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| Alaska-Aleutian tsunami source characterization      January 22, 2019 |

# Prepared for:

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# Introduction

The purpose of this project is to develop source models for tsunami modeling, in particular probabilistic tsunami hazard analysis, for the Alaska-Aleutian Subduction Zone (AASZ). This project was carried out in conjunction with the USGS Powell Center for Tsunami Sources. The final deliverable of this projects is a set of AASZ sources with distributed slip and a rate of occurrence that corresponds to the probabilistic model.

# Probabilistic framework

The purpose of a hazard analysis is to compute the probability of a certain kind of hazard (e.g. ground shaking, flooding) to reaching or exceeding a certain level. In the simplest case of a probabilistic analysis, the so-called direct method, this can be done by simply tallying observations of the particular hazard at the site. An example of this approach is a hazard curve that is directly obtained from historical observations of water levels (Figure 2‑1). In earthquake related studies, this approach is seldomly used, since it requires a long (relative to the recurrence times) and reliable record of observations, which is rarely achievable. In seismic hazard analyses, it is therefore common to use an earthquake approach, where we compute the ground motions from an earthquake catalog (synthetic or empirical) where every earthquake is defined by a magnitude, location and recurrence rate. For tsunami we follow a similar approach, and the purpose of this study is to provide a framework and earthquake scenario catalog that can be used for probabilistic tsunami hazard analysis.

Because of the highly non-linear character of tsunami inundation, and its high computational cost, we have developed a two-step approach to the tsunami hazard analysis at the site. In the first step, we compute a comprehensive probabilistic tsunami hazard analysis for an offshore location near the site, making use of the linear behavior of tsunami in deep water. This allows us to efficiently integrate over thousands of scenarios, which are needed to model the hazard from many different sources.

The methodology behind the seismic equivalent, Probabilistic Seismic Hazard Analysis (PSHA) is well known (e.g., McGuire, 2004), and here we will only briefly describe the adaptations that are made for PTHA. Whereas in PSHA we are usually interested in the exceedance of some ground motion measure such as peak ground acceleration (PGA) or spectral acceleration (SA), in PTHA a parameter of interest (not necessarily the only one) is the maximum tsunami amplitude that is expected to be exceeded at sites along the coast.

The earthquake recurrence models behind the two methods are the same (**Error! Reference source not found.**). The difference lies in the process that relates the occurrence of an earthquake with certain magnitude and location to the hazard at the site, such as the Ground Motion Prediction Equations (GMPE) in PSHA. In the empirically derived GMPE, this relationship is a simple function of magnitude and distance, with some corrections applied for source and site characteristics. Because of the aforementioned strong laterally varying nature of tsunami propagation, we have adopted a waveform excitation and propagation approach instead of trying to develop analogous tsunami prediction equations. In fact, current developments in PSHA include the replacement of the GMPEs with ensembles of numerically generated ground motions, which is analogous to the approach proposed here.

The excitation and propagation of tsunamis in deeper water can be modeled using the shallow water wave approximation, which is linear for amplitudes that are significantly smaller than the water depth. We can solve the equation of motion numerically using a finite-difference method, which has been validated to produce accurate tsunami heights for propagation through the oceans, although for very shallow water the amplitudes may become too large, and more sophisticated nonlinear methods are required to model the details of the run-up accurately. Nevertheless, the linear approach provides a very good first approximation of tsunami propagation, taking into account the effects of lateral variations in seafloor depth.

The procedure followed here is similar to the one used for the development of the Tsunami Design Maps that have been introduced in the American Society of Civil Engineer’s ASCE 7-16 standard “Minimum Design Loads for Buildings and Other Structures” (ASCE, 2017; Thio et al., 2017).

## Epistemic uncertainty and aleatory variability

An inherent element of a probabilistic analysis is the accounting for limits to our ability of predicting natural processes, either because of a lack of knowledge, referred t as epistemic uncertainty, or because of the random nature of these processes (aleatory variability).

