Constraining Cascadia Subduction Zone Ground Motions via Paleoliquefaction Evidence: A Case Study from Kellogg Island, Washington, with Regional Implications

Ryan A. Rasanen, S.M.ASCE[1]; Clinton M. Wood, A.M.ASCE[2]; and Brett W. Maurer, A.M.ASCE[3]

[1]Graduate Research Assistant, Univ. of Washington, Seattle. Email: rrasanen@uw.edu
[2]Associate Professor, Univ. of Arkansas. Email: cmwood@uark.edu
[3]Assistant Professor, Univ. of Washington, Seattle. Email: bwmaurer@uw.edu

ABSTRACT

Physics-based ground motion simulations are a valuable tool for studying seismic sources with missing historical records, such as Cascadia Subduction Zone (CSZ) interface earthquakes. The last such event occurred in 1700 CE and is believed to be an M8-M9 rupture. The United States Geological Survey recently developed 30 physics-based simulations of a CSZ rupture to predict ground motions across the Pacific Northwest. Consideration of key modeling uncertainties across these simulations leads to estimates of ground motion intensity that vary by ~100% in some areas (e.g., Seattle). Paleoliquefaction, or soil liquefaction from past earthquakes, provides the best geologic evidence for constraining or “ground truthing” the intensity of past shaking, yet while paleoliquefaction has been documented throughout Cascadia, limited analyses have been performed to exploit this evidence. This study focuses on Kellogg Island, 2 mi south of Seattle, where liquefaction has been documented from several earthquakes, but not from the 1700 CE event. Therefore, using the CSZ simulations and in situ cone penetration test data, this study predicts the probability of surficial liquefaction manifestation at Kellogg Island during an M9 CSZ event. As part of this effort, velocity profiles are developed from multichannel analysis of surface waves, and non-linear site response analyses are used to propagate simulated motions to the surface. Results show a high probability of liquefaction near Kellogg Island for most simulations, whereas to date no evidence of 1700 CE liquefaction has been discovered at Kellogg Island, nor at any other location in the Puget Sound. The discrepancy between predictions and observations might indicate that the 1700 CE ground motions were less intense in Seattle than most predictions of M9 earthquakes indicate. Toward the goal of elucidating the expected impacts of future CSZ earthquakes, similar analyses are ongoing at additional sites across the region.

INTRODUCTION

Ground motion simulations are increasingly used to complement empirical ground motion models, particularly where seismic sources have long-return periods, as in the Cascadia Subduction Zone (CSZ). These simulations not only fill gaps in ground-motion datasets but also provide a better understanding and quantification of complex effects, such as those related to topography, basins, subsurface velocity structures, and directivity. By explicitly modeling fault rupture, wave propagation, and nonlinear behavior, these simulations can help to better predict ground-motion time histories. Given the premise of a full-fault M9 CSZ earthquake, physics-based seismograms (i.e., ground-motion time histories) were recently developed at the USGS (Frankel et al. 2018; Wirth et al. 2018) to predict motions across the Pacific Northwest. This suite of simulations includes 30 different realizations that reflect uncertainties in key modeling parameters, such as the down-dip limit of fault rupture, the slip distribution and location of asperities, the rupture direction, and the hypocenter location. Since the last CSZ interface earthquake occurred in 1700 CE, the actual motions are unknown, and thus, are quite uncertain. Figure 1 shows two such realizations in the vicinity of Kellogg Island, WA, which is located in the city of Seattle on the Duwamish River. Although both simulations portray an M9 CSZ earthquake, large differences exist (e.g., peak ground accelerations (*PGA*s) differ by ~100%). Correspondingly, the expected downstream consequences of these motions (e.g., structural damage, landslides, liquefaction, and so on) are likely also very different across the simulations. This uncertainty potentially makes it difficult to identify, plan for, and mitigate the expected impacts of an M9 CSZ rupture.

