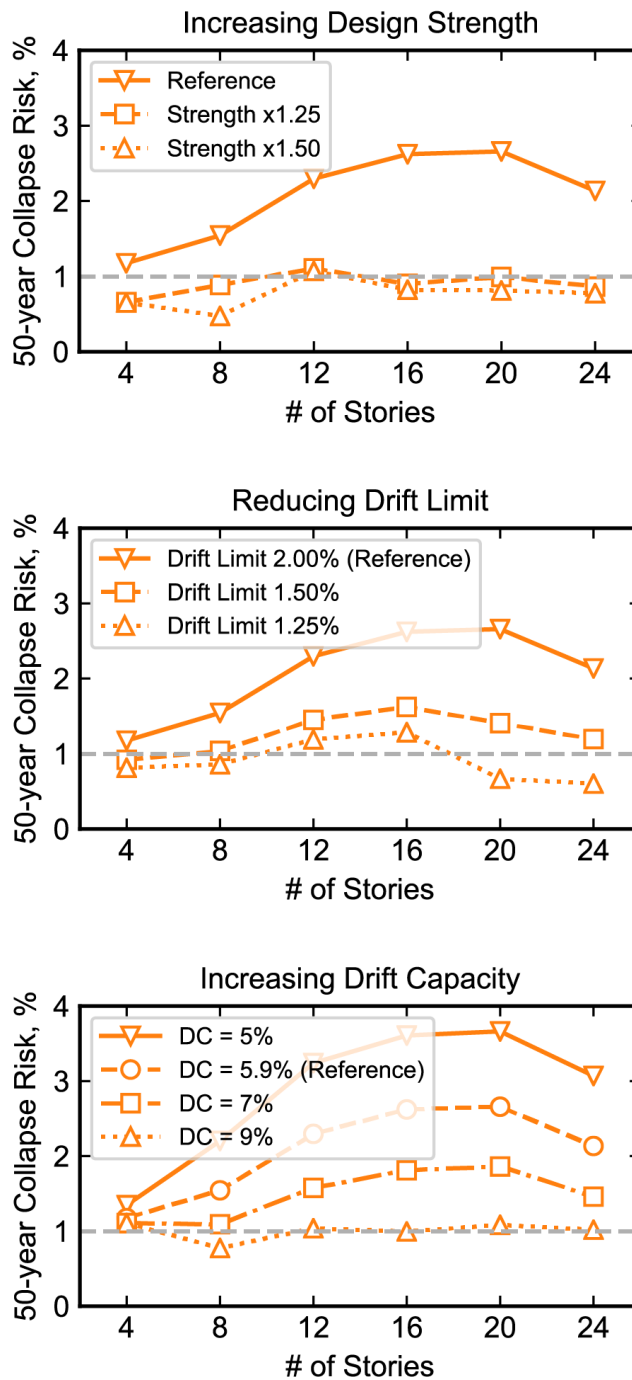


Figure 3. 50-year collapse risk with respect to archetype number of stories using the 2018 National Seismic Hazard Model for (a) various levels of archetype design lateral forces, (b) various levels of archetype design drift limits, and (c) various levels of gravity system drift capacity.



## Conclusions

The inclusion of basin effects in the 2018 National Seismic Hazard Model (NSHM) resulted in an increase in long-period spectral accelerations for sites located on deep basins. For Seattle, this increase in spectral acceleration was particularly significant, around 50% greater than the 2014 NSHM version for periods between 0.5 s to 1.5 s. The results of a series of multiple stripe analyses showed that the 50-year collapse risk for archetypes designed to ASCE 7-16 increased from 0.8% to 2.1% on average when basin effects were considered in the 2018 NSHM. To mitigate collapse risk due basin effects, it was shown that engineers could: (a) increase the ASCE 7-16 design lateral forces by 25%, (b) reduce the design drift limit from 2.0% to 1.25%, or (c) increase the gravity system slab-column connection rotational capacity to 9%.