### Epistemic uncertainty

Probabilistic tsunami hazard analysis, like its seismic counterpart, follows a dualistic approach to probability. Whereas some aspects are defined in the familiar terms of frequency of occurrence (such as intermediate earthquake recurrence, magnitude distribution), others are more based on judgment, which is a subjective approach (Vick, 2002). For instance, we may characterize the recurrence of intermediate earthquakes in terms of a Gutenberg-Richter distribution, constrained by a catalog of historical earthquakes. The assumption is that the occurrence of earthquakes is a stationary process, and that the catalog represents a homogenous sample of the long-term seismic behavior of a source. For large earthquakes however, the return times are often so long relative to our historic record, even when paleo-seismic data is included, that the recurrence properties of these events cannot be described with a stationary model based on a regression of observed earthquake occurrence. We therefore need to introduce the concept of judgment, where we use our current understanding of earthquake processes, including analyses of similar structures elsewhere, such as local geological conditions, fault geometry (**Error! Reference source not found.**), strain rates etc., to make assumptions on the recurrence and scaling (**Error! Reference source not found.**) of large earthquakes. This is a subjective or epistemic approach to probability, centered on the observer rather than the observations, and will inevitably be different from one practitioner to another. A rigorous PTHA model therefore includes the use of logic trees to express alternative understandings of the same process, e.g. large earthquake recurrence models, weighted by the subjective likelihood of that alternative model (“degree of belief”), where the weights of the alternatives sum to unity.

### Aleatory variability

All aspects of earthquake occurrence and effects contain a measure of natural randomness, even if certain average behavior and measures are clearly identified. This variability is usually expressed in terms of distribution functions around the mean and are included in a PTHA by sampling or integrating over this distribution function. More details on the aleatory variability are discussed in the sections on the various components that contribute to the PTHA.

# Source characterization

The source characterization for the tsunami models consists of a geometrical characterization of the source, recurrence models for earthquakes that define magnitudes and their recurrence rate, and a generation mechanism for slip distribution on the fault.

## Source geometry

The subduction zone source representations used in this study are based on the Slab2.0 model of Hayes (2018). We fit the depth contours for every subduction zone with a set of quasi-rectangular subfaults that are small enough to represent the slip variability of large tsunamigenic earthquakes (**Error! Reference source not found.**). The nominal dimension for these elementary subfaults is 30 km along strike by 10 km in the dip direction but varies according to the curvature of the fault. In order to capture the curvature of the subduction interface, these subfaults are further divided into small patches of 1x1 km. This fine subdivision is strictly meant to accommodate the geometrical complexity; for the actual analysis, the slip on every 30x10 km subfault is uniform.

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## Earthquake recurrence model

The earthquake recurrence model defines the magnitude of earthquake with their rate of occurrence. In seismic hazard practice the most common magnitude distributions that are used are the (truncated) Gutenberg-Richter (G-R) relation, the Maximum Magnitude (MM) model and the Characteristic Model (CM). Whcdereas the G-R model is most often used to describe the background seismicity, it is often assumed that the MM and CM models are more appropriate for large faults. In any case, it is important to define the upper limit for the magnitude that can occur on a fault and for this purpose we make use of earthquake scaling relations. For example, for any rupture configuration we can determine the area (*A – km2*), which through the published scaling relations (**Error! Reference source not found.**, Strasser et al., 2010):

gives us magnitude (*M*), and thus earthquake moment (*M0* – in Nm):

The average slip (*D*) is then obtained through:

where is the elastic shear modulus, we have used a typical crustal value of 30 GPa. In the first equation, the sigma term represents the aleatory variability as the standard deviation of the distribution around the mean. We approximate this distribution using a discrete set of alternative values (-2σ, -σ, median, +σ, +2σ) with weights derived from the normal distribution (.4, .24 and .06 for median, ±σ and ±2σ respectively.

