Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 785

EVALUATING THE SEISMIC HAZARD IN ANCHORAGE, ALASKA

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ABSTRACT

Anchorage is situated in one of the most seismically active regions in the U.S. The Alaskan subduction zone, which underlies the city, is the source of the 1964 moment magnitude (**M**) 9.2 Great Alaskan earthquake. Intraslab and crustal earthquakes could also generate future strong ground shaking in the city. A site-specific probabilistic seismic hazard analysis (PSHA) of the Port of Anchorage was performed to estimate future levels of ground motions. The Alaskan subduction zone, both the megathrust and Wadati-Benioff zone, crustal faults, and crustal background seismicity were included in the PSHA. Several Quaternary-active and potentially Quaternary-active structures within the Cook Inlet were included as seismic sources. The new Next Generation of Attenuation (NGA) relationships for crustal earthquakes and recent attenuation models for subduction zones were selected for use in the PSHA. Based on these input, we calculated site-specific probabilistic hazard for a firm rock site condition. The 2,475-year return period PGA at the Port is 0.58 g. The intraslab zone dominates the PGA hazard at all return periods. The intraslab zone and the 1964 segment control the long-period (> 1.0 sec) hazard. The Castle Mountain fault, the closest significant crustal fault to the site, is not a major contributor to the probabilistic hazard in Anchorage.

Introduction

Anchorage is situated in one of the most seismically active regions in the U.S. (Fig. 1). The Alaskan subduction zone, which underlies the Port, is the source of the 1964 moment magnitude (**M**) 9.2 Great Alaskan earthquake. Intraslab earthquakes within the subduction zone and crustal faults such as the Castle Mountain fault will generate future strong ground shaking in the city (Fig. 1). A site-specific probabilistic seismic hazard analysis (PSHA) has been performed for the Port of Anchorage and three levels of design ground motions have been

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developed. The three design earthquakes have corresponding exceedance probabilities of 50%, 10%, and 2% in 50 years or return periods of 72, 475, and 2475 years, respectively.

The primary objective of this study is to estimate the future levels of ground motions at the Port that will be exceeded at a specified probability. Available geologic and seismologic data including inputs used in the U.S. Geological Survey's (USGS) Alaska hazard maps (Wesson et al. 1999, 2007) have been used to evaluate and characterize potential seismic sources, the likelihood of earthquakes of various magnitudes occurring on those sources, and the likelihood of the earthquakes producing ground motions over a specified level. The PSHA approach used in this study is based on the model developed principally by Cornell (1968). The PSHA calculations were performed using the computer program HAZ38 developed by Norm Abrahamson. This program has been validated in the Pacific Earthquake Engineering Research (PEER) Center-sponsored "Validation of PSHA Computer Programs" Project (Thomas et al. 2009).

