SHANNON & WILSON

March 22, 2024

Mr. Steve Drahota
HDR
1050 SW Sixth Avenue, Suite 1700
Portland, OR 97204

RE: BEST-ESTIMATE PROBABILITY OF CASCADIA SUBDUCTION ZONE INTERFACE EVENTS FOR THE EARTHQUAKE READY BURNSIDE BRIDGE PROJECT

Dear Mr. Drahota:

This letter report summarizes our study, analysis, and best-estimate probability of Cascadia Subduction Zone (CSZ) interface earthquakes over the next approximately 120 years for the Earthquake Ready Burnside Bridge project life span. This analysis and best estimate are based on:

- The CSZ interface paleoseismic earthquake record, rupture model, and recurrence interval (RI) documented by Goldfinger and others (2012 and 2017), which is the basis for modeling the CSZ interface earthquake recurrence in the U.S. Geologic Survey Nation Seismic Hazard maps; and
- The Brownian Passage of Time (BPT) recurrence model (Matthews and others, 2002).

Below, we will briefly describe the palesoseismic earthquake record, rupture model, and RI, the BPT recurrence model, and discuss the best-estimate probabilities from the paleoseismic RI and BPT model.

PALEOSEISMIC EARTHQUAKE RECORD AND RECURRENCE INTERVALS

The CSZ interface paleoseismic earthquake record and corresponding rupture and RI models were developed by Goldfinger and others (2012) and updated in Goldfinger and others (2017) from mapping and dating turbidite deposits of the Washington, Oregon, and northern California coast. The Goldfinger and others (2017) rupture models are provided in Figure 1. Based on the 10,000-year Holocene turbidite record, Goldfinger and others (2017) determined that the CSZ has ruptured in a single event not only along its entire length (full rupture) but also in smaller fault segments (partial ruptures) for a total of 46 great earthquakes. They developed seven CSZ Holocene rupture models including both full and partial ruptures. These seven rupture areas with RIs are shown in Figure 1 and include:

- Twenty (20) full or nearly full-length ruptures (Model A)
- Three nearly full-length ruptures involving coastal Washington, Oregon, and northern California (Model B)
- Seven ruptures involving the southern three-quarters of the margin, between Astoria and northern California (Model C) and two ruptures along the southern Oregon and northern California margin (Model C′)
- At least nine smaller ruptures between the mouths of the Rogue River in southern Oregon and the Eel River in northern California (Model D)
- Four smaller ruptures in northern California, between the mouths of the Smith River and the Eel River (Model E)
- One rupture along the northern margin, between Astoria and southern Vancouver Island (Barkley) (Model F)

Table 1 summarizes the RIs from Goldfinger and others (2017) for each of the above models. Model Hybrid 1 and Model Hybrid 2, which are based on combined turbidite data from Goldfinger and others (2017) are also summarized in Table 1. Model Hybrid 1 is a combination of rupture models A, B, C, C′ and F where an earthquake generated by any of these models may have a significant impact on Burnside Bridge and is the basis for the best-estimate probability. Model Hybrid 1 does not include rupture model E based on the assumption that this smallest and most distant rupture from the project would not result in significant or strong ground shaking in the project area. Model Hybrid 2 is a combination of all rupture models (i.e., A, B, C, C′, D, E, and F) and included as a point of reference for the total seismic activity on CSZ interface regardless of rupture size and location.

We estimated moment magnitude (Mw) Mw=8.9, Mw≥8.4, and Mw≥7.7 for each of the Models A, Hybrid 1, and Hybrid 2, respectively, using three equally weighted magnitude-scaling relationships Murotani and others (2008), Strasser and others (2010), and Papazachos and others (2004).

RECURRENCE MODEL

The paleoseismic data by Goldfinger and others (2012 and 2017) show that rupture of the CSZ has some periodicity. That is the chance of an earthquake to occur is a function of the time elapsed since the last earthquake (i.e., time-dependent). The underlying premise of this periodicity is that a sufficient period of time is needed to build up stress on the source before it ruptures again and releases the accumulated stress in another event. We adopted Brownian Passage Time (BPT) (Matthews and others, 2002) which is a widely accepted renewal model and commonly used in practice. One key parameter in the BPT model, other than RI and the time since the last earthquake, is the coefficient of variation (CV). The CV, which is also known as aperiodicity, is a measure that includes the uncertainty in the RI estimate (for instance, the perfectly periodic sequence of earthquakes has a CV of zero).

