Strong ground shaking in the Portland, Oregon, metropolitan area: Evaluating the effects of local crustal and Cascadia subduction zone earthquakes and near-surface geology

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ABSTRACT

In its 150-year existence, the Portland metropolitan area has gone relatively unscathed by damaging earthquakes. However, an increasing amount of geologic and seismologic data indicate that crustal earthquakes in the Portland region larger than Richter magnitude (M_L) 6 and Cascadia subduction zone earthquakes of moment magnitude (M_W) 8 or greater will occur in the future. If either were the case, strong ground shaking generated by these events would have a major impact on the Portland area. In this study, we have estimated deterministically site-specific ground motions at four sites located in Portland using a state-of-the-art stochastic methodology. The events modeled were crustal earthquakes of M_W 6 and M_W 6.5 at source-to-site distances of 5, 10, and 15 km and a M_W 8.5 Cascadia subduction earthquake at a distance of about 120 km. In all cases, ground motions will be significant and damaging. The severity of such ground shaking in the Portland metropolitan area will be controlled in large part by the nature of the unconsolidated sediments at each specific location.

INTRODUCTION

The Portland metropolitan area and surrounding vicinity have been the most seismically active region in Oregon in historical times. Based on the relatively brief 150-year historic record, six earthquakes of Richter magnitude (M_L) 5 or greater have occurred within the greater Portland area (Bott and Wong, 1993). The recent occurrence of the damaging M_L 5.6 event of March 25, 1993, at Scotts Mills is testimony to the hazards posed by apparently randomly occurring crustal earthquakes. Recent geophysical studies suggest the presence of crustal faults beneath the Portland metropolitan area, which—albeit speculatively—could generate a potentially much more damaging crustal earthquake of M_L 6 or larger. A recent evaluation of earthquake recurrence suggests that a crustal earthquake of M_L 6 or larger should occur somewhere in the Portland region every 300–350 years and an event of M_L 6½ or larger about every 800–900 years (Bott and Wong, 1993). The seismic hazards posed by these earthquakes occurring within the earth's

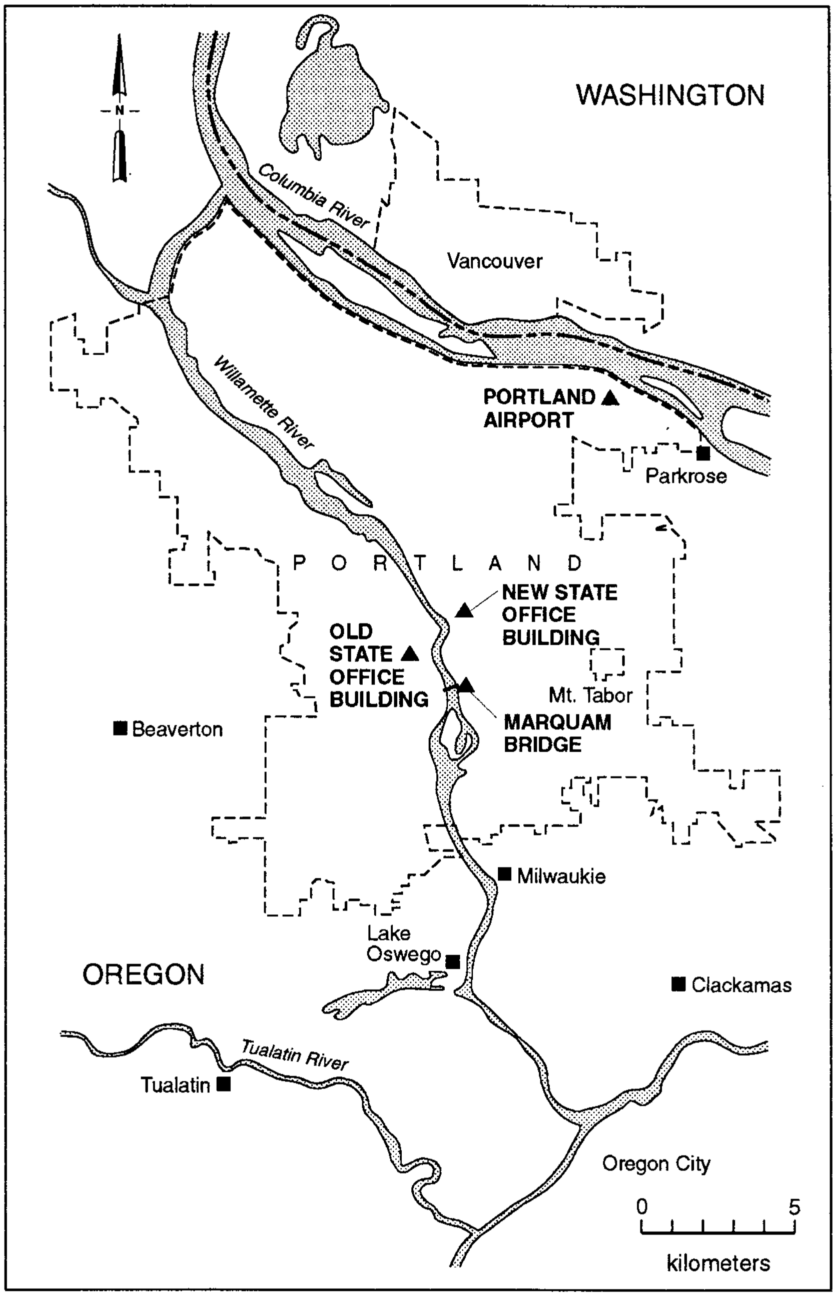

Figure 1. Location of sites (triangles) evaluated in this study.

crust are in addition to the recently recognized threat from a future great earthquake (moment magnitude $M_W \geq 8$) occurring along the interface between the Juan de Fuca and North American plates within the Cascadia subduction zone.