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## References

- [1] Choi, Y., Stewart, J. P., and Graves, R. W. (2005). "Empirical Model for Basin Effects Accounts for Basin Depth and Source Location." *Bulletin of the Seismological Society of America*, 95(4), 1412–1427.
- [2] Marafi, N. A., Eberhard, M. O., Berman, J. W., Wirth, E. A., and Frankel, A. D. (2017). "Effects of Deep Basins on Structural Collapse during Large Subduction Earthquakes." *Earthquake Spectra*, 33(3), 963–997.
- [3] Heaton, T. J., Yang, J., and Hall, J. (2006). "Simulated performance of steel moment-resisting frame buildings in the 2003 Tokachi-Oki earthquake." *Bull. Earthq. Res. Inst., Univ. Tokyo*, 81, 325–329.
- [4] Bijelić, N. (2018). "Utilization of physics-based simulated earthquake ground motions for performance assessment of tall buildings." Stanford University.
- [5] Marafi, N. A., Makdisi, A. J., Eberhard, M. O., & Berman, J. W. (2020). Impacts of an M9 Cascadia Subduction Zone Earthquake and Seattle Basin on Performance of RC Core Wall Buildings. *Journal of Structural Engineering*, 146(2), 04019201. [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0002490](https://doi.org/10.1061/(ASCE)ST.1943-541X.0002490)
- [6] Petersen, M. D., Shumway, A. M., Powers, P. M., Mueller, C. S., Moschetti, M. P., Frankel, A. D., Rezaeian, S., McNamara, D. E., Luco, N., Boyd, O. S., Rukstales, K. S., Jaiswal, K. S., Thompson, E. M., Hoover, S. M., Clayton, B. S., Field, E. H., & Zeng, Y. (2019). The 2018 update of the US National Seismic Hazard Model: Overview of model and implications. *Earthquake Spectra*, 875529301987819. <https://doi.org/10.1177/8755293019878199>



- [7] Gregor, N., Abrahamson, N. A., Atkinson, G. M., Boore, D. M., Bozorgnia, Y., Campbell, K. W., Chiou, B. S.-J., Idriss, I. M., Kamai, R., Seyhan, E., Silva, W., Stewart, J. P., and Youngs, R. (2014). "Comparison of NGA-West2 GMPEs." *Earthquake Spectra*, 30(3), 1179–1197.
- [8] Petersen, M. D., Moschetti, M. P., Powers, P. M., Mueller, C. S., Haller, K. M., Frankel, A. D., Zeng, Y., Rezaeian, S., Harmsen, S. C., Boyd, O. S., Field, N., Chen, R., Rukstales, K. S., Luco, N., Wheeler, R. L., Williams, R. A., and Olsen, A. H. (2014). Documentation for the 2014 Update of the United States National Seismic Hazard Maps.
- [9] McKenna, F. (2016). "OpenSees." Pacific Earthquake Engineering Research Center, <<http://opensees.berkeley.edu/>> (Apr. 24, 2018).
- [10] Rathje, E. M., Dawson, C., Padgett, J. E., Pinelli, J.-P., Stanzione, D., Adair, A., Arduino, P., Brandenberg, S. J., Cockerill, T., Dey, C., Esteva, M., Haan, F. L., Hanlon, M., Kareem, A., Lowes, L., Mock, S., and Mosqueda, G. (2017). "DesignSafe: New Cyberinfrastructure for Natural Hazards Engineering." *Natural Hazards Review*, 18(3), 06017001.
- [11] Kunnath, S. K., Heo, Y., and Mohle, J. F. (2009). "Nonlinear Uniaxial Material Model for Reinforcing Steel Bars." *Journal of Structural Engineering*, 135(4), 335–343.
- [12] Jalayer, F., and Cornell, C. A. (2009). "Alternative non-linear demand estimation methods for probability-based seismic assessments." *Earthquake Engineering & Structural Dynamics*, 38(8), 951–972.
- [13] Haselton, C. B., Liel, A. B., Deierlein, G. G., Dean, B. S., and Chou, J. H. (2011). "Seismic Collapse Safety of Reinforced Concrete Buildings. I: Assessment of Ductile Moment Frames." *Journal of Structural Engineering*, 137(4), 481–491.
- [14] Zhou, Y., and Hueste, M. B. D. (2017). "Review of test data for interior slab-column connections with moment transfer." *American Concrete Institute Special Publication*, 315, 141–166.
- [15] ASCE. (2017). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE/SEI 7-16. Reston, VA: American Society of Civil Engineers.