The typical CV value used in a BPT model is between 0.4 and 0.6, but it is roughly invariant across sequences from different regions in the world with different characteristic time scales. We estimated the CV from the mean and standard deviation of the RIs for CSZ interface using the Goldfinger and others (2012) turbidite data. Similar data values are not available in Goldfinger and others (2017). Using Goldfinger and others (2012) turbidite data for rupture Models A and Hybrid 2 in Table 1, we estimated the following:

- Model A: RI mean = 529 years, RI standard deviation = 272 years, CV= 0.51
- Model Hybrid 2: RI mean = 243 years, RI standard deviation = 120 years, CV= 0.49

BEST-ESTIMATE EARTHQUAKE PROBABILITY

The best-estimate probability of large CSZ interface earthquakes over the next approximately 120 years that could result in significant ground shaking in the project area is shown in Figure 2. This probability shown in the figure is based on RI Model Hybrid 1 and the BPT renewal model for CV equal to 0.4, 0.5, and 0.6. We recommend the BPT renewal model as it appropriately incorporates the extensive paleoseismic recurrence data for the last +10,000 years. Furthermore, we recommend using the BPT with CV = 0.5 for the best estimate as it is consistent with the CSZ interface paleoseismic data in Goldfinger and others (2012 and 2017). The tabulated values for the probabilities shown in Figure 2 are provided in Table 2.

As points of reference and comparison, we replot in Figure 3 the best-estimate probability (RI Model Hybrid 1 and BPT renewal model with CV of 0.5) along with probability using RI Model Hybrid 2 (all ruptures regardless of whether or not it would likely induce strong ground shaking in the project area) and RI Model A (only full rupture of the CSZ) for BPT renewal model with CV of 0.5. As expected, the probability of any CSZ rupture regardless of whether or not it results in strong shaking at the site (RI Model Hybrid 2) is higher than the best-estimate probability. Also as expected, the probability of full rupture of the CSZ in a single event (RI Model A) is lower than the best-estimate based on premise that other events that do not rupture the entire CSZ can still cause strong ground shaking in the project area.

We also include in Figure 3 earthquake probability calculated using a time-independent Poisson recurrence model for reference and comparison. In a Poisson recurrence model, the chance of an earthquake occurring each year does not depend on how long it has been since the last earthquake. Because the CSZ has a robust paleoseismic record, we do not recommend this model but have included it as comparative data. Relying on a Poisson recurrence model for the CSZ earthquake probability calculations is inappropriate since this model does not have any "memory" of past earthquakes and does not account for known seismological processes that require stresses to develop, or buildup, on a fault prior to being released in a seismic event. However, we present this model in Figure 3 as a point of reference because this assumption is frequently used in probabilistic hazard analyses as a simplification for ground motion modeling sources with periodic recurrence intervals smaller than the ground motion return period of interest (e.g., acceptable simplification for estimating 1,000-year ground motions for a seismic source with a 500-year recurrence interval) or the paleoseismic records is sparse (i.e., few documented earthquakes). But where the return period range of interest is smaller than the recurrence interval and a large percentage of the earthquake recurrence interval has passed, the Poisson model underestimates the actual earthquake probability. This underestimation is indeed the case for this project. The Poisson-based probabilities in Figure 3 are lower than the BPT-base probabilities as the years since the last earthquake (323 years – see Table 1) exceeds or is a large percentage of the recurrence rates for the models (303 years, 217 years, and 500 years for models Hybrid 1, Hybrid 2 and A, respectively – see Table 1), and the return period range of interest is 120 years.

Our recommended use of the BPT renewal model over the Poisson recurrence model for the CSZ is consistent with and supported by the expert panel review of the U.S. Geological Survey National Seismic Hazard Model (NSHM). Specifically, the panel recommends that the "time-dependent extensions to ERF23 [Earthquake Rupture Forecast 2023] become an immediate priority for the NSHM research model" and that the future releases of the NSHM "properly incorporate CSZ time dependence" (Jordan and others, 2024).