Various authors have developed scaling relationship for subduction zone earthquakes, which vary significantly due to different assumptions and regression models used. In order to take these different views of the earthquake scaling relations into account, we have applied several logic tree branches that represent these different models. The equally weighted models we considered are from Strasser et al., 2010, Papazachos et al. (2004) and Murotani (2008, 2013) (**Table 3‑1**).

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| --- | --- | --- | --- | --- |
| Scaling relation | a | b | σ | Weight |
| Skarlatoudis et al. |  |  |  | 1/3 |
| Murotani |  |  |  | 1/3 |
| Goda |  |  |  | 1/3 |

**Table 3‑1 Scaling relations used to relate magnitude with rupture area.**

## Generation of slip models

While in earlier analyses (e.g. Thio et al., 2010), we have used uniform slip models to produce tsunami waves. At local distances however, the slip variability is an important factor and asperities with large amounts of slip can cause significantly higher tsunami waves, especially locally, as is illustrated by the recent Tohoku earthquake where the maximum slip exceeded the average slip by at least a factor of 2.

Murotani et al. (2008) studied the slip distributions of several subduction zone earthquakes and found a ratio of maximum slip over average slip of 2.2. To include this aleatory slip variability, we used variable slip rupture models with one third of the rupture as an asperity with twice the average slip and the other two-thirds of the rupture at half the average slip. In order to achieve uniform long-term slip, we computed a total of three scenarios for each event where the asperity occupies every part of the rupture once. This way, we avoid the risk that in some areas the hazard is over- or under-estimated due to incomplete or overlapping asperity coverage offshore.

## Segmentation

In 2019, a USGS Powell Center workshop on tsunami sources for Alaska was organized with the aim of developing an updated community source model for the Alaska/Aleutian subduction zone. Although this effort is still ongoing, we have included the early results from this workshop into our model as well, as a separate branch of the logic tree. This alternative has an updated multi-segment rupture model (**Error! Reference source not found.**) and also includes a branch where earthquake can occur along the entire subduction (“floating sources”) irrespective of any segmentation but primarily constrained by local slip rates. In practical terms, this last alternative extends the magnitude range to smaller vents compared to the original ASCE7-16 model. A partial logic tree of the different branches is shown in **Figure 3‑1**.

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| **Figure 3‑1. Partial logic tree showing the different branches for the segmentation of the Alaska/Aleutian subduction zone used in ASCE 7-16.**  The numbers at each branch are relative weights given to that branch. |

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| Chart, bar chart  Description automatically generated |
| Figure 3‑2 Record of large events along the Alaska-Aleutian subduction zone |

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Segmentation model** | | | **Year of Historical Events** | | | | | | | | |
| Nishenko  & Jacobs (1990) | Wesson  et al. (2007) | McCaffrey (1997) | 1849 | 1899 | 1917 | 1938 | 1946 | 1957 | 1964 | 1965 | **1986** |
| Yakataga | Yakataga | Alaska |  | + |  |  |  |  |  |  |  |
| Prince-William Sound | Prince-William Sound |  |  |  |  |  |  | + |  |  |
| Kodiak | Kodiak |  |  |  |  |  |  | + |  |  |
| Semidi | Semidi |  |  |  | + |  |  |  |  |  |
| Shumagin | Shumagin |  |  | - |  |  |  |  |  |  |
| Unimak | Western Aleutian | Eastern Aleutians |  |  |  |  | + |  |  |  |  |
| Fox Island |  |  |  |  | - |  |  |  |  |
| Andreanof |  |  |  |  |  |  |  |  | + |
| Delarof |  |  |  |  |  | + |  |  |  |
| Rat Island | Western Aleutians |  |  |  |  |  |  |  | + |  |
| Near Island |  |  |  |  |  |  |  | + |  |
| Komandorsky | Komandorsky | + |  |  |  |  |  |  |  |  |

**Table 3‑2 Segmentation models of the Alaska-Aleutian subduction zone and the extent of recent large earthquakes. + means the entire segment ruptures, - means partial rupture**

### Segmentation logic tree

The logic tree for fault segmentation was established during the 2019 Powell center workshop. The first branch point (Figure 3‑3) concerned the question whether ruptures are thought to follow the current segmentation model (including multi-segment ruptures) or whether ruptures follow a floating model where they can occur anywhere irrespective of segment boundaries. These two branches were thought to be roughly equal in probability. In this paper we follow the segmented rupture branch with the floating rupture branch to be defines at a later stage.