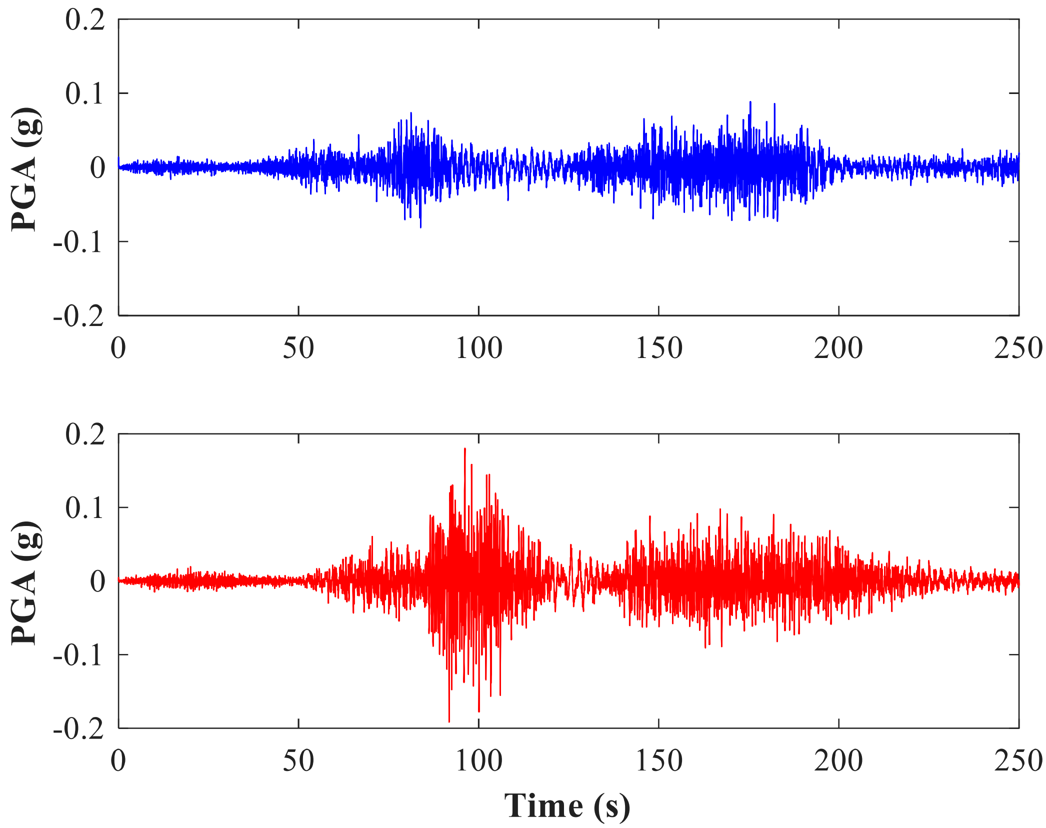

Figure 1. Two ground-motion simulations of an M9 CSZ earthquake in the vicinity of Kellogg Island, WA, reflect the influence of salient modeling uncertainties (e.g., PGA varies by ~100%). Simulations by Frankel et al. (2018) and Wirth et al. (2018).

Among these many impacts, soil liquefaction could conceivably be the most consequential, given its potential to damage roads, bridges, buildings, lifelines, ports, and rail lines, thereby also severely inhibiting post-event mobility and recovery. Liquefaction is also notable for its potential to "ground truth," or validate, ground-motion predictions. The motions experienced in 1700 or in any other prehistoric event can be determined only through analyses of paleoseismic evidence. But, among the many types of such evidence, including dendrochronology, turbidites, tsunami deposits, microfossils, geochemical markers, seafloor morphology, and liquefaction, the last of these is the only artifact that is both presently documented at numerous sites in the CSZ (e.g., Rasanen et al., 2021) and capable of "recording" ground motions (e.g., Rasanen and Maurer 2022). This latter distinction arises because well-validated, probabilistic, mechanics-based models are available to predict liquefaction as a function of seismic loading. In this way, the presence and absence of liquefaction can quantitatively constrain the ground-motion intensities experienced.

In this regard, Kellogg Island offers a unique window into both the pre-anthropogenic Duwamish River landscape (Feliks 2019) and the history of strong ground motions that have been experienced in Seattle. Despite fill placement in the late 1930s, paleoliquefaction is preserved on the island and has been documented during low tides. Davis (2018, 2019), for example, documented two distinct episodes of liquefaction, including sand dikes and/or sand volcanoes, at distributed sites on the island and on the east bank of the Duwamish River. Radiocarbon dating indicates these features were formed between 1000 CE and 1640 CE, making it highly unlikely they resulted from the 1700 CE Cascadia earthquake (Davis 2018, 2019). Although the minimum ages (i.e., latest dates of formation) have not been bound by dating for some features in the area, Davis (2018) concluded: "none of the dikes observed are likely to be as young as the 1700 Cascadia earthquake." This conclusion is consistent with the lack of 1700 CE evidence elsewhere in the Puget Lowland (e.g., Bourgeois and Johnson 2001). Despite investigations at multiple locations with recurrent liquefaction episodes dated to other earthquakes, no evidence of the 1700 CE Cascadia earthquake has been found in Seattle, or in the broader Puget Sound.