CLOSURE

Within the limitations of scope, schedule, and budget, the analyses, conclusions, and recommendations presented in this letter report were prepared in accordance with generally accepted professional geologic and geotechnical engineering principles and practices in this area at the time this letter report was prepared. No field explorations, fault field studies, or lab tests were performed for this study. We make no other warranty, either expressed or implied. Additional information regarding the limitations and use of this letter report are provided in the document, "Important Information About Your Geotechnical/ Environmental Report," at the back of this letter report. The conclusions and recommendations are based on our understanding of the Earthquake Ready Burnside

Bridge project as described in this letter report. This letter report was prepared for exclusive use of HDR, the Bridge owner, and their consultants working on this project.

We appreciate the opportunity to work with you on this project. Please contact us at (206) 695-6908 if you have any questions or comments regarding this letter report.

Sincerely,

SHANNON & WILSON

Ali Shahbazian, PhD 3/22/2024
Associate

Bill Perkins 3/22/2024
Vice President

AAS:WJP/sss:myw

Enc. References
Table 1 – Summary of Goldfinger and Others (2017) Data Models Adopted for This Study
Table 2 — Probability of Earthquake on CSZ Interface – Rupture Model Hybrid 1 in Table 1
Figure 1 – CSZ Rupture Models Derived from Paleoseismic Evidence, Goldfinger and Others (2017)
Figure 2 – Best-Estimate Earthquake Probability, CSZ Interface Rupture Model Hybrid 1
Figure 3 – CSZ Interface Earthquake Probability Comparisons
Important Information About Your Geotechnical/Environmental Report

REFERENCES

Goldfinger, Chris; Galer, Steve; Beeson, Jeffrey; and others, 2017, The importance of site selection, sediment supply, and hydrodynamics: a case study of submarine paleoseismology on the northern Cascadia margin, Washington USA: Marine Geology, v. 384, p. 4-46.

Goldfinger, Chris; Nelson, C.H.; Morey, A.E., and others, 2012, Turbidite event history—methods and implications for Holocene paleoseismicity of the Cascadia subduction zone: U.S. Geological Survey Professional Paper 1661–F, 170 p.

Jordan, T. H.; N. Abrahamson; J. G. Anderson; G. Biasi; K. Campbell; T. Dawson; H. DeShon; M. Gerstenberger; N. Gregor; K. Kelson, and others, 2024, Panel review of the USGS 2023 conterminous U.S. time-independent earthquake rupture forecast, Bulletin of the Seismological Society of America, vol. 114, no.1, p. 572–607.

Matthews, M.V.; Ellsworth, W.L.; Reasenberg, P.A., 2002, A Brownian model for recurrent earthquakes, Bulletin of the Seismological Society of America, vol. 92, no. 6, p. 2233-2250.

Murotani, Satoko; Miyake, Hiroe; and Koketsu, Kazuki, 2008, Scaling of characterized slip models for plate – boundary earthquakes: Earth, Planets and Space, v. 60, no. 9, p. 987-991.

Papazachos, B. C.; Scordilis, E. M.; Panagiotopoulos, D. G.; and others, 2004, Global relations between seismic fault parameters and moment magnitude of earthquakes: Bulletin of the Geological Society of Greece, v. 36, no. 3, p. 1482-1489.

Strasser, F. O.; Arango, M. C.; and Bommer, J. J., 2010, Scaling of the source dimensions of interface and intraslab subduction-zone earthquakes with moment magnitude: Seismological Research Letters, v. 81, no. 6, p. 941-950.

Table 1: Summary of Goldfinger and Others (2017) Data Models Adopted for This Study

Rupture Model	Approximate Length (km)	RI (years)	Years Since Last Earthquake[a]
A	1027	500	323[b]
B	850	3,333	2,064
C	630	1,429	1,090
C'	430	5,000	4,462
D	240	1,111	572
E	95	2,500	527-820[c]
F	300	10,000	8,483-8,930[c]
Hybrid 1[d]	-	303	323[b]
Hybrid 2[d]	-	217	323[b]

NOTES:

a. The Years Since Last Earthquake are from statistical interpretation of Goldfinger and others (2012) and are based on the estimated mean turbidite age. Age of the turbidites in Goldfinger and others (2012) were modified in this study to reflect the years passed since collection of the turbidite samples (i.e., 2023).

