BUGNI

EARTHQUAKE RISK ANALYSIS

FINAL REPORT

VOLUME TWO

Submitted To

The City of Portland, Oregon

by
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DISCLAIMER

All interpretations, results and conclusions drawn in this report are those of the contractor, Goettel & Horner Inc., and not necessarily those of the City of Portland or the Bureau of Buildings. Goettel & Horner Inc. and its subcontractors have exercised diligence in the collection of data and care in performing the calculations upon which results and conclusions are based. However, our results and conclusions are necessarily based on the limited data, resources and time available for this study. Furthermore, many important aspects of this project rely on subjective professional judgements based on experience. Therefore, other persons knowledgeable in the fields of this study (seismology, engineering, risk assessment and economics) may draw conclusions which differ from ours.

The material presented in this report should not be used or relied upon for any specific application without verification of its accuracy, suitability, and applicability by professionals knowledgeable in the appropriate fields of study. Users of information in this report assume all liability arising from any such use.

ACKNOWLEDGEMENTS

Goettel & Horner Inc. gratefully acknowledges the contributions of our subcontractors on this project. James E. Russell, a building codes consultant, contributed extensively to the writing of this report and his experience in helping many cities develop seismic retrofit ordinances was invaluable. John M. Eidinger and Tom Desmond of G & E Engineering Systems Inc. contributed extensively to the seismic hazards and building seismic vulnerability sections of this report. Their engineering experience and judgement were essential to this project. Clare F. Laufenberg provided careful editorial review of this report and contributed significantly to helping us make it as understandable as possible for the general audience.

EXECUTIVE SUMMARY

Focus of This Study

This study is designed to help the City of Portland make decisions about life safety seismic retrofits of existing buildings. We evaluate life safety seismic retrofits for those classes, locations and uses of buildings which may constitute a significant life safety risk in Portland. In evaluating these life safety retrofits, we also examine the full economic benefits of the retrofits, including reduced damages and reduced loss of functionality, to provide the information necessary for the City and building owners to make better informed decisions about possible retrofit alternatives.

This study includes information on four main topics:

1) a review of Portland's earthquake hazard from known faults or fault zones,

2) an assessment of the life safety risks associated with some classes of buildings when subjected to the range of future earthquakes that can affect Portland,

3) an analysis of the benefits associated with life safety seismic retrofits of vulnerable existing buildings compared to the typical costs of such retrofits, and

4) conclusions regarding the types, locations and uses of buildings that would be good candidates for seismic retrofit.

Volume One

Volume One addresses the four main topics listed above. Volume One contains a non-technical overview of the context and assumptions underlying our assessment of the life safety risk posed by existing buildings in Portland and our main results and conclusions about the life safety benefits and non-life safety benefits of prospective seismic retrofits and compares these benefits to typical costs of retrofits. The intended audience for Volume One includes all persons interested in the seismic life safety of existing buildings in Portland. The level of technical detail is minimized to make Volume One as accessible as possible for the general reader.

Volume Two

Volume Two contains technical appendices which outline the detailed calculations and assumptions which underlie the results presented in Volume One. Each technical appendix in Volume Two has a brief introductory section which sets the context of the technical material. However, much of the material in Volume Two is highly technical and is intended primarily for technical specialists in seismology, risk assessment, and earthquake engineering. The level of technical detail is high, to allow professionals in these fields to evaluate the assumptions, methods, and data used in our analyses.

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TECHNICAL APPENDIX 1

SEISMIC HAZARDS IN PORTLAND

In discussing the potential impact of earthquakes on the Portland area it is helpful to consider two separate, but related concepts: seismic "hazard" and seismic "risk". Seismic "hazard" is defined as the probabilities of earthquake ground motions at a given location. Seismic "risk" is defined as the potential for damages and casualties to the built environment.

Seismic "hazard" is discussed in this Technical Appendix. Seismic "risk" is discussed in Technical Appendix 2, which deals with the vulnerability of existing buildings in Portland to seismic damages.