Accordingly, the objective of this study is to predict liquefaction surface manifestations in the vicinity of Kellogg Island for 30 physics-based realizations of an M9 CSZ rupture. This effort will utilize multi-channel-analysis of surface waves (MASW) to develop shear-wave velocity (Vs) profiles of the area, nonlinear site-response analyses to propagate simulated time-histories to the surface, and an ensemble of 18 cone-penetration-test (CPT) based models to predict liquefaction response. Comparisons between predicted and observed liquefaction will be made to assess which ground-motion simulations represent more and less plausible realizations of the motions experienced in 1700 CE, as evidenced by the lack of observed liquefaction near Kellogg Island.

DATA AND METHODOLOGY

Six CPTs from the east bank of the Duwamish River, proximal to features studied by Davis (2018, 2019) and others, will be analyzed. The locations of these CPTs, and of MASW tests to be discussed subsequently, are shown in Figure 2. Both Kellogg Island and the CPT locations consist of varying amounts of fill over marsh deposits (mud and peat), underlain by a thick layer of dark gray/black andesitic sand derived from Mount Rainier lahars (Cisternas 2000, Pringle et al. 1997, Scott et al. 1995). Borings from Zehfuss (2003), in addition to borings from five separate geotechnical field investigations (e.g., Shannon & Wilson 1997), corroborate the presence of gray/black andesitic sand extending to at least ~20 m depth at the locations of the CPTs. Davis (2018) attributes this thick lahar derived sand layer as that which liquefied during past earthquakes. In general, the soil profile at the CPT location consists of 0.8-1.6 m of fill, 1 m of marsh deposits, and andesitic sand extending to ~20 m depth where the borings terminate. Although the fill is not extensive, its absence in 1700 CE will be accounted for and is discussed subsequently.

Figure 2. Site overview of MASW and CPT test locations in the vicinity of Kellogg Island, WA, located two miles south of downtown Seattle. Imagery from Google Earth.

Inherent to the Frankel et al. (2018a) and Wirth et al. (2018) simulations is the Stephenson et al. (2017) velocity model, which assumes a minimum surficial Vs of 600 m/s. That is, the simulations implicitly assume rock exists everywhere at the surface and do not consider the potential for soils to impart significant changes. Therefore, the simulated ground-motions were first modified for local conditions using site response analyses. Towards that end, MASW testing was conducted using both active and passive methods to develop a Vs profile. To explore shallow depths, an active linear array of 23 geophones, spaced at 1-m intervals, measured Rayleigh waves generated by a 5.5 kg hammer strike. To enhance data quality, six source offsets were employed. Additionally, a 100-m diameter circular array consisting of eight geophones on the circumference, along with one central geophone and seismometer, was deployed to record ambient noise. Figure 3 shows the resulting median Vs profile, confidence bounds, and reference Vs profiles for comparison. Adopting the median profile, nonlinear time-domain site response analyses were performed using *Seismosoil* (Asimaki and Shi 2017), which employs the finite-difference method. This approach includes: (i) stress-strain and damping behaviors described by the hybrid hyperbolic model (Shi and Asimaki 2017), which has shown improved performance over the popular MKZ model; and (ii) hysteresis behavior governed by the model of Li and Assimaki (2010), rather than by Masing rules. Additional details and discussion are provided by Shi and Asimaki (2017).