In this study, we have estimated the strong earthquake ground shaking that might be experienced at four sites in the Portland metropolitan area due to (1) moderate to large crustal earthquakes of M_W 6 and 6.5 occurring somewhere beneath the Portland Basin and (2) a M_W 8.5 Cascadia subduction zone earthquake. Our analysis is based on a state-of-the-art methodology that combines the Band-Limited-White-Noise (BLWN) ground-motion model and random vibration theory (RVT). An equivalent-linear site response technique is also employed to accommodate nonlinear soil behavior. This general approach has been previously used in a preliminary assessment of earthquake ground shaking in the Portland area (Wong and others, 1990).

Compared to our earlier study, we have (1) expanded our analyses to four sites and seven hypothetical earthquakes, (2) utilized recently acquired near-surface geologic and shear wave velocity data for the sites, and (3) refined our characterization and approach to modeling the Cascadia subduction zone event. Peak horizontal accelerations and five-percent damped acceleration response spectra have been computed for the following sites (Figure 1): (1) a soft soil site at the east end of the Marquam Bridge in southeast Portland, (2) a deep soft soil site at the Portland airport, (3) the moderately stiff soil site of the old State Office Building in downtown Portland, and (4) the relatively thin soil site of the new State Office Building in northeast Portland. The earthquakes modeled are two crustal earthquakes of M_W 6 and 6.5 at source-to-site distances of 5, 10, and 15 km and the M_W 8.5 Cascadia event at a distance of about 120 km.

It should be noted that our analysis is deterministic with no consideration for the frequency of occurrence of these earthquakes other than they are credible events with some finite probability of occurring. Thus the ground motions estimated in this study, specifically for the crustal earthquakes occurring in the Portland area, should not be used directly for seismic design but as potential scenarios for the greatest ground shaking that might be expected. It is also important that the uncertainties in any ground motion evaluation be fully appreciated given the uncertainties in earthquake source, path, and geologic site parameters that are the basic input into such analyses.

METHODOLOGY

The BLWN-RVT methodology is a stochastic ground motion modeling technique that has been used successfully in recent years to estimate earthquake ground shaking. Because the methodology can incorporate aspects of the source, path, and site that are specifically appropriate for the earthquake region and location to be modeled, it is particularly valuable in areas where few, if any, strong motion records exist. Such is the case for the Portland area. In this study, the crustal earthquakes have been modeled based on a point source representation of the BLWN model. This approach is applicable, given the magnitudes of the events and source-to-site distances being considered. However, because source dimensions will be significant for a great Cascadia subduction zone earthquake relative to its source-to-site distance, the finite fault version of the BLWN-RVT methodology is employed to estimate the ground motions for this event. Details of the point source and finite fault approaches can be found in Silva and others (1992) and Silva and others (1990), respectively.

INPUT PARAMETERS

The earthquake source, propagation path, and site parameters that are required for the site-specific ground motion estimates are described in the following paragraphs.

Earthquake sources

Although the largest known crustal earthquake in the Portland region was the recent 1993 Scotts Mills earthquake, events as large as or larger than M_L 6½ (or M_W 6½) are thought to be possible. Thus, the two crustal earthquakes modeled in this study were M_W 6 and M_W 6.5. The distance defined in the stochastic point source approach is measured from the site of interest to the center of energy release or approximately the center of the potential rupture plane. Source-to-site distances of 5 to 15 km were chosen to evaluate the potential ground shaking that might result from an earthquake occurring on a crustal fault beneath Portland.

Although to date no seismogenic faults have been identified in the Portland area, the relatively high level of crustal seismicity suggests that such faults do exist. Their maximum earthquake generating potential is as yet unknown. Crustal earthquakes in western Oregon tend to occur at depths down to 20–25 km, deeper than do most western U.S. earthquakes. Consequently, the likelihood of a moderate to large earthquake at a source-to-site distance of 5 km is low in the Portland region, unless the event occurs on a fault whose rupture extends up to or close to the earth's surface.

In order to estimate ground motions using the BLWN-RVT point source approach, the stress drop of the modeled earthquake is required. Recently, Youngs and Silva (1992) observed that a stress drop of about 85 bars provides a good fit to recently developed empirical rock attenuation relationships for spectral acceleration based on strong motion data from California. Given the uncertainty of stress drops for Pacific Northwest crustal earthquakes, a value of 100 bars was selected as a reasonable value to use in the point source estimates.