b. The turbidite age estimated by Goldfinger and others (2012) for these models is 289. However, the last known earthquake for these models is 1,700 A.D (323 years ago). We modified the age of the youngest turbidite data provided in Goldfinger and others (2012) (in Model A) according to the last known earthquake in this table.

c. The statistical interpretation for Years Since Last Earthquake is not available for these Models. A range is provided from turbidites which such interpretation is provided in Goldfinger and others (2012).

d. The turbidite data from individual rupture models in Goldfinger and others (2017) (see Figure 1) were combined in these hybrid models to estimate RI and Years Since Last Earthquake. For Hybrid 1, we combined rupture Models A, B, C, C’, and F. For Hybrid 2, we combined all rupture models from Figure 1 (i.e., A, B, C, C’, D, E, and F)

A.D. = anno Domini; km = kilometers

Table 2: Probability of Earthquake on CSZ Interface – Rupture Model Hybrid 1 in Table 1

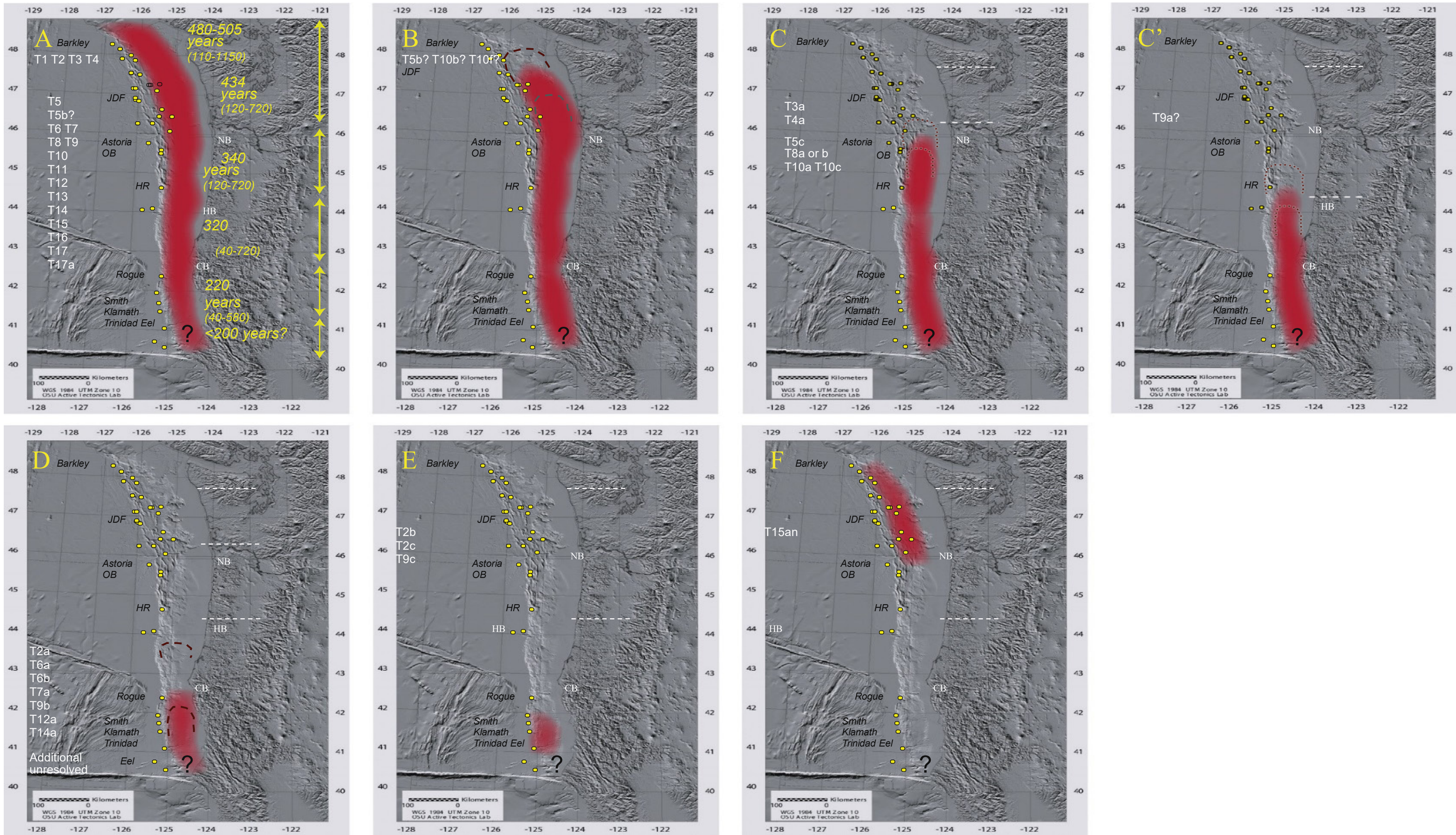
Time[1]	Renewal (CV=0.4) Model[2]	Renewal (CV=0.5) Model[2,3]	Renewal (CV=0.6) Model[2]
10	0.080	0.065	0.056
20	0.154	0.126	0.108
30	0.224	0.184	0.158
40	0.289	0.239	0.206
50	0.350	0.290	0.251
60	0.406	0.338	0.293
70	0.458	0.384	0.333
80	0.506	0.426	0.371
90	0.550	0.466	0.407
100	0.591	0.503	0.440
110	0.628	0.537	0.472
120	0.663	0.570	0.502