1.1 Seismic Sources Affecting Portland

Recent studies[1,2] of the seismicity of the Pacific Northwest indicate that there are three sources of earthquakes which may affect the Portland area:

1) Cascadia subduction zone (interplate) earthquakes on the interface between the Juan de Fuca plate and the North America plate,

2) Deep intraplate earthquakes within the subducting Juan de Fuca plate, and

3) Shallow crustal earthquakes within the North America plate.

The seismicity which affects Portland is shown on Figures 1.1, 1.2 and 1.3.

> Figure 1.1, Epicenters of Earthquakes in the Pacific Northwest Since 1960, shows large numbers of earthquakes off the coast at plate boundaries, with scattered earthquakes elsewhere offshore and within the North American plate.
>
> Figure 1.2, Historic and Instrumentally Recorded Seismicity Near Portland, provides a close-up map of Oregon showing the historic and instrumentally recorded earthquakes near Portland.
>
> Figure 1.3, Cross-Section of Seismicity Centered on Latitude 45.5 with Inferred Location of Subduction Portion of Juan de Fuca Plate, is a cross section through Oregon which illustrates the geographic and depth distribution of observed earthquakes affecting Oregon. Figure 1.3 shows large numbers of mostly small to moderate, shallow crustal earthquakes, a couple of earthquakes within the subducting Juan de Fuca plate (deep intraplate earthquakes) and the location of the locked interface zone where Cascadia subduction zone earthquakes are expected.