Within the segmented branch, the

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| Figure 3‑3 Basic branches of the AASZ logic tree produced by the Powell center workshop. The branches on the right are further expanded in the following figures. |

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| Figure 3‑4 Single Segment branch of the AASZ logic tree produced by the Powell center workshop. |

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| Figure 3‑5 Two Segment branch of the eastern AASZ logic tree produced by the Powell center workshop. |

## Event rates

Earthquake rates can be defined in several ways: directly from empirical observations (e.g. earthquake catalogs), or derived from physical models of the Earth. When using earthquake catalogs, it is common to fit the earthquake magnitude occurrences in time using an exponential function (decaying with increasing magnitude), such as the Gutenberg-Richter relations. For larger earthquakes it is common to assign earthquake recurrence times directly to the earthquake scenarios based on observed earthquake interval times. The historical record of earthquakes in Alaska is very short, although when paleo-seismic data is included it can stretch into thousands of years back. Unfortunately, the observations are still very sparse, and for pre-historic earthquakes, it is currently not possible to unambiguously distinguish between a sequence of earthquakes along the AASZ, or a single very large one. Independent estimates of the size of these events are often not available. Because of these problems, we are using simple physical models of earthquake recurrences based on plate models and geodetic observations instead.

### Plate model

The overall plate configuration of the AASZ is relative straightforward with the Pacific Plate under the North American Plate. But with the large extent and geometry of the AASZ, there are significant changes in the convergence along strike, with trench normal rates ranging from almost zero in the west to 70 mm/yr in the central and eastern AASZ. Additionally, in the west where the convergence is oblique, there is evidence for strain partitioning with one or more micro-plates along the chain bounded by the AASZ to the south and strike-slip faults to the north.

The plate rates along the AASZ are summarized in Table 3‑3.

### Geodetic observations and seismic coupling

Plate rates are only one element in the determination of the recurrence properties of the earthquake set. Often, a significant part of the slip rate on subduction zone interfaces is accommodated by aseismic slip, or creep. Such behavior reduces the effective slip rate by a factor called the seismic efficiency or coupling coefficient (the fraction of the slip that is accommodated in seismic events).