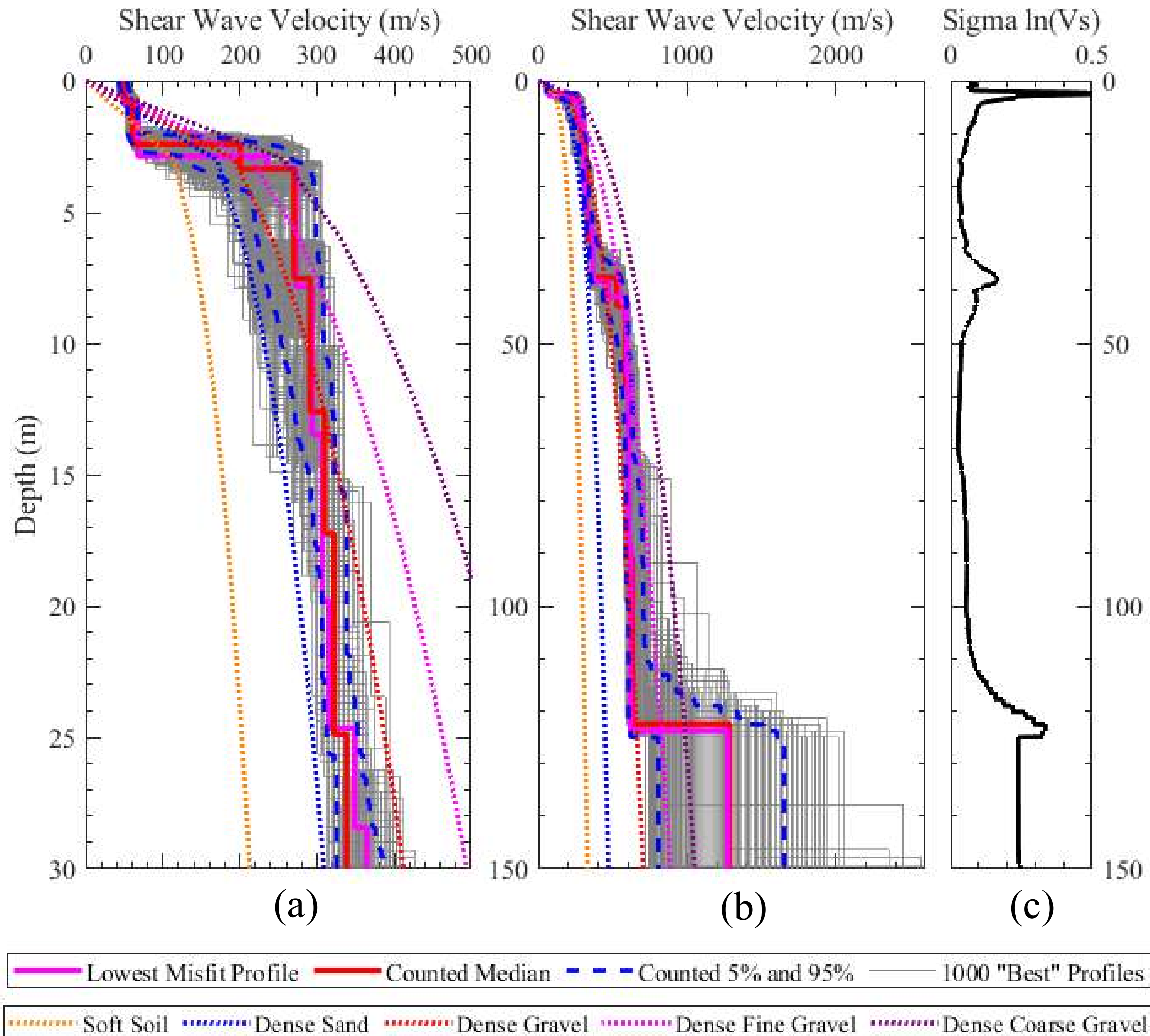

Figure 3. V_S profiles generated from MASW. A median profile computed from the 1000 lowest misfit V_S profiles from a pool of 2 million are shown for (a) 30 m depth and (b) 150 m depth. Reference V_S curves from Lin et al. (2014) are shown for comparison. Standard deviations of the natural logarithm of Vs (σlnVs) are shown in (c).

An ensemble of 18 CPT-based liquefaction models were used to predict liquefaction response at CPT sites. Specifically, the liquefaction triggering models of Robertson and Wride (1998), Architectural Institute of Japan (2001), Moss et al. (2006), Idriss and Boulanger (2008), Boulanger and Idriss (2014), and Green et al. (2019) were each separately used in series with the liquefaction manifestation models of Iwasaki et al. (1978), van Ballegooy et al. (2014), and Maurer et al. (2015). Using global case-history data, Geyin and Maurer (2020) conditioned fragility functions on each of these 18 models, thereby permitting probabilistic predictions of liquefaction surface manifestation to be made. These models have been shown in global analyses to have typical prediction efficiencies of ~75-85% (Geyin et al. 2020). Studying case-history data from the 2001 Nisqually, WA, earthquake, for example, this ensemble of models was ~90% efficient (Rasanen et al. 2023). Before applying the triggering models, liquefaction susceptibility was inferred from the CPT soil behavior type index (I_c) per Robertson and Wride (1998). However, due to uncertainties in the relationship between I_c and susceptibility, the I_c-susceptibility model developed by Maurer et al. (2019) was used to probabilistically predict susceptibility from the measured I_c. Incorporating this uncertainty, the probability of manifestation is computed as:

$$P(\text{Manifestation}) = \int_{I_c} P(\text{Manifestation}|PGA, I_c)\, f(I_c) \cdot \mathrm{d}I_c$$

Where $f(I_c)$ is the probability density function of the I_c threshold used to discriminate susceptibility and $P(\text{Manifestation}|PGA, I_c)$ is the probability of surface manifestation conditioned on PGA and the threshold I_c, as computed using the fragility functions of Geyin and Maurer (2020), which were separately trained for each of the 18 models adopted herein.

To account for the lack of artificial fill in 1700 CE, the in-situ CPT profile and groundwater table (GWT) at the time of testing were used to stress-normalize CPT measurements, whereas the trimmed profile with ~ 1 m of fill removed was used to infer saturation and compute the cyclic stress ratio at the time of shaking. In this regard, the 1700 CE GWT was assumed to be at the same elevation as present day (i.e., it was ~ 1 m closer to the ground surface in 1700 CE). While this introduces uncertainty, our results are ultimately insensitive to this assumption and would only change if the GWT was considerably deeper in 1700 CE than at present, which is highly unlikely.

RESULTS AND DISCUSSION

Probabilities of liquefaction manifestation were computed for 30 CSZ M9 realizations using 18 CPT-based liquefaction models. Figure 4 shows the probabilities of surface manifestation computed at each site. Specifically, the 2.5th, 50th, and 97.5th probability percentiles are provided to show the range of expected response across the 30 ground-motion simulations, which vary in amplitude (e.g., as shown in Figure 1). It can be seen in Figure 4 that manifestation probabilities are relatively consistent between CPTs and also relatively high, even for the weakest of expected motions. The 2.5th percentile manifestation probabilities, for example, are 68%-78%. This attests to the low liquefaction resistance of the profile, which is consistent with the observation of liquefaction in several earthquakes, but inconsistent with the lack of 1700 CE evidence. This discrepancy might indicate that either: (i) the strength of ground shaking was considerably less than predicted by CSZ M9 simulations, possibly suggesting that the 1700 CE event was a smaller magnitude, partial fault rupture; (ii) limitations in the methods used to predict site response, liquefaction triggering, and/or liquefaction manifestation result in the overprediction of liquefaction-induced ground failure; or (iii) liquefaction was indeed induced in 1700 CE, but has yet to be found in the area despite extensive searches (e.g., Davis 2018). With respect to the latter, it is worth reiterating that no liquefaction tied to the 1700 CE CSZ rupture has been discovered in the Puget Sound despite an abundance of liquefaction-susceptible soils and the discovery of liquefaction evidence from numerous other events both older and younger than 1700 CE (e.g., Sherrod (2001), Martin and Bourgeois (2012), Rasanen et al. 2021). It should be noted that if CPTs were not "trimmed" to remove ~1 m of fill, the predicted manifestation probabilities would decrease by 4.5% on average, considering all CPTs and simulations. Similarly, the median probability of liquefaction manifestation remains well above 50% for a wide range of GWT depths. Lastly, any accounting for the fact that CPT tip resistances might have been lower in 1700 CE would only result in the computed probabilities being higher. Any reasonable handling of uncertainties in the 1700 CE soil profile result in high probabilities of liquefaction manifestation, which is at odds with the lack of observed field evidence.

Figure 4. Probabilities of liquefaction surface manifestation expected in 30 different ground motion simulations; the 2.5th, 50th, and 97.5th percentiles of the probability of manifestation, considering all 30 simulations, are mapped at each CPT site.