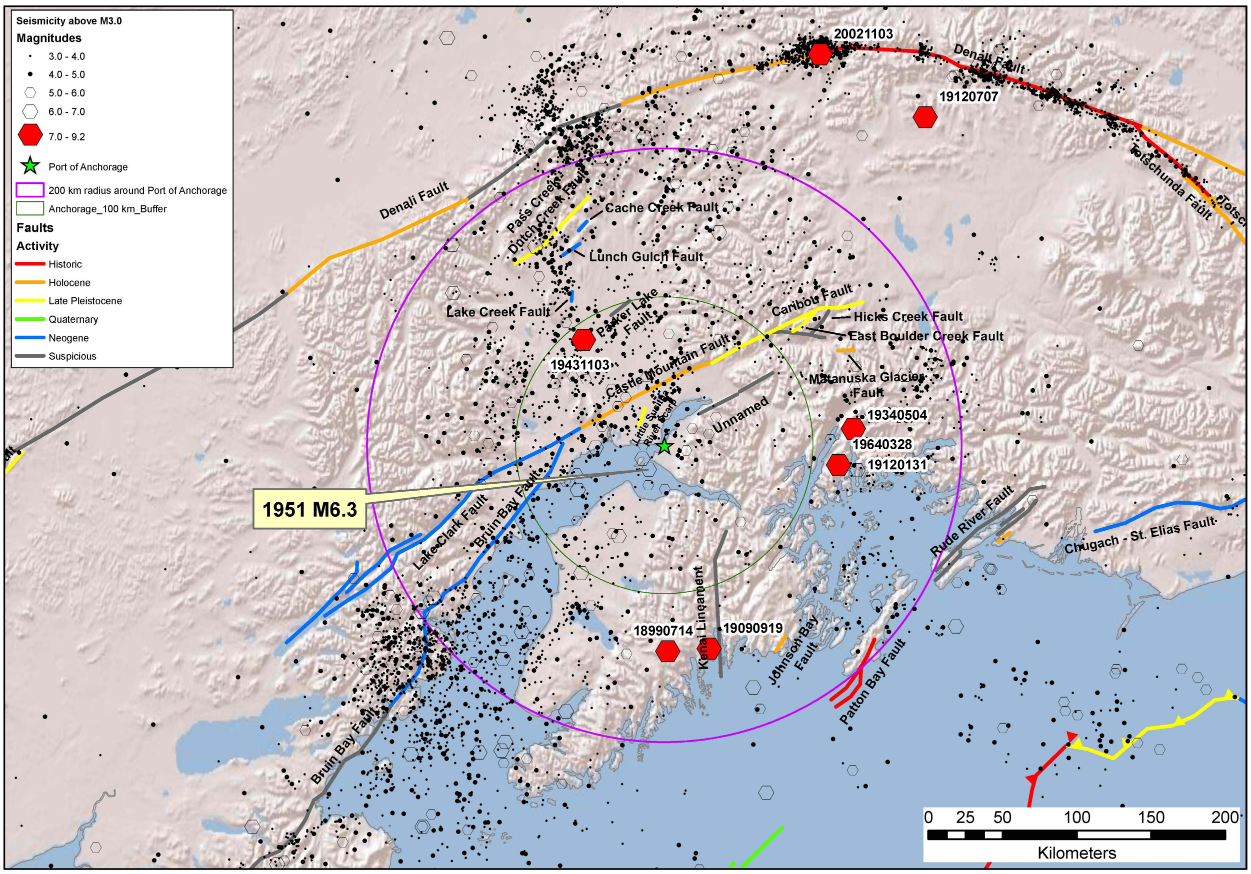


Figure 1. Historical seismicity and significant earthquakes (**M** ≥ 3.0), 1898 to 2007, within 200 km of Anchorage.

Seismotectonic Setting and Historical Seismicity

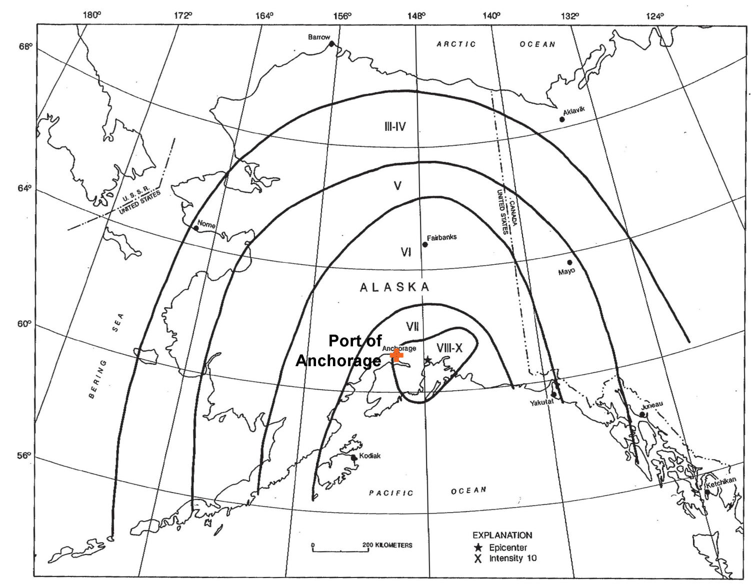
Anchorage is in one of the most seismically active parts of the U.S. (Fig. 1). Earthquakes in southern Alaska result primarily from interactions between the Pacific and North American plates. Northwestward motion of the Pacific plate relative to the North American plate is accommodated by subduction of the Pacific plate at the Aleutian megathrust and by dextral transform faulting in southeastern Alaska on the Queen Charlotte and Fairweather fault zones.