Geologic and seismologic studies conducted over the last five years have led, in the earth science community, to a general acceptance of the view that the Cascadia subduction zone interface has produced large megathrust earthquakes ($M_W \geq 8$) in the prehistoric past and is likely to produce them in the future (e.g., Rogers and others, 1991). The M_W 7.0 Cape Mendocino earthquake of 1992 in northwestern California probably

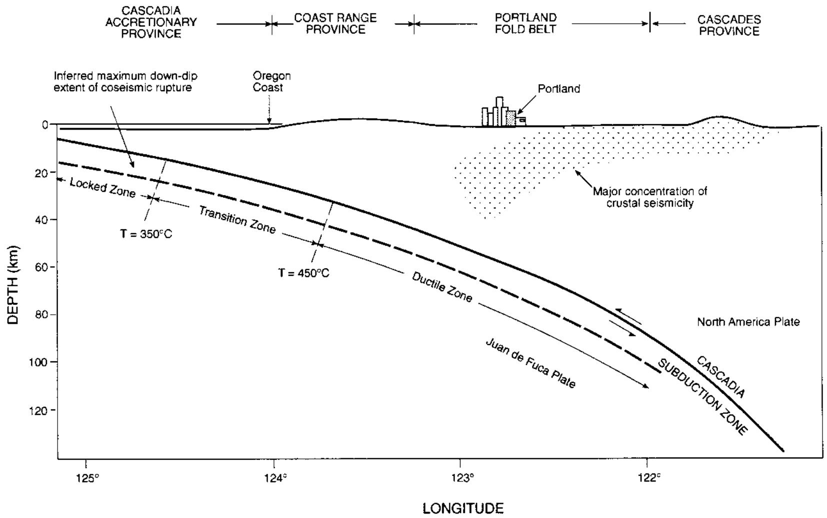

Figure 2. Schematic cross-section through the Cascadia subduction zone at the latitude of Portland, Oregon, modified from Unruh and others (1993). Divisions of subduction zone from Hyndman and Wang (1993). We have assumed that coseismic rupture will extend approximately into the western third of the transition zone.

occurred on the interface and hence demonstrates that the subduction zone, at least at its southern end, is seismogenic (Oppenheimer and others, 1993). The size of the maximum magnitude earthquake that might occur along the interface is, however, the subject of considerable current debate and research. The size of the earthquake is dependent on the length and width of the rupture zone (hence rupture area), which is in turn primarily dependent on the segmented nature and downdip extent of the subducted slab. Current estimates of these rupture parameters are uncertain, given our existing knowledge of the subduction zone. In this study, we have assumed a maximum magnitude of M_W 8.5 as a reasonable value to use at this time.

On the basis of thermal modeling, Hyndman and Wang (1993) defined four down-dip divisions of the Cascadia subduction zone interface (Figure 2, showing zones 2–4): (1) a zone of stable sliding in the unconsolidated and/or clay-rich sediments at the seaward end of the detachment; (2) a locked zone of unstable sliding behavior that allows elastic strain to accumulate; (3) a transition zone in which slip would occur, in part, during earthquake displacement and, in part, during post-seismic slip; and (4) a zone of plastic behavior (ductile) associated with high temperatures. The width of the zone defined by Hyndman and Wang (1993) as locked is about 70 km wide off the coast of Oregon. Adopting their locked zone as the primary site of future rupture, we also conservatively assume that a third of the transition zone will be involved in coseismic rupture. These assumptions result in a rupture width of about 90 km off the coast of Oregon. As derived from an empirical relationship between rupture area and magnitude (Wells and Coppersmith, in preparation), the corresponding rupture length for a M_W 8.5 earthquake would be approximately 300–350 km. Such a length is comparable to other values suggested by investigators who assume a segmented Cascadia subduction zone. Extending the rupture one-third into the transition zone also results in a source-to-site distance from the eastern extent of the rupture to the Portland area of about 120 km. This distance probably has an uncertainty of several tens of kilometers. The depth of the eastern edge of the potential 10° eastward-dipping rupture plane will be approximately 20 km (Figure 2).

In the absence of *a priori* information on the actual slip distribution of a future event, randomized slip distributions were used in the finite fault modeling for the Cascadia subduction zone earthquake. A total of 50 randomized slip models were used. Samples of these models are shown in Figure 3. In order to generate these slip models, the two-dimensional wave-number spectrum of the slip model for the M_W 8 earthquake of 1985 at Michoacan, Mexico, was computed and its phase spectrum randomized.