NOTES:

1 Number of years after 2023.

2 Renewal model here is Brownian Passage Time (BPT) model (Matthews and others, 2002).

3 The renewal model (CV=0.5) is our recommended recurrence model.



NOTES

1 Figure from Goldfinger and others (2017). Recurrence intervals in yellow. See the original paper for notation on this figure.

2 Seven rupture models for CSZ Interface inferred from turbidite stratigraphic correlation: Full or nearly full rupture (A), Mid-northern rupture from northern Washington southward (B), Mid rupture from northern or mid Oregon southward (C and C'), Southern Oregon/northern California rupture (D), Nothern California rupture (E), and Northern rupture from northern Oregon northward (F).

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CSZ RUPTURE MODELS DERIVED FROM PALEOSEISMIC EVIDENCE GOLDFINGER AND OTHERS (2017)

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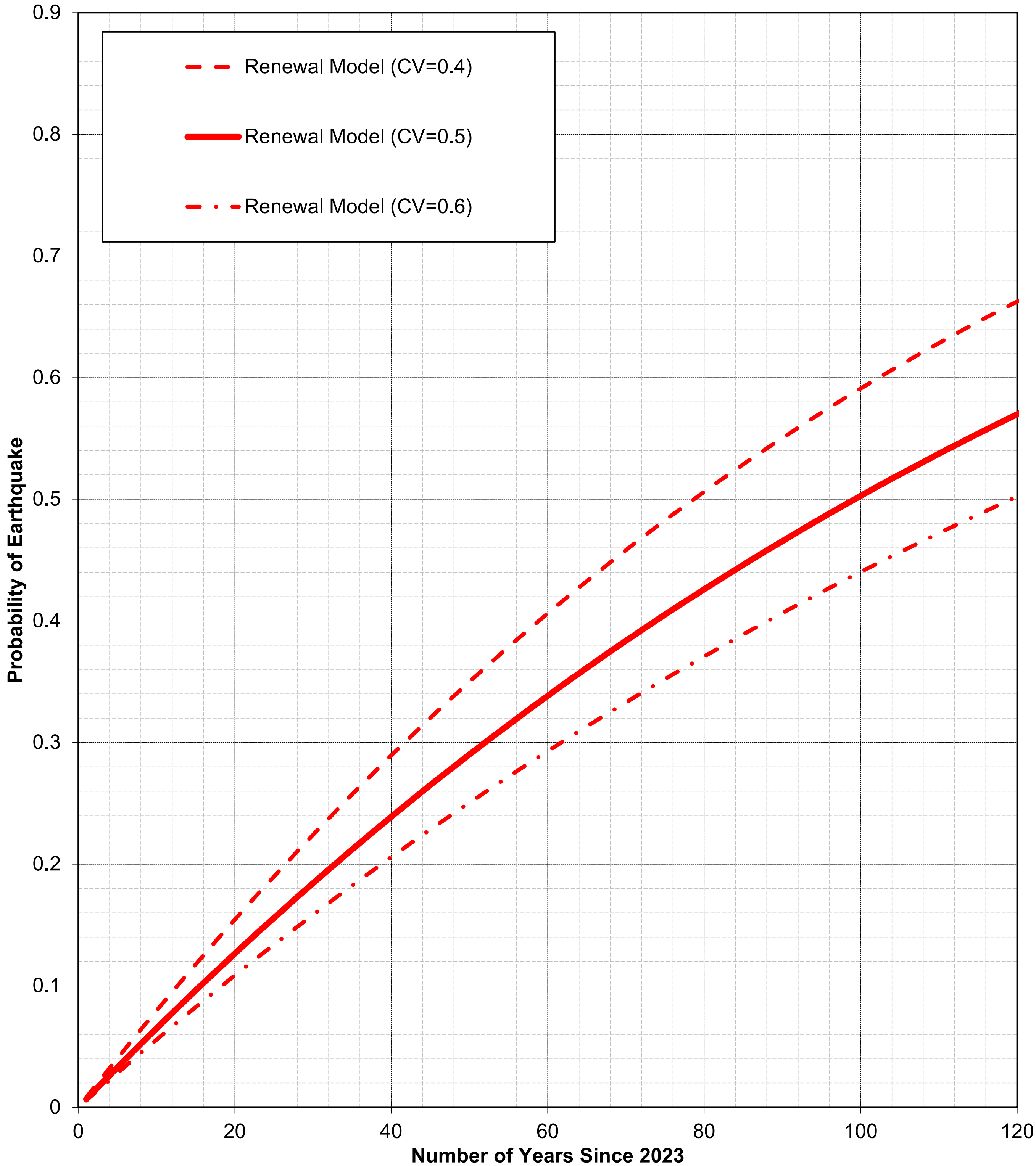
FIG. 1