Earthquakes occur in several settings within the subduction zone: (1) bending-moment normal fault events in the Pacific plate near and seaward of the trench, (2) megathrust earthquakes that have a maximum depth of seismic coupling of about 35 to 40 km, (3) within the down-going slab (Wadati-Benioff zone) to depths of about 150 km in the Gulf of Alaska region, and (4) within the upper North American plate. Most damaging earthquakes in Alaska have occurred on the megathrust. Davies and House (1979) and Tichelaar and Ruff (1993) argue that low levels of seismicity in the megathrust zone to about 40 km depth suggest that these shallow zones are dominated by great earthquakes and their aftershocks, with little inter-event seismicity. Conversely, the Wadati-Benioff zone below about 40 km shows relatively continuous seismicity.

There have been more than 2,400 earthquakes above **M** 3.0 within 200 km of the Anchorage (Fig. 1). A total of 31 earthquakes have occurred within 200 km of the city above **M** 5.0. Three pre-instrumental earthquakes within 200 km of Anchorage have been larger than **M** 7.0: in 1899 (**M** 7.2), 1909 (**M** 7.4), and 1912 (**M** 7.0). There have been three events above **M** 7.0 recorded with modern instrumentation within 200 km (Fig. 1): in 1934 (**M** 7.1), 1943 (**M** 7.4), and the most recently, the 3 November 2002 **M** 7.9 Denali earthquake. The latter event ruptured 320 km of the central Denali fault and part of the Totschunda fault (Carver et al. 2004).

1964 Great Alaska Earthquake

The 1964 earthquake was one of the most violent earthquakes on record and the second or third largest earthquake ever recorded. The earthquake was centered near the northern margin of Prince William Sound, and was felt over 1.8 million km^2 in Alaska, and northwesternmost Canada (Fig. 2). Rupture initiated about 100 km east of Anchorage along the Prince William Sound asperity (e.g., Christensen and Beck 1994). The source mechanism for the 1964 earthquake is sinstral reverse slip with a displacement of about 20 m. The greatest amount of damage from the earthquake occurred in Anchorage, which recorded a Modified Mercalli intensity VIII (Fig. 2). Numerous landslides, rockslides, avalanches were triggered from the strong ground shaking. Observers in Anchorage documented shaking lasting between 4 to 5 minutes. There were 15 deaths attributed to the earthquake and



Source: Stover and Coffman (1993)

Figure 2. Isoseismal map of the 1964 **M** 9.2 Great Alaska earthquake.

another 113 following the tsunami. The most destruction was attributed to four major landslides, two of which were near the Port at L Street and Turnagain Heights.

Crustal Faults

In order to identify active and potentially active crustal faults in the vicinity of the Port, we relied primarily on the Neotectonic Map of Alaska (Plafker et al. 1994), which is currently the most comprehensive and recent published map of fault activity for Alaska. We have supplemented this compilation with additional published sources to include other faults and structures not included in this compilation. In contrast to the National Seismic Hazard Maps for Alaska (Wesson et al. 2007), which only includes the Castle Mountain fault as a potential near-field seismic source, we have expanded the number of seismic sources to include potentially active Quaternary faults capable of **M** ≥ 6.5 within 200 km of Anchorage. Of particular importance are several Quaternary-active and potentially Quaternary-active structures within the Cook Inlet (Fig. 3) that may significantly contribute to the seismic hazard in Anchorage (Haeussler et al. 2002). Although Wesson et al. (2007) recognized the existence of these structures, they did not include them in the 2007 maps due to insufficient data. Our review of the literature also concludes that these faults are poorly understood. However, because of their potential to cause earthquakes of significant size that could impact the Port, we include them in our model, adopting many of the source parameters of Haeussler et al. (2002) which, currently represents the best available science for the purposes of site-specific seismic hazards.