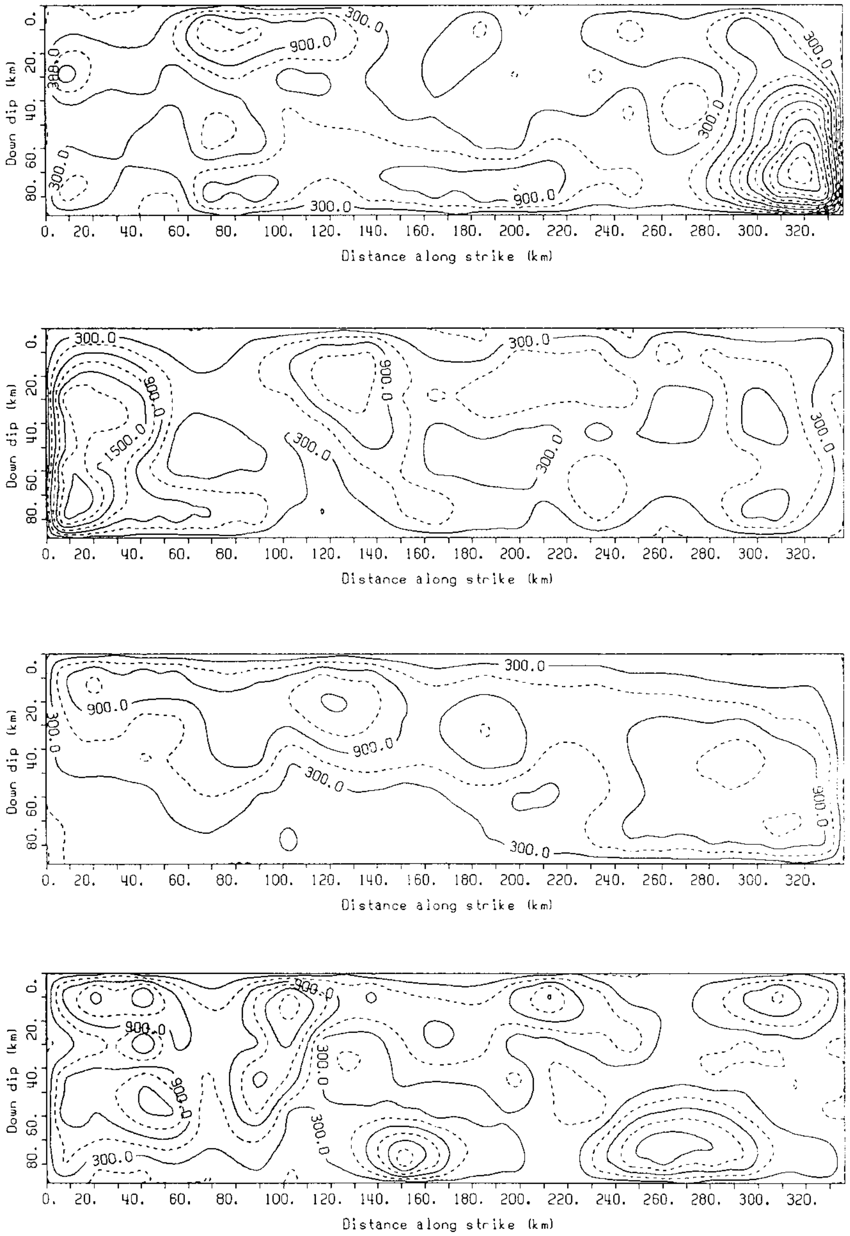

Figure 3. Examples of the 50 randomized slip distribution models used in the estimation of ground motions for the M_W 8.5 Cascadia subduction zone earthquake. Contours represent coseismic slip along the rupture planes in cm. Areas of large slip are called asperities.

Again, in the absence of *a priori* knowledge, points of rupture initiation were randomized along a zone that extends along strike and is located in the lower half of the fault plane toward its eastern edge. Rupture is expected to proceed updip in a Cascadia megathrust earthquake.

Path

To describe the frequency (f)-dependent seismic wave attenuation along the crustal path between source and site (described as $Q[f] = Q_0 f^{\eta}$) for the crustal events, a Q_0 of 200 and η of 0.35 were adopted from Singh and Herrmann (1983), who analyzed the coda waves of recorded local and near-regional earthquakes. These values were determined from the seismograph station located in Corvallis. Given the short source-to-site distances for the crustal events, attenuation has very little effect on the computed ground motions. A shear wave velocity (v_s) of 3.8 km/s and density of 2.8 g/cm^3 were used to characterize the path between the source and the site.

For the Cascadia earthquake, a Q_0 of 273 and η of 0.66 were used to characterize the attenuation of seismic waves along the path from the subduction zone to the site. This attenuation model was adopted from observations of the 1985 Michoacan earthquake (Humphrey and Anderson, 1992).

Sites

All four sites analyzed in this study are located in the alluvium-filled Portland Basin. Near-surface stratigraphy based on borehole data and shear-wave velocities from downhole profiling was provided by DOGAMI (Mabey and Madin, 1992) for the Marquam Bridge and airport sites (Figure 4). The profile for the new State Office Building was slightly revised from the one previously used in Wong and others (1990). Subsurface data for the old State Office Building site are from Shannon and Wilson and Agbabian Associates (1980). The stratigraphy beneath the boreholes is based largely on a few deep exploration boreholes in the Portland Basin and a limited amount of seismic data (Wong and others, 1990). Due to this lack of site-specific data, considerable uncertainties are associated with deeper portions of the geologic profiles, although ground motions of engineering interest in the frequency range of 1 to 10 Hz are controlled largely by the shallow site geology, particularly the unconsolidated sediments.