FIG. 1



NOTES

1. Renewal model used here is Brownian Passage Time (BPT) (Matthews and others, 2002) which is a time-dependent model. Our recommended model is BPT with a CV value of 0.5.
2. The estimated magnitude for rupture Model Hybrid 2 in Table 1 is Mw≥~8.4.
3. CSZ = Cascadia subduction zone; CV = coefficient of variation (aperiodicity) in BTP model; Mw = moment magnitude

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BEST ESTIMATE EARTHQUAKE PROBABILITY, CSZ INTERFACE RUPTURE MODEL HYBRID 1

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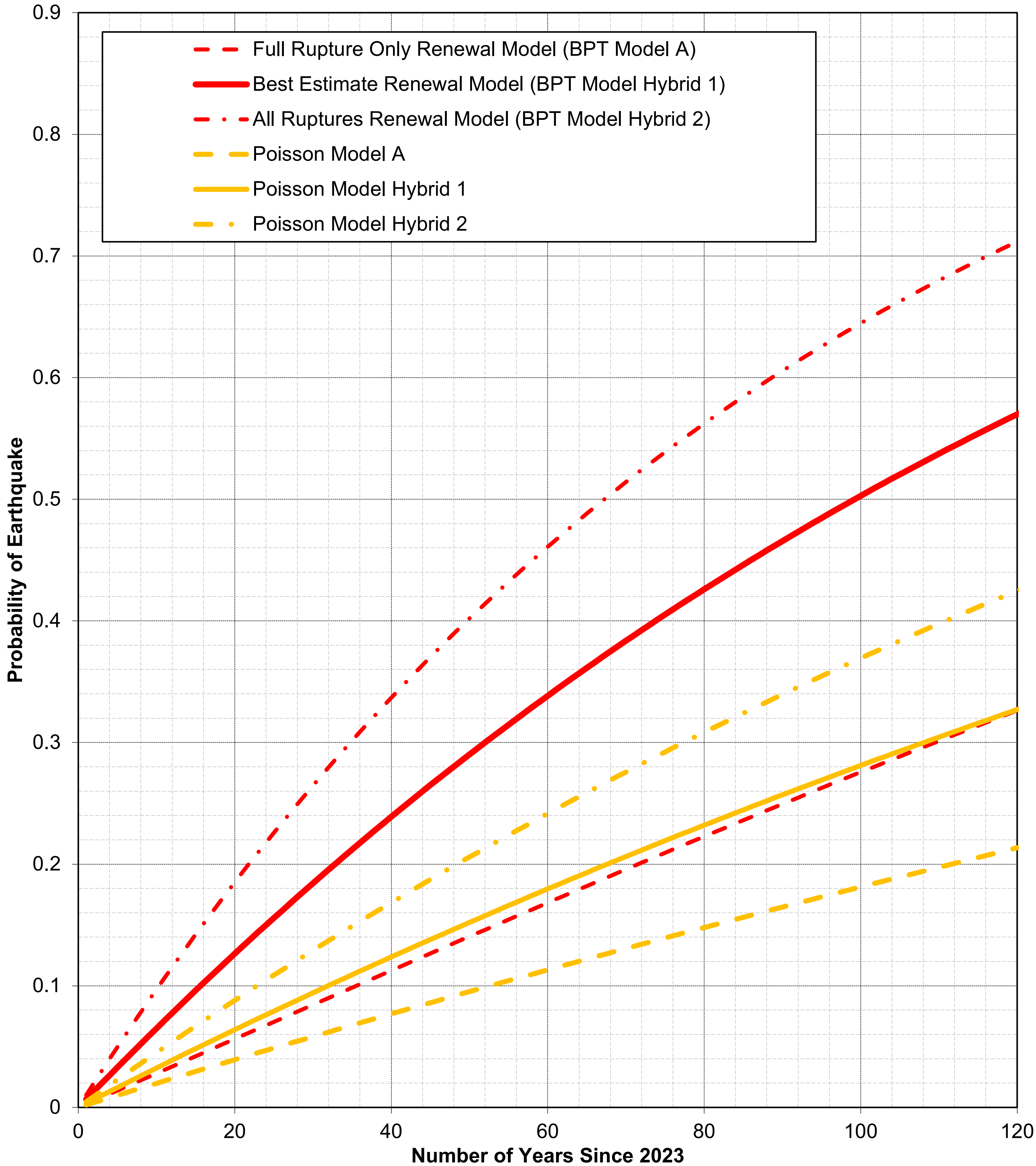
FIG. 2



NOTES

1. BPT = Brownian Passage Time; CSZ = Cascadia subduction zone

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CSZ INTERFACE EARTHQUAKE PROBABILITY COMPARISONS

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FIG. 3

IMPORTANT INFORMATION ABOUT YOUR GEOTECHNICAL/ENVIRONMENTAL REPORT

CONSULTING SERVICES ARE PERFORMED FOR SPECIFIC PURPOSES AND FOR SPECIFIC CLIENTS.

Consultants prepare reports to meet the specific needs of specific individuals. A report prepared for a civil engineer may not be adequate for a construction contractor or even another civil engineer. Unless indicated otherwise, your consultant prepared your report expressly for you and expressly for the purposes you indicated. No one other than you should apply this report for its intended purpose without first conferring with the consultant. No party should apply this report for any purpose other than that originally contemplated without first conferring with the consultant.

THE CONSULTANT'S REPORT IS BASED ON PROJECT-SPECIFIC FACTORS.

A geotechnical/environmental report is based on a subsurface exploration plan designed to consider a unique set of project-specific factors. Depending on the project, these may include the general nature of the structure and property involved; its size and configuration; its historical use and practice; the location of the structure on the site and its orientation; other improvements such as access roads, parking lots, and underground utilities; and the additional risk created by scope-of-service limitations imposed by the client. To help avoid costly problems, ask the consultant to evaluate how any factors that change subsequent to the date of the report may affect the recommendations. Unless your consultant indicates otherwise, your report should not be used (1) when the nature of the proposed project is changed (for example, if an office building will be erected instead of a parking garage, or if a refrigerated warehouse will be built instead of an unrefrigerated one, or chemicals are discovered on or near the site); (2) when the size, elevation, or configuration of the proposed project is altered; (3) when the location or orientation of the proposed project is modified; (4) when there is a change of ownership; or (5) for application to an adjacent site. Consultants cannot accept responsibility for problems that may occur if they are not consulted after factors that were considered in the development of the report have changed.

SUBSURFACE CONDITIONS CAN CHANGE.