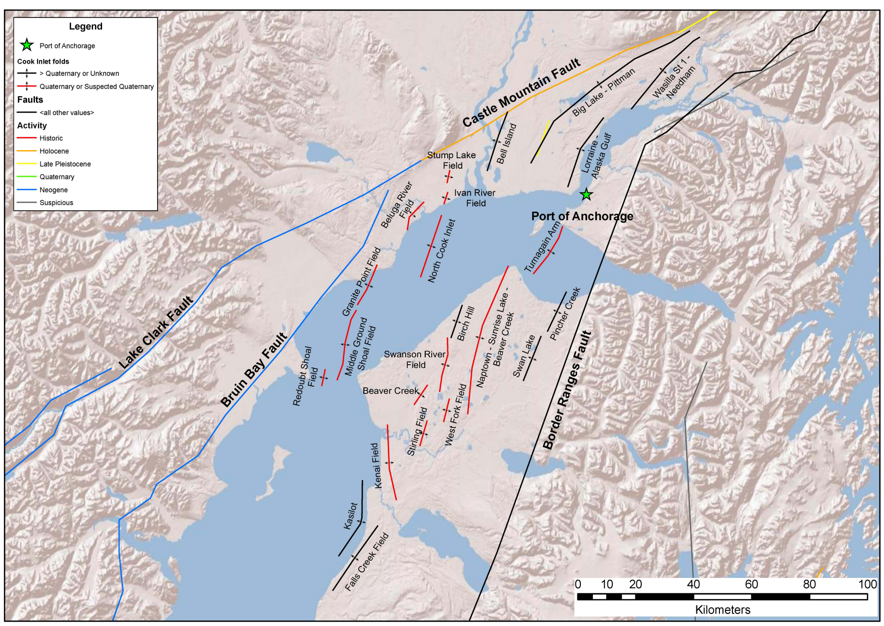


Figure 3. Neogene and Quaternary faults in the vicinity of Anchorage.

In certain cases, we also include Neogene faults within 200 km of Anchorage if they are judged to be potentially active (Fig. 1). Our criteria include: 1) whether the fault is in a favorable orientation within the present stress regime to accommodate ongoing deformation; 2) if the fault is on-strike with another active structure; and 3) if there is adequate resolution in the geomorphology and geologic mapping to identify evidence of active faulting. This is particularly difficult to assess, because we did not conduct a geomorphic or geologic analysis of the faults ourselves. However, it is apparent that many of the existing studies are reconnaissance in nature and it is possible that subtle expressions indicative of active faulting have been missed. In order to accommodate this uncertainty, but also honor the consensus that these faults are not active, we generally assign a lesser probability of activity to these faults. In our model, these considerations are applied to the Bruin Bay fault and the Lake Clark fault (Fig. 3). Finally, we include features labeled “suspicious” by Plafker et al. (1994) if they are judged to be in an orientation similar to other active faults in the region, as well as long enough in mapped trace to warrant inclusion as a potentially significant seismic source. These features are also assigned a lower probability of activity in order to account for the uncertainty that they may not be Quaternary active. Finally, although the Denali fault lies outside of the 200 km radius surrounding Anchorage (Fig. 1), we have included it due to its potential to generate large **M** > 7.5 relatively frequent earthquakes.