Occurring within the Portland Basin is the Columbia River basalt (Figure 4), which serves as the top of rock at the four sites in this study despite the relatively high shear-wave velocities for the Troutdale gravel. The basalt is overlain by the Sandy River Mudstone at three of the four sites, by the Troutdale gravel, and then by varying thicknesses of soft, relatively low-velocity alluvial sands and silts. All layers above rock were considered in the equivalent-linear analysis. Three shear modulus reduction curves were used to characterize the dynamic behavior of the unconsolidated sediments at each site: Seed and Idriss (1970) for upper-range sand and mid-range gravel (Troutdale) and Sun and others (1988) for the Sandy River Mudstone. Seed and Idriss (1970) mid-range damping curves for sand and gravel were used for the sands and Troutdale gravels, respectively. A damping curve was developed and used in this study specifically for the mudstone. Modulus reduction and damping curves are a source of uncertainty, since they are based on laboratory measurements of non-site-specific samples.

RESULTS

Earthquake ground shaking on soil sites is influenced by two opposing effects: site amplification and material damping. Amplification by unconsolidated sediments often results in the increase in amplitudes at certain frequencies due to (1) conservation of energy effects as the seismic waves travel from a faster, more rigid material to a slower, softer material; and (2) resonant effects due to constructive interference of multiple reflections. Damping in soils is the dissipation of energy due to a variety of loss mechanisms.

The five-percent damped acceleration response spectra computed in this study for the crustal earthquakes are shown in Figures 5 and 6. The estimated peak horizontal accelerations are summarized in Table 1. For comparison, we have also computed peak horizontal accelerations based on several state-of-the-practice empirical attenuation relationships for crustal earthquakes (Table 2). Inherent in the empirical approach to estimating ground motions is the inability to incorporate site-specific geologic data and hence, site response effects unique to each location.

For the Marquam Bridge site, peak horizontal accelerations range from 0.13 to 0.43 *g*, levels which can result in minor to

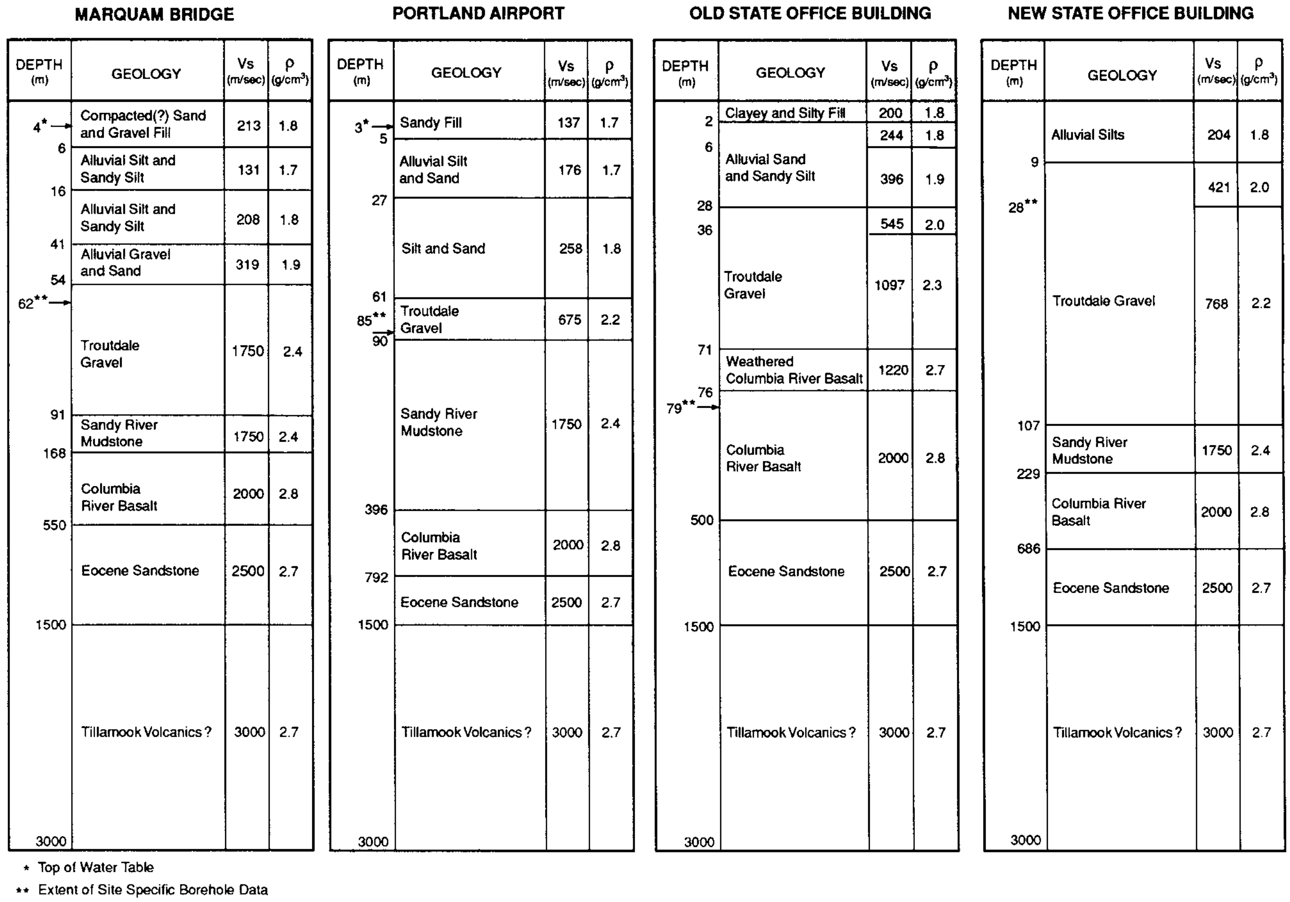

Figure 4. Geologic profiles beneath the four sites analyzed in this study.