Table 3‑3 Sumary of tectonic parameters for the AASZ from geologic and geodetic data per segment.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Segment | Length (km) | Width (km) | Av. geologic recurrence  interval (yr) | Convergence rate (mm/yr) | | Slip deficit (%) | User efficiency | Coupling width (km) | Coupling area | Mmax | Av. slip/event | Return period | Data | Ref. |
|  |  |  |  | Pac-Arc | Pac-Arc GPS |  |  |  |  |  |  |  |  |  |
| Yakataga | 250 | 215 | 750 | 57 | 57 | 50 | 50 | 350 | 49392.76 | 8.57 | 5.80 | 203.61 | G, P, S, T | E20, Sh09a, Sh09b |
| PWS | 240 | 400 | 590 | 59 | 59 | 100 | 100 | 200–300 | 126018.95 | 9.10 | 13.79 | 233.80 | H, G, P | E20, Sh14a, SF09 |
| Kenai | 110 | 335 | 516 | 61 | 61 | 100 | 100 | 100 | 16956.34 | 7.98 | 2.16 | 35.40 | G, P | E20, K05, Sh18, SF09 |
| Kodiak | 425 | 270 | 295 | 63 | 63 | 100 | 100 | 175 | 77823.94 | 8.83 | 8.83 | 140.23 | H, G, P | B14, E20, Sh14a, SF09 |
| Semidi | 255 | 135 | 212 | 66 | 66 | 100 | 100 | 200 | 53714.32 | 8.62 | 6.27 | 95.01 | H, G, P | E20, N15 |
| Shumagin | 225 | 110 | >3400 | 68 | 68 | 20–40 | 30 | 100 | 24754.99 | 8.19 | 3.06 | 150.20 | H, G, P | E20, W14 |
| Sanak | 285 | 80 | 2000 | 69 | 70 | 2 | 2 | 65 | 21778.63 | 8.12 | 2.72 | 1972.33 | H, G, P | E20 |
| Fox | 435 | 75 | 210 | 71 | 72 | 46–100 | 73 | 75 | 42387.71 | 8.49 | 5.04 | 97.20 | H, G, P | E20, W16, W19 |
| Andreanof | 370 | 75 | nd | 70 | 75 | 100 | 100 | 30 | 27077.43 | 8.24 | 3.33 | 47.56 | H, G | C08, F08 |
| Adak | 325 | 75 | nd | 66 | 70 | 25 | 25 | 75 | 36950.16 | 8.41 | 4.44 | 268.92 | H, G, S | C08, F08 |
| Amchitka | 330 | 70 | nd | 59 | 68 | nd? | 50 | nd? | 28423.57 | 8.27 | 3.48 | 118.02 | H, G, S, T | C08, F08, G88 |
| Attu | 405 | 65 | nd | 51 | 65 | 62 | 62 | 85 | 36307.11 | 8.40 | 4.37 | 138.07 | H, G, S, T | C08, F08, G88 |
| Komandorsky | 560 | 80 | nd | 47 | 38 | 100 | 100 | 40 | 36395.16 | 8.40 | 4.38 | 93.10 | S, T | C08, G88 |

Average of maximum and minimum widths measured from trench to 40 km contour depicted in Slab 2 (Hayes et al., 2018). Width of the Yakataga fault section measured from trench to 20 km contour.

Data that defines fault section: G, geodesy; H, historical seismicity; P, paleoseismology; S, forearc structure; T, topography.

References: eB14, Briggs et al. (2014); C08, Cross and Freymueller (2008); E20, Elliott and Freymueller (2020); F08, Freymueller et al. (2008); G88, Geist et al. (1988); K15, Kelsey et al. (2015); N15, Nelson et al. (2015); N16, Nicolsky et al. (2016); Sh09a, Sh09b, Sh14a, Sh14b, Sh16, Sh18, Shennan et al. (2009a, 2009b, 2014a, 2014b, 2016, 2018); SF09, Suito and Freymueller (2009); W14, W16, W19, Witter et al. (2014, 2016, 2019).

## Slip distributions

Slip tends to be heterogeneously distributed for every earthquake, and the slip distribution displays both random variations as well as systematic patterns. Systemic patterns are due to underlying physical conditions such as rheology and elastic behaviour whereas random (aleatory) patterns are more unpredictable due to the randomness of earthquake processes. The aleatory variability in slip average out to the long-term (systematic) slip distributions. An example of the systematic variation is the variation of slip with depth due to depth-dependent elastic behaviour. Along strike there are several factors that can lead to systematic differences in fault slip:

* Variations in slip rate – along a the length of the AASZ, the effective slip rate varies considerable due to changes in plate rates and interface geometry as well as seismic coupling.
* Variations in coupling – geodetic data indicates that the coupling varies along strike, leading to a change in effective slip rates
* Variation in fault width – if the maximum slip follows a static stress drop model, then the differences in fault width will also results in differences in maximum slip along the subduction zone.

It should be noted that these along-strike variations can be accommodated by systematic slip patterns per scenario, but also by different earthquake statistics along strike. In our model these two effects are included implicitly by the way the slip distributions are computed and by the final weighting of the different scenarios. It may be useful to state these alternatives explicitly in the logic tree.