A total of 12 active faults were included in our PSHA including the Bruin Bay fault, Castle Mountain-Caribou fault system, Denali fault system, Lake Clark fault, Parker Lake fault, Pass Creek-Dutch Creek fault, an unnamed fault near Palmer, and several faults in Cook Inlet (Figs. 1 and 3). Preferred maximum magnitudes of the active faults were calculated using the empirical relationships of Wells and Coppersmith (1994) and Hanks and Bakun (2002), weighted equally. Seismogenic crustal thickness in the Anchorage area is based on observations of shallow crustal earthquakes that show the depth of seismicity is about 20 km (Flores and Doser 2005).

Cook Inlet Folds

While little is known about these faults in the Cook Inlet, the proximity of these structures to the Port of Anchorage make them, next to the Castle Mountain fault, the closest shallow crustal seismic sources (Fig. 3). Haeussler et al. (2000) suggest that these faults may present a greater short-term hazard than 1964-type subduction zone earthquakes. Our source characterization includes structures capable of **M** ≥ 6.5 earthquakes and identified by Haeussler et al. (2000) as Quaternary-active or potentially Quaternary-active. We also include the Turnagain Arm structure because it is the closest potentially Quaternary-active structure to the Port (Fig. 3). Because very little additional information exists about these structures in order to characterize them, we mostly adopt the source parameters of Haeussler et al. (2000).

Slip rates are unknown for most of the structures in Cook Inlet. Using assumptions of the start of deformation in the region and balanced cross-sections, Haeussler et al. (2000) calculated slip rates for the North Cook Inlet, Middle Ground Shoal and Granite Point structures. Although they indicate some preference for their higher estimates of the slip rates, we find the 2.72 mm/yr slip rate calculated for the Middle Ground Shoal and Granite Point structures to be too high, making it comparable to the Castle Mountain fault in terms of activity. Instead, we prefer their slip rate estimates that are based on a 5.3 Ma start of deformation, but give some weight (0.2) to both their lower and upper bounds.

Crustal Background Seismicity

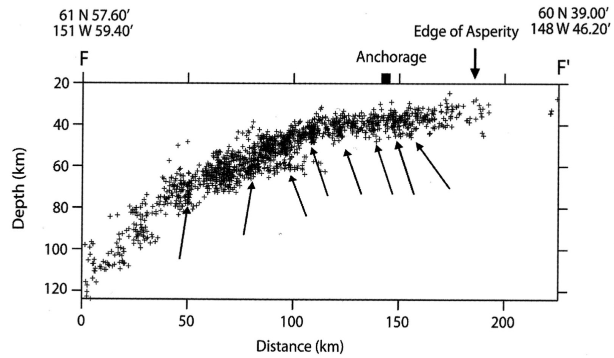
The hazard from crustal background (floating or random) earthquakes that are not associated with the known or mapped faults must be incorporated into the hazard analysis.

Background seismicity can be treated as an areal source zone where earthquakes are assumed to occur randomly or the historical seismicity can be assumed to be stationary in space and hence smoothed using a Gaussian filter. Both approaches were equally weighted in the PSHA.

The recurrence of the background seismicity was estimated using the maximum likelihood procedure and the estimated completeness intervals for the region. Dependent events were also identified and removed from the historical catalog. In this study, we adopt a value of **M** 7 ± ¼ because of the thick seismogenic crust that could conceal **M** 7 events. The best estimate value and one-sigma uncertainties are weighted in a logic tree similar to the maximum magnitude for the faults.

Alaskan Subduction Zone

The Alaskan subduction zone is defined by a northward-dipping Wadati-Benioff zone (Fig. 4). Large historical earthquakes have ruptured much of the length of the megathrust. The four segments of the subduction zone considered in the PSHA were the Semidi, Kodiak, Prince William Sound, and Yakataga (Fig. 5).



Source: Veilleux and Doser 2007

Figure 4. Seismicity cross-section through Alaskan subduction zone near Anchorage.