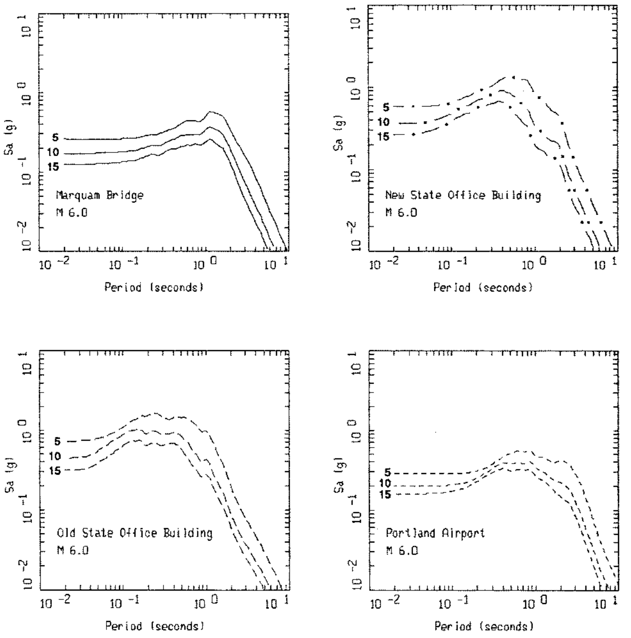

Figure 5. Site-specific five-percent damped median acceleration response spectra for the M_W *6 crustal earthquake at source-to-site distances of 5, 10, and 15 km for the four sites analyzed.*

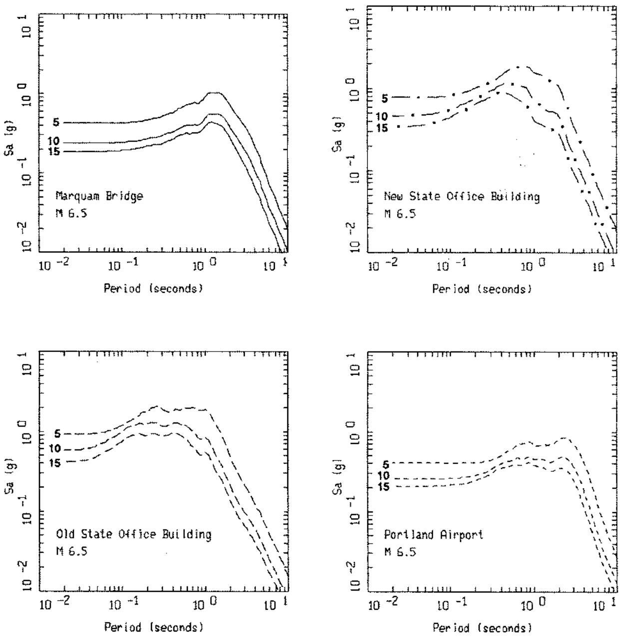

Figure 6. Site-specific five-percent damped median acceleration response spectra for the M_W *6.5 crustal earthquake at source-to-site distances of 5, 10, and 15 km for the four sites analyzed.*