Subsurface conditions may be affected as a result of natural processes or human activity. Because a geotechnical/environmental report is based on conditions that existed at the time of subsurface exploration, construction decisions should not be based on a report whose adequacy may have been affected by time. Ask the consultant to advise if additional tests are desirable before construction starts; for example, groundwater conditions commonly vary seasonally.

Construction operations at or adjacent to the site and natural events such as floods, earthquakes, or groundwater fluctuations may also affect subsurface conditions and, thus, the continuing adequacy of a geotechnical/environmental report. The consultant should be kept apprised of any such events and should be consulted to determine if additional tests are necessary.

MOST RECOMMENDATIONS ARE PROFESSIONAL JUDGMENTS.

Site exploration and testing identifies actual surface and subsurface conditions only at those points where samples are taken. The data were extrapolated by your consultant, who then applied judgment to render an opinion about overall subsurface conditions. The actual interface between materials may be far more gradual or abrupt than your report indicates. Actual conditions in areas not sampled may differ from those predicted in your report. While nothing can be done to prevent such situations, you and your consultant can work together to help reduce their impacts. Retaining your consultant to observe subsurface construction operations can be particularly beneficial in this respect.

A REPORT'S CONCLUSIONS ARE PRELIMINARY.

The conclusions contained in your consultant's report are preliminary, because they must be based on the assumption that conditions revealed through selective exploratory sampling are indicative of actual conditions throughout a site. Actual subsurface conditions can be discerned only during earthwork; therefore, you should retain your consultant to observe actual conditions and to provide conclusions. Only the consultant who prepared the report is fully familiar with the background information needed to determine whether or not the report's recommendations based on those conclusions are valid and whether or not the contractor is abiding by applicable recommendations. The consultant who developed your report cannot assume responsibility or liability for the adequacy of the report's recommendations if another party is retained to observe construction.

THE CONSULTANT'S REPORT IS SUBJECT TO MISINTERPRETATION.

Costly problems can occur when other design professionals develop their plans based on misinterpretation of a geotechnical/environmental report. To help avoid these problems, the consultant should be retained to work with other project design professionals to explain relevant geotechnical, geological, hydrogeological, and environmental findings, and to review the adequacy of their plans and specifications relative to these issues.

BORING LOGS AND/OR MONITORING WELL DATA SHOULD NOT BE SEPARATED FROM THE REPORT.

Final boring logs developed by the consultant are based upon interpretation of field logs (assembled by site personnel), field test results, and laboratory and/or office evaluation of field samples and data. Only final boring logs and data are customarily included in geotechnical/environmental reports. These final logs should not, under any circumstances, be redrawn for inclusion in architectural or other design drawings, because drafters may commit errors or omissions in the transfer process.

To reduce the likelihood of boring log or monitoring well misinterpretation, contractors should be given ready access to the complete geotechnical engineering/environmental report prepared or authorized for their use. If access is provided only to the report prepared for you, you should advise contractors of the report's limitations, assuming that a contractor was not one of the specific persons for whom the report was prepared, and that developing construction cost estimates was not one of the specific purposes for which it was prepared. While a contractor may gain important knowledge from a report prepared for another party, the contractor should discuss the report with your consultant and perform the additional or alternative work believed necessary to obtain the data specifically appropriate for construction cost estimating purposes. Some clients hold the mistaken impression that simply disclaiming responsibility for the accuracy of subsurface information always insulates them from attendant liability. Providing the best available information to contractors helps prevent costly construction problems and the adversarial attitudes that aggravate them to a disproportionate scale.

READ RESPONSIBILITY CLAUSES CLOSELY.

Because geotechnical/environmental engineering is based extensively on judgment and opinion, it is far less exact than other design disciplines. This situation has resulted in wholly unwarranted claims being lodged against consultants. To help prevent this problem, consultants have developed a number of clauses for use in their contracts, reports, and other documents. These responsibility clauses are not exculpatory clauses designed to transfer the consultant's liabilities to other parties; rather, they are definitive clauses that identify where the consultant's responsibilities begin and end. Their use helps all parties involved recognize their individual responsibilities and take appropriate action. Some of these definitive clauses are likely to appear in your report, and you are encouraged to read them closely. Your consultant will be pleased to give full and frank answers to your questions.

The preceding paragraphs are based on information provided by the Geoprofessional Business Association (https://www.geoprofessional.org)