We adopted the USGS model for the Alaskan subduction zone but only that portion that would impact the Port in terms of ground motions of engineering relevance. In the megathrust area, for earthquakes larger than **M** 8.0, the USGS (Wesson et al. 2007) weighted equally the characteristic model and the maximum magnitude model for the Prince William Sound and Kodiak segments. For earthquakes between **M** 7 and 8, the USGS used the same probability of occurrence throughout the megathrust zone, and based the likelihood on an average of the entire zone's instrumental seismicity.

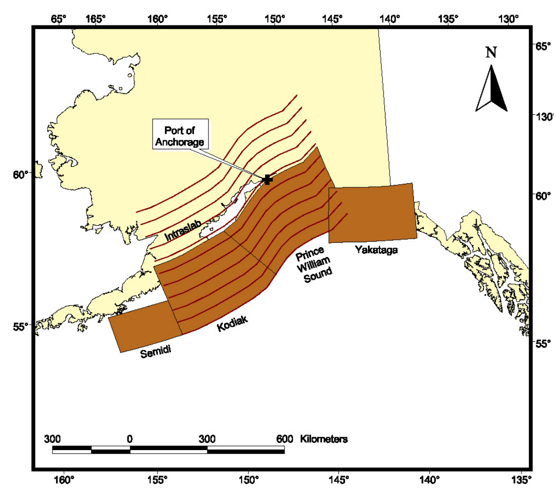


Figure 5. Model of megathrust and intraslab used in hazard analyses.

The USGS cites paleoseismology studies in the eastern part of the megathrust to assign an average recurrence time of 650 years for the Prince William Sound (1964 rupture zone) segment (Wesson et al. 2007). However, the USGS concludes that the southwestern part of the 1964 rupture zone (the Kodiak Island segment) ruptures separately, more frequently than the segment to the east. We also allow for this possibility and treat the 1964 rupture zone as both a segmented fault section in which only the Kodiak Island segment ruptures (weighted 0.5) and an unsegmented fault reach in which the entire 1964 rupture zone breaks in single events.

The Semidi segment, which has been previously referred to as the Shumagin gap, is assumed not to produce great earthquakes, based, in part, on recent geodetic analysis that indicates that the plates are decoupled in this region (Wesson et al. 2007). However, earthquakes up to about **M** 8 have been observed, and we thus allow for **M** 8.2 ± 0.3 events.

Fig. 5 shows the geometric model used for the megathrust and slab in the PSHA. The shaded area is treated as locked and capable of producing great megathrust earthquakes. Zweck et al. (2002) use GPS data to model the locked and slipping parts of the plate interface. They conclude that the present extent of the locked plate boundary closely resembles the area of the interface that broke in the 1964 earthquake. The area to the northwest of this locked patch is experiencing postseismic creep parallel to the direction of plate motion. The boundary between these locked and creeping patches trends to the northwest and is very near Anchorage.

In the PSHA, we model the Wadati-Benioff zone (Fig. 4) as staircasing blocks, each 10 km thick. Similar to our evaluation of crustal background seismicity, recurrence was calculated for the intraslab zone. A maximum magnitude of **M** 7½ ± ¼ was adopted based on the historical record of earthquakes greater than 30 km in depth in the Alaskan subduction zone.

Ground Motion Attenuation Relationships

To characterize the attenuation of ground motions in the PSHA, we used the recently developed PEER Next Generation of Attenuation (NGA) empirical attenuation relationships appropriate for tectonically active regions such as southern Alaska. The relationships by Chiou and Youngs (2008), Campbell and Bozorgnia (2008), Abrahamson and Silva (2008), and Boore and Atkinson (2008) were used in the PSHA weighted equally. A standard NEHRP B/C V_S30 (shear-wave velocity in the top 30 m) of 760 m/sec was adopted based on the V_S structure of the Anchorage area as portrayed by Dutta et al. (2007).

For the megathrust source of the Alaskan subduction zone, the Youngs et al. (1997), Atkinson and Boore (2003), and Gregor et al. (2002) attenuation relationships for rock were used and weighted 0.4, 0.4, and 0.2, respectively. The weighting is based on our subjective judgment of the validity of each model. For the intraslab sources, the Youngs et al. (1997) and Atkinson and Boore (2003) attenuation relationships were used and equally weighted.