## Weighting of individual sources

The source characterization that we propose here is as follows;

For every subfault *i* we determine an effective slip rate *Ri*. this slip rate is mostly based on the geodetic coupling models of Freymuller et al (20.., 2020, etc.)

For all rupture extents we develop slip distributions based on a set of rules. These rules contain characteristics of observed rupture. They may be as simple (as in the current case) as dimensions of asperities and tapering of slip towards the edges of the rupture area, but in a more sophisticated manner can be statistical parameters that have been obtained from a regression of megathrust earthquake slip models (e.g. Murotani, Skarlatoudis et al.), applied to stochastic models (Pitarka and Graves., Leveque et al. ).

These various methods can lead to a large number of slip models (scenarios), even for a single segment. In order to calculate rates for every scenario, an inversion procedure (e.g. Andrews and Scherer, 2000) is used to make sure that the cumulative slip rates are consistent with the desired slip rates per subfault.

### Inversion procedure

For the inversion we use a non-negative least squares routine (Lawson and Hansen, 19..) in the following way:

Here, the *Si,j* represent the slip at subfault *i* (out of *ns* total subfaults) for scenario *j*. Since *ns* is the total number of subfaults that are capable of rupturing in this particular logic tree branch, and typically all subfaults of the AASZ, a lot of *Si,j* will be zero. *Ri* is the target slip rate for subfault *i*. The weights *Wj* define the actual slip rate for every scenario *j*, and are solved for using the inversion procedure.

Additional constraints such as paleoseismic recurrence rates and the workshop weights are added to the scheme as additional below the regular normal equations. In our current scheme, because of the limited degrees of freedom, the inversion results are close to the original input weights since they were already constrained per segment to conform to the overall slip rates. The addition of the multi-scenario events only changed the complexity slightly because of their low weights. However, as more complexities are added to the schema, duh sd stochastic sources or floating ruptures, the inversion will make a significant impact in the weighting of the individual scenarios.

# Rupture scenarios

The logic tree presented in this report resulted in 4932 unique rupture scenarios and associated event rates. Figure 4‑1 shows some examples of slip distribution patterns for single and multi-segment scenarios along the AASZ. These models are available on the GitHub site (see appendix A). These scenarios are characterized by a set of rectangular fault elements with their centroid location (lat/lon/depth), orientation (strike/dip/slip) length (horizontal) and width (downdip) and amount of slip (meters).

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| A picture containing text, archery, sport  Description automatically generated | Diagram  Description automatically generated | Diagram  Description automatically generated |
| Diagram  Description automatically generated | Diagram  Description automatically generated | Diagram  Description automatically generated |
| Diagram  Description automatically generated | Diagram  Description automatically generated | Diagram  Description automatically generated |
| Figure 4‑1 Examples of slip distributions for single-,double-, triple- and quadruple-segment ruptures (top to bottom row respectively) with the three different asperity locations (left to right columns). | | |

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| A picture containing graphical user interface  Description automatically generated | A picture containing graphical user interface  Description automatically generated |
| Figure 4‑2 Cumulative magnitude recurrence relations for the four eastern segments. | |

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| Figure 4‑3 Cumulative magnitude recurrence relations for the four central segments. | |

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| A picture containing line chart  Description automatically generated | A picture containing line chart  Description automatically generated |
| Figure 4‑4 Cumulative magnitude recurrence relations for the four western segments. | |

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| Figure 4‑5 Coupling coefficients for the final logic tree model. |

# Data and software dissemination

The rupture scenarios, event rates and associated software currently available through Github:

<https://github.com/hkthio/PHA>

Explanations of the file formats are included on that site.

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1. Source files

The rupture scenarios that were developed for this project (and future updates) are described

1. Complete logic trees

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| Diagram  Description automatically generated |
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