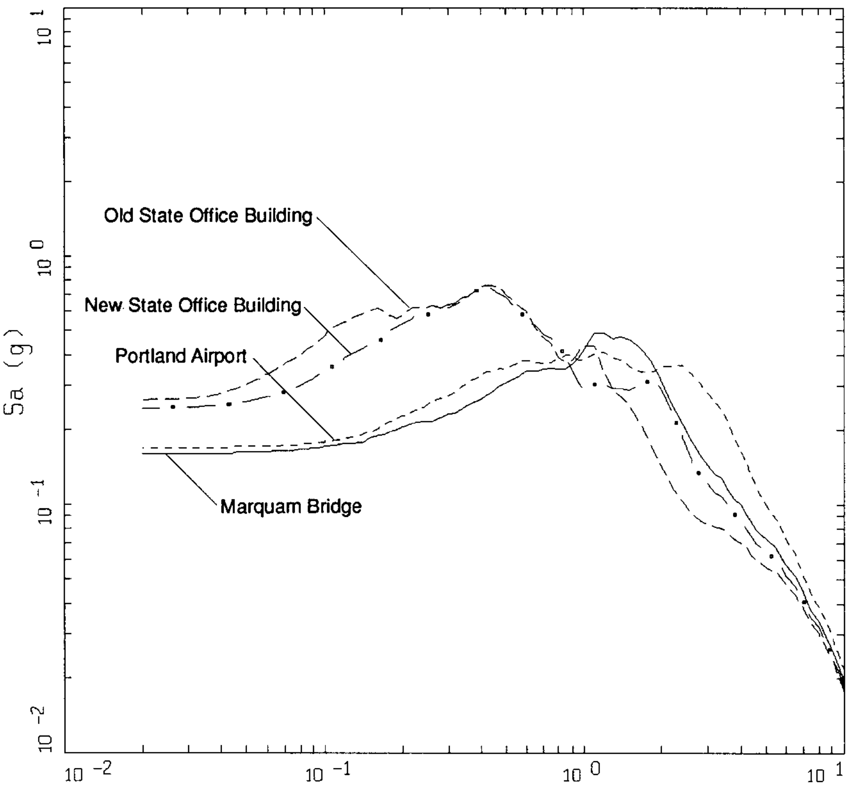

Figure 7. Site-specific five-percent damped median acceleration response spectra for the M_W *8.5 Cascadia subduction zone earthquake for the four sites analyzed, at a source-to-site distance of 120 km.*

significant structural damage (Table 1). (Ground acceleration is often expressed in terms of "*g*," or the gravitational acceleration at the earth's surface.) For comparison, ground shaking recorded 50 km away in the Portland area during the recent Scotts Mills earthquake was less than 0.05 *g* (U.S. Geological Survey, 1993).

The strong velocity contrast at the top of the Troutdale gravel beneath the Marquam Bridge site (Figure 4) probably accounts for some site amplification of the ground motions, although this effect appears to be offset by damping in the 54-m-thick low-velocity silts and sands. The low-velocity zone (131 m/s) between the depths of 6 and 16 m (Figure 4) may also act to trap some upgoing energy. In almost all cases, the site-specific stochastic peak horizontal accelerations for the crustal earthquakes are less than typical median empirical values (Tables 1 and 2), attesting to the damping effects of this relatively deep-soil site. The spectral shapes, in particular the resonant peak at a period of 1.5 s, are similar for both the M_W 6 and the M_W 6.5 earthquakes, reflecting the influence of the near-surface site geology (Figures 5 and 6).

The ground motions at the Portland airport reflect the site response of a deep-soil site, although the absence of a low-velocity zone may account for the slightly higher peak horizontal accelerations compared to the Marquam Bridge (Table 1; Figures 5 and 6). Significant short-period damping is probably occurring within the 90-m-thick unconsolidated to poorly consolidated sediments (including the low-velocity Troutdale gravels) (Figure 4). The peak accelerations for this site are comparable to the median empirical values estimated with the relationship of Idriss (1985) for deep-soil sites (Tables 1 and 2).

In contrast, significant site amplification appears to be influencing the ground motions at the old State Office Building site and to a slightly lesser extent at the new State Office Building site. The site-specific stochastic peak horizontal accelerations for both sites significantly exceed typical empirical values (Tables 1 and 2). Beneath the old State Office Building, a strong velocity contrast is located at the boundary between the weathered top of the Troutdale gravel and the rest of the layer (Figure 4). Material damping is not as significant at these sites, due to the thinner nature of the soils and unconsolidated sediments. If a crustal earthquake of M_W 6 or greater were to occur at source-to-site distances of 5–15 km, such as beneath downtown Portland, very strong ground shaking would be experienced (Figures 5 and 6). Given the uncertainties in ground motion estimates, the peak accelerations for the old State Office Building site could exceed 0.6 *g* (Table 1).

Velocity contrasts exist beneath the new State Office Building at boundaries within the Troutdale gravel. The Sandy River Mudstone represents a low-velocity zone within the profile, which probably accounts for the lower peak accelerations and spectral accelerations at short periods, compared to the old State Office Building (Table 1 and Figure 4). The highest spectral accelerations at these two sites occur at periods of 0.1 to 1.0 s (1 to 10 Hz) (Figures 5 and 6), the bandwidth of significant engineering relevance.

Despite the source-to-site distance of 120-km, the M_W 8.5 Cascadia earthquake could generate significant ground shaking in the Portland metropolitan area, particularly at the old and new State Office Building sites (Figure 7 and Table 1). These ground motions, however, must be viewed cautiously, given the large uncertainties surrounding the source-to-site distances to the eastern extent of rupture of a megathrust earthquake and, of course, the maximum magnitude of such an event. The shift in the broad spectral peaks to longer periods for the Portland airport and Marquam Bridge compared to the old and new State Office Buildings reflects the influence of the deep unconsolidated sediments at the former two sites (Figure 7).

An important effect not addressed in this study, especially for the Cascadia earthquake, is the duration of strong ground shaking. Given the extended rupture dimensions of a large megathrust earthquake, duration is a parameter that needs to be considered in seismic design and seismic safety evaluations, particularly for long-period structures, such as tall buildings and bridges, and in areas where soil liquefaction is a potential hazard.