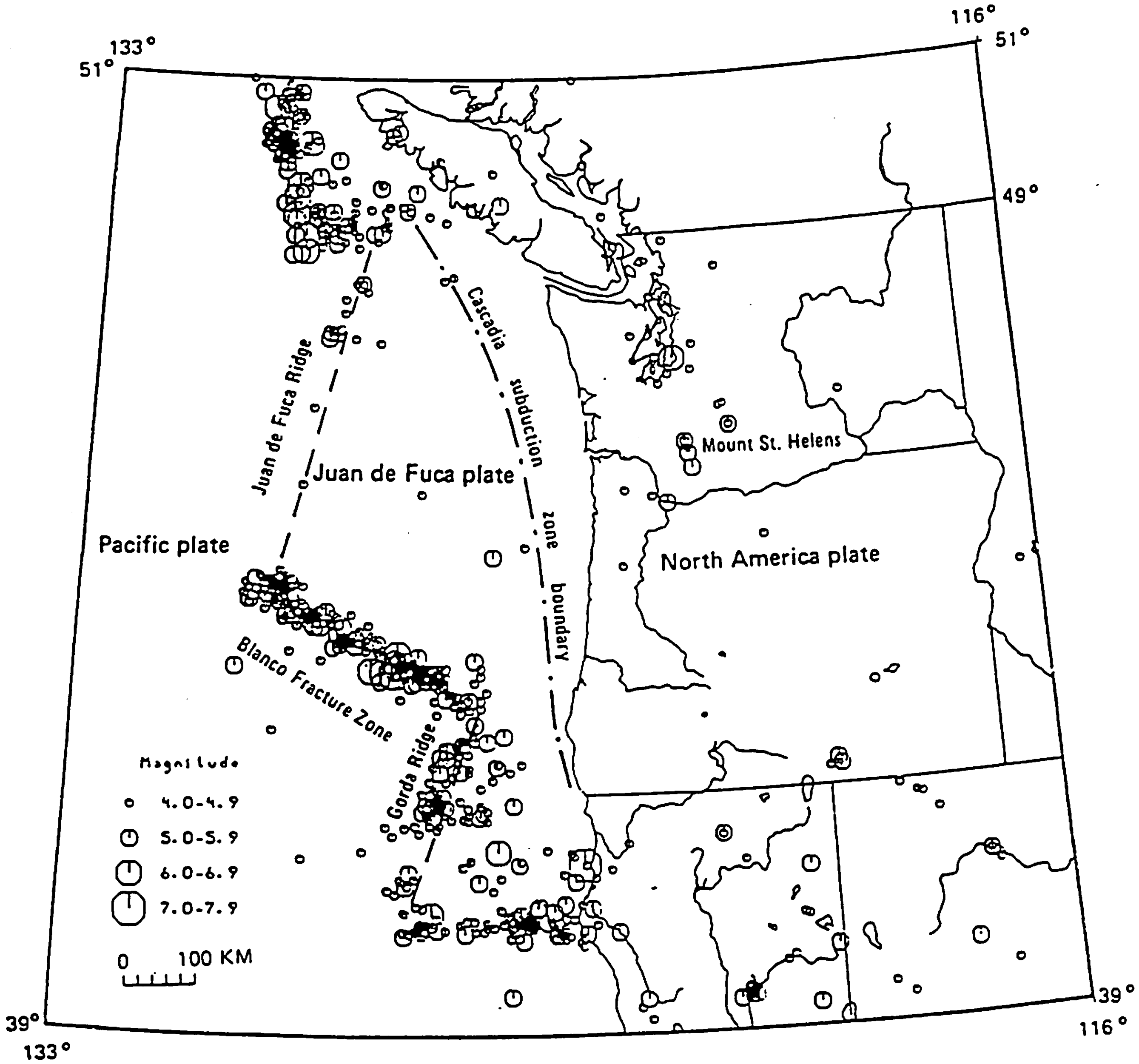

Figure 1.1 Epicenters of Earthquakes in the Pacific Northwest Since 1960

Only the largest earthquakes near Mount St. Helens are indicated. (Data from the National Oceanic and Atmospheric Administration and the University of Washington. Adapted from Washington State Earthquakle Hazards, November 1988.)