Hazard Results

The results of the for a V_S30 of 760 m/sec PSHA are presented in terms of ground motion as a function of annual exceedance probability or average return period. Table 1 lists selected spectral accelerations for the three design return periods. The contributions of the various seismic sources to the mean PGA hazard are shown on Fig. 6. The intraslab zone dominates the peak horizontal ground acceleration (PGA) hazard at all return periods. At long-period ground motions (≥ 1.0 sec), the intraslab zone also controls the hazard at periods up to 5,000 years (Fig. 7). At longer return periods, the 1964 rupture controls the long-period hazard. The Castle

Mountain fault, the closest most significant crustal fault to the site, and the Cook Inlet faults are not major contributors to the hazard in Anchorage (Figs. 6 and 7).

Table 1. Probabilistic spectral accelerations.

Return Period (yrs)	PGA (g)	0.3 Sec SA (g)	2.0 Sec SA (g)
72	0.16	0.26	0.10
475	0.34	0.59	0.24
2,475	0.58	1.02	0.44

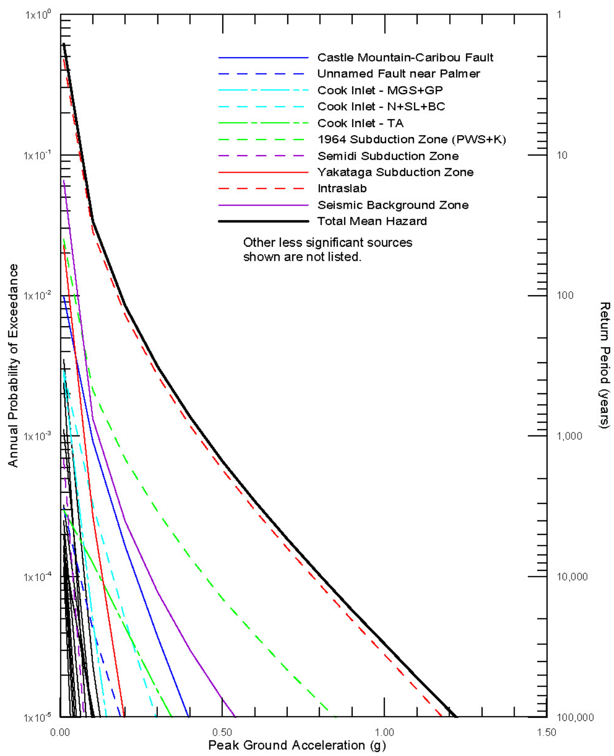


Figure 6. Seismic source contributions to mean PGA hazard.

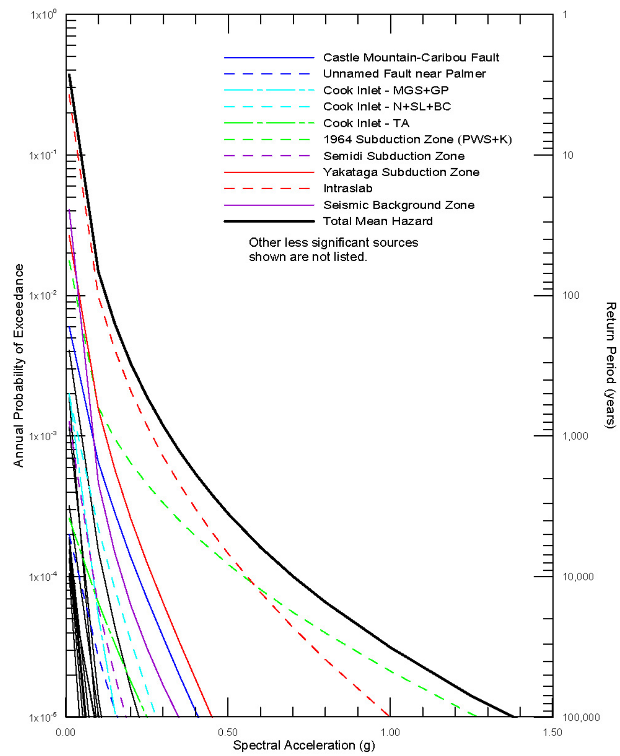


Figure 7. Seismic source contributions to mean 1.0 sec horizontal spectral acceleration hazard.