Table 1. *Site-specific stochastic peak horizontal accelerations. MB = Marquam Bridge, NB = new State Office Building, OB = old State Office Building, PA = Portland airport*

			Peak horizontal accelerations			
Earthquake	**Magnitude (M_W)**	**Distance[1] (km)**	**MB (*g*)**	**NB (*g*)**	**OB (*g*)**	**PA (*g*)**
Cascadia	8.5	120	0.16	0.24	0.26	0.17
Crustal	6	5	0.26	0.58	0.72	0.29
		10	0.18	0.36	0.44	0.20
		15	0.13	0.26	0.31	0.16
	6.5	5	0.43	0.78	0.92	0.41
		10	0.24	0.47	0.57	0.26
		15	0.19	0.35	0.41	0.21

[1] Source-to-site

Table 2. *Median empirical peak horizontal accelerations for crustal earthquakes*

				Idriss (1985)	
Magnitude (M_W)	**Distance[1] (km)**	**Campbell (1990) (*g*)**	**Sadigh (1987)[2] (*g*)**	**Stiff[3] (*g*)**	**Deep[4] (*g*)**
6	5	0.37	0.29	0.36	0.31
	10	0.22	0.20	0.25	0.22
	15	0.15	0.14	0.18	0.17
6.5	5	0.43	0.37	0.43	0.36
	10	0.28	0.26	0.30	0.27
	15	0.20	0.20	0.23	0.20

[1] Source-to-site

[2] Described in Joyner and Boore (1988)

[3] Stiff-soil sites are underlain by cohesionless soils or stiff clays less than 61 m deep

[4] Deep-soil sites are underlain by more than 76 m of cohesionless soil deposits

SUMMARY

If a crustal earthquake of moderate or larger magnitude (M_W 6) should occur beneath the Portland Basin, significant strong ground shaking is likely. As has been observed in numerous cases worldwide, the amplitudes and frequency content of such ground motions will be strongly influenced by the nature of the soils and unconsolidated sediments beneath a given location in the Portland metropolitan area. Thin-soil sites such as the old and new State Office Buildings can produce severe ground shaking in either a nearby crustal earthquake or a distant large event on the Cascadia subduction zone. Deep-soil sites such as at the Marquam Bridge and the Portland airport, though still capable of experiencing strong shaking, will dampen as well as shift short-period ground motions to longer periods. The range of ground motions observed in this study further emphasizes the need for assessing such hazards on a site-specific basis in the Portland metropolitan area.

ACKNOWLEDGMENTS

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BLM protects "Cenozoic Park" fossils

by John Zancanella; reprinted from BLM News, *September 1993, page 4.*

With the popularity of the movie *Jurassic Park*, interest in fossils is greater than ever before. Few people realize, however, that the Bureau of Land Management is steward to many fossil treasures here in Oregon.

"Fossil remains of dinosaurs like those portrayed in the movie are generally found in the Great Plains and Rocky Mountains regions," explained paleontologist Dr. James Martin. "In Oregon, we have fossils from the Age of Mammals, the Cenozoic Era, which extends back nearly 50 million years."

Martin, from the South Dakota School of Mines and Technology, has been hired by BLM to develop a statewide plan for paleontology, the study of ancient life through the fossil record.

"After conducting research in Oregon for 20 years, I understand that educating people about this resource is as important as working to preserve it," Martin said. "Public responsibility is the key."

In central Oregon, the red, blue-green, and buff-colored sedimentary rocks of the Clarno, John Day, Mascall, and Rattlesnake Formations represent environments that changed from tropical and subtropical forests to a cooler and dryer savanna. The fossils found in these rocks include horses, elephants, rhinoceroses, rodents, cats, dogs, camels, and large piglike animals called oreodonts.

The John Day Formation, visible along the upper John Day River and the surrounding hills, was punctuated by volcanic ash falls that now allow scientists to accurately determine how the plants and animals have changed over time. This formation is significant because its seven- to ten-million-year sequence of fossil-bearing rock is one of the most complete and continuous in the world.

"In fact," Martin explained, "evolutionary changes of the horse were first determined from fossils recovered from the John Day River basin. Erosional and volcanic forces since that time have combined to sculpt and mold these ancient landscapes into the dramatic and wonderful scenes we see today."

In June, the resurgence of excitement about fossils and their importance to scientific study prompted BLM's Oregon/Washington State Director Dean Bibles to visit two Cenozoic fossil sites on BLM-managed lands in central Oregon.

Bibles and Martin toured Logan Butte in BLM's Prineville District and Fossil Lake in BLM's Lakeview District. Ted Fremd, paleontologist with the John Day Fossil Beds National Monument, was also on hand to attest to the importance of the Logan Butte site.

"I was impressed with the wide variety and sheer quantity of the fossil record at these sites," Bibles said. "At the same time, however, I'm disturbed to see so much evidence of unauthorized collection and destruction caused by careless visitors."

Current federal law prohibits the collection of any vertebrate fossils from federal lands without a permit, whereas most invertebrate and plant fossils can be collected by the general public.

"It is essential that we carefully collect and document specimens on public lands, but the process doesn't stop there," explained Martin. "We must preserve fossils for those to come and be able to retrieve them for future study."

Bibles showed enthusiastic support for Dr. Martin's efforts and stated that more education of both BLM staff and the public is needed to protect fossil resources on public lands.

"Fossils are a nonrenewable resource, and vertebrate fossils are the rarest," Bibles said. "We're committed to doing whatever is necessary to ensure that BLM's 'Cenozoic Park' may be studied and enjoyed by future generations." □