The high predicted probabilities of liquefaction at locations devoid of 1700 CE evidence may indicate that 1700 CE ground motions were less intense in Seattle than forecasts indicate. While further research is needed, this could have important implications for our understanding of the 1700 CE rupture, and possibly of CSZ seismic hazards more broadly. Shown in Figure 5 are PGAs at sites of interest throughout the CSZ, as predicted by one simulation (csz-005) that predicted amongst the lowest PGAs at Kellogg Island. It should be emphasized that these mapped PGAs assume a surficial Vs of 600 m/s and have not been adjusted for local site conditions that could significantly alter the predictions motions. This simulation predicts weaker shaking inland in the north (e.g., in Seattle, WA and Vancouver, BC) and stronger shaking inland in the south (e.g., Portland). Given the constraints provided by Kellogg Island, the PGAs mapped in Figure 5 could depict those experienced in CE 1700, albeit there is much uncertainty. In this regard, analogous analyses are ongoing at the sites of other paleoliquefaction investigations in the CSZ and will ultimately confirm or revise the conclusions reached in this study and summarized below.

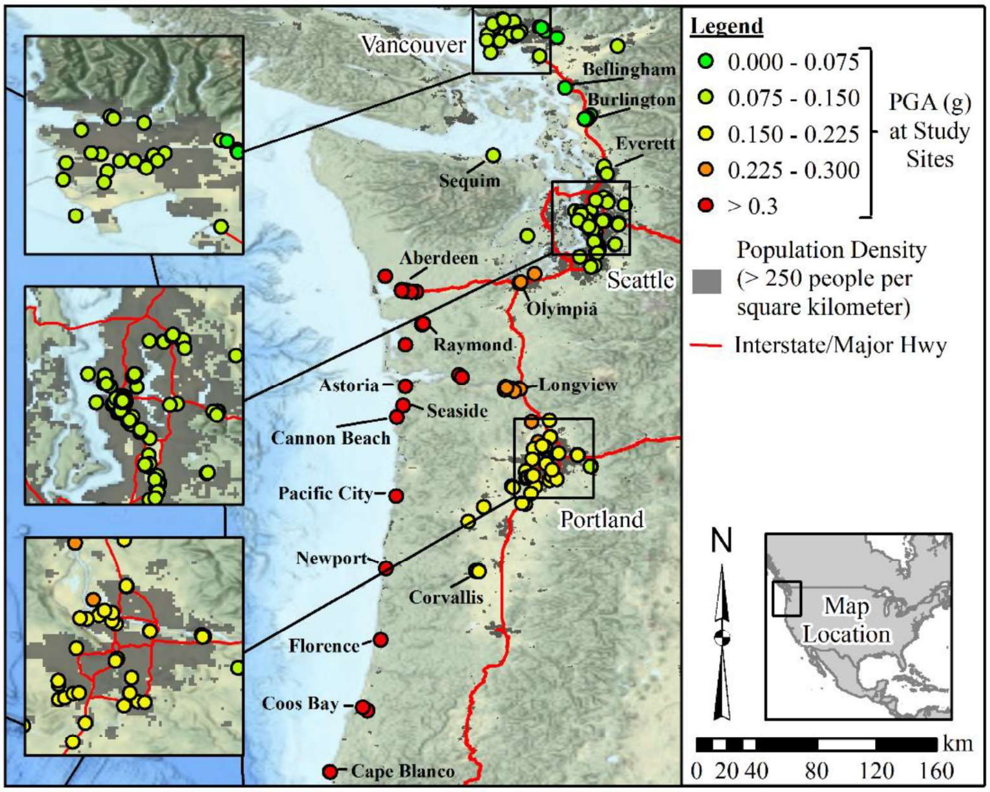

Figure 5. PGAs at select regional sites for ground-motion simulation csz-005.

CONCLUSION

This study predicted the probability of liquefaction manifestation at Kellogg Island in Seattle, WA, for 30 physics-based ground motion simulations of an M9 CSZ rupture. The median predicted probability of manifestation across all simulations ranged from 78%-85%. Even the simulation that produced the weakest motions led to probabilities well above 50%, given the very low liquefaction resistance at the study site. This is at odds with paleoliquefaction evidence, which has been found from multiple past earthquakes at Kellogg Island, but not the 1700 CE CSZ rupture. This discrepancy may indicate the strength of ground shaking in Seattle was less than that predicted by physics-based simulations, albeit there are other feasible explanations that must be investigated in conjunction with additional, analogous analyses at other paleoliquefaction research sites in the CSZ. In this regard, a regional analysis of CSZ paleoliquefaction evidence is ongoing. As more sites are studied, better constraint of regional ground-motion intensities in 1700 CE will result.

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