Fig. 8 illustrates the contributions by magnitude and distance. At a 2,475-year return period, the PGA hazard comes from events associated with the intraslab earthquakes of **M** 5.0 to 7.5 at distances of 25 to 75 km.

For a 2,475-year return period, the 2007 USGS Alaska map indicates a firm rock PGA of 0.69 g for the Port. The site-specific PGA computed in this study for the same return period is 0.58 g (Table 1), 16% lower than the USGS value. Similarly, the USGS 2475-year return period 0.2 and 1.0 sec SA values are 1.55 g and

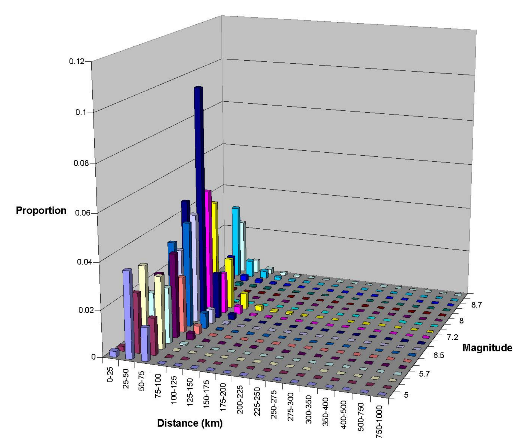


Figure 8. Magnitude and distance contributions to the mean PGA hazard at a 2,475-year return period.

0.52 g, respectively (Wesson et al. 2007), compared to this study's values of 1.18 g and 0.44 g, respectively. Thus, the results of this study are about 15 to 23% lower than the USGS results. This may be due to several reasons. First there may be a difference in the partitioning of the hazard contributions from the crustal and shallow intraslab seismicity. Based on the 1999 USGS hazard deaggregation, there appears to be a significant contribution coming from background crustal earthquakes, **M** 5.0 to 7.5 at distances of less than 25 km. We believe because the USGS does not distinguish between crustal and intraslab earthquakes at depths less than 50 km in their gridded seismicity (Wesson et al. 2007), the apparent crustal contribution in their hazard is actually also coming from shallow intraslab earthquakes. In our calculations, the rate of intraslab earthquake activity dominates the seismicity rates near Anchorage and this is consistent with the historical record. There have been at least 15 earthquakes of **M** 6.5 and greater within 200 km of Anchorage since 1898 that we believe have an intraslab source due to their relatively deep depths (30 to 120 km). In general, the hazard from crustal earthquakes will be higher than intraslab seismicity given the same magnitude and distance. Secondly, the use of the NGA attenuation models in our study is also decreasing the hazard contribution from the crustal seismicity including the Castle Mountain fault. Finally, the USGS used the megathrust attenuation relationships of Youngs et al. (1997) and Sadigh et al. (1997) at distances less than 70 km and only Youngs et al. (1997) at greater distances for the megathrust. The Atkinson and Boore (2003) used in this analysis with a 0.4 weight gives significantly lower hazard than the Youngs et al. (1997) model and so the hazard from the megathrust in Anchorage is higher in the USGS maps than in our study.

Acknowledgments

Our appreciation to the U.S. Department of Transportation Maritime Administration for their work on the Port of Anchorage Intermodal Expansion Project. Our appreciation to Richard Pearce with Terracon Consulting Engineers & Scientists and to Diana Carlson with ICRC for their support of this study. We would also like to thank Dr. Uptal Dutta for providing us shear-wave velocity data.

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