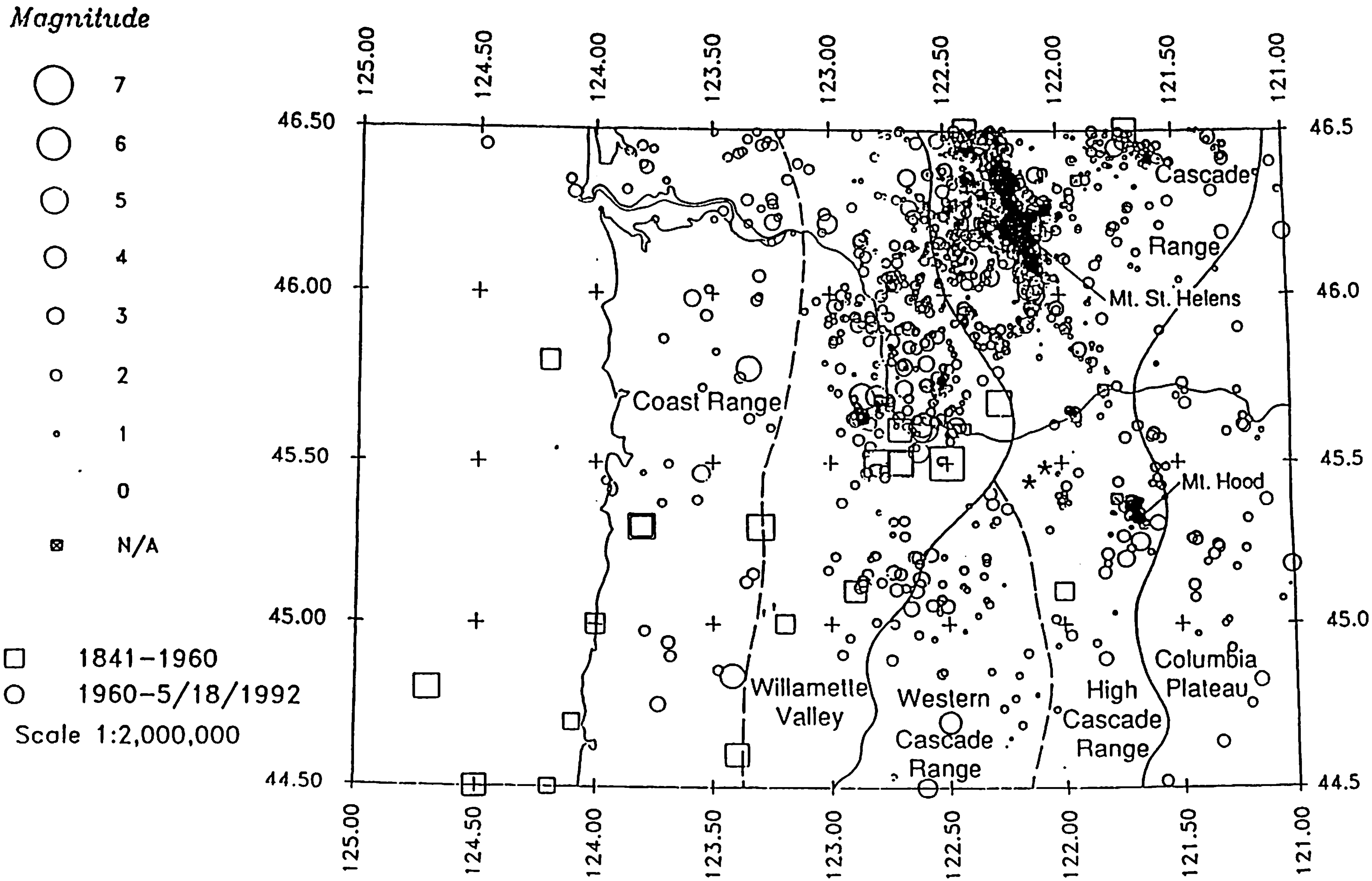

Figure 1.2 Historic and Instrumentally Recorded Seismicity Near Portland

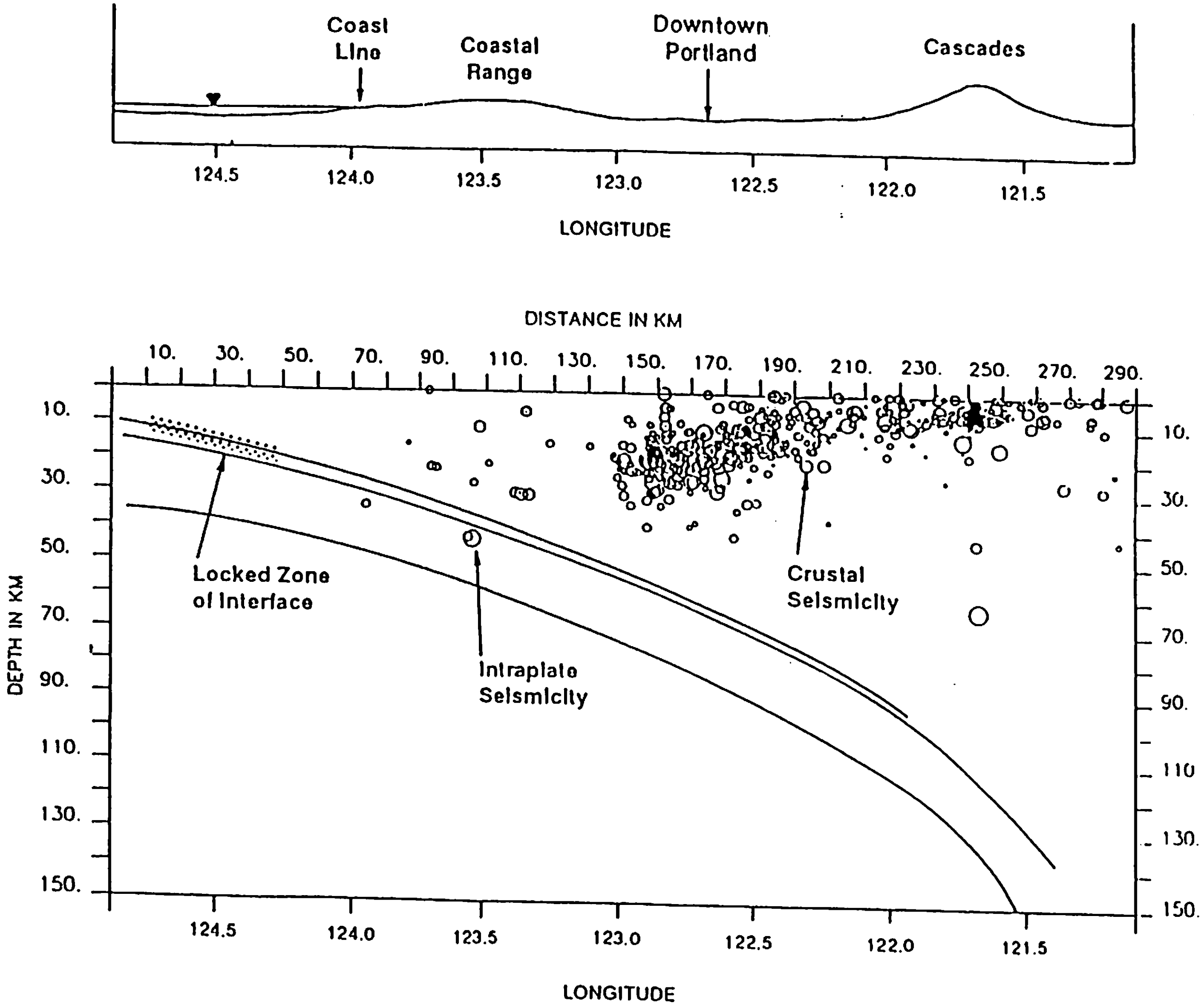

Figure 1.3 Cross Section of Seismicity Centered on Latitude 45.5 with Inferred Location of Subduction Portion of Juan de Fuca Plate

1.2 Assumptions

The intensity or severity of earthquake ground motions can be described in many different ways in terms of ground displacement, velocity, or acceleration. For the purposes of this study, we use peak acceleration (PGA) which is a commonly-used measure of ground accelerations. PGA is expressed as a percentage of the acceleration of gravity, g.

The ground motions observed at a site under consideration which arise from any given earthquake depend on several variables, including: the magnitude of the earthquake, the distance between the earthquake and the site under consideration, the attenuation relationship which accounts for the diminution of ground motion with distance from the epicenter, and the site characteristics which may amplify or deamplify ground motions.
Seismic hazard calculations for Portland were made using the attenuation relationships used by Geomatrix[1,2] (for Cornforth Consultants) for crustal earthquakes and those proposed by Crouse[3] subduction zone earthquakes (interplate and deep intraplate).

The ground motions observed at any particular site depend not only on the characteristics of the earthquake (magnitude, location) and on the attenuation relationship, but also on the characteristics of the site. Whether the site is rock, firm soil or soft soil profoundly affects earthquake ground motions. Thus, consideration of both seismic "hazard" and seismic "risk" must consider site characteristics. Typical relationships between PGA levels on rock, firm soil and soft soil are shown in Figure 1.4. Firm soils produce slightly higher PGA levels than rock sites at PGAs below about 15% of g and lower levels than rock sites at PGAs above about 15% of g. Soft soils produce higher PGA levels than rock sites at PGAs below about 40% of g and lower PGA levels than rock sites at PGAs above about 40% g.

The extent of damage to the built environment from earthquake ground motions depends not only on PGA but also on the spectral content of ground motions (i.e., the period or frequency). The period or frequency of ground motion is a measure of how rapidly or slowly the ground motions rock the earth. Short period (high frequency) ground motions are rapid, jerky motions. Long period (low frequency) ground motions are smoother, swaying motions. The spectral content of ground motion varies substantially depending on the earthquake source and distance. In general, larger earthquakes have more energy at longer periods. Nearby small crustal earthquakes produce more short period ground motions.

Building damages depend on the relationship between the vibration period of a building, which depends on building height and stiffness, and the period of earthquake ground motions. Thus crustal earthquakes, with more short period ground motions tend to exacerbate damage to short-period (low-rise) buildings Conversely, large subduction zone earthquakes produce ground motions with more long period ground motions which may exacerbate damage to taller buildings with longer building periods.

Site conditions also strongly affect the spectral content of ground motions. Softer sites (firm soil or soft soil) have stronger ground motions at longer periods (lower frequencies), compared to rock sites. These differences are illustrated in the typical response spectra shown in Figure 1.5. In addition, the period of maximum spectral acceleration is shifted to longer periods (lower frequencies) on firm soil and soft soil sites, compared to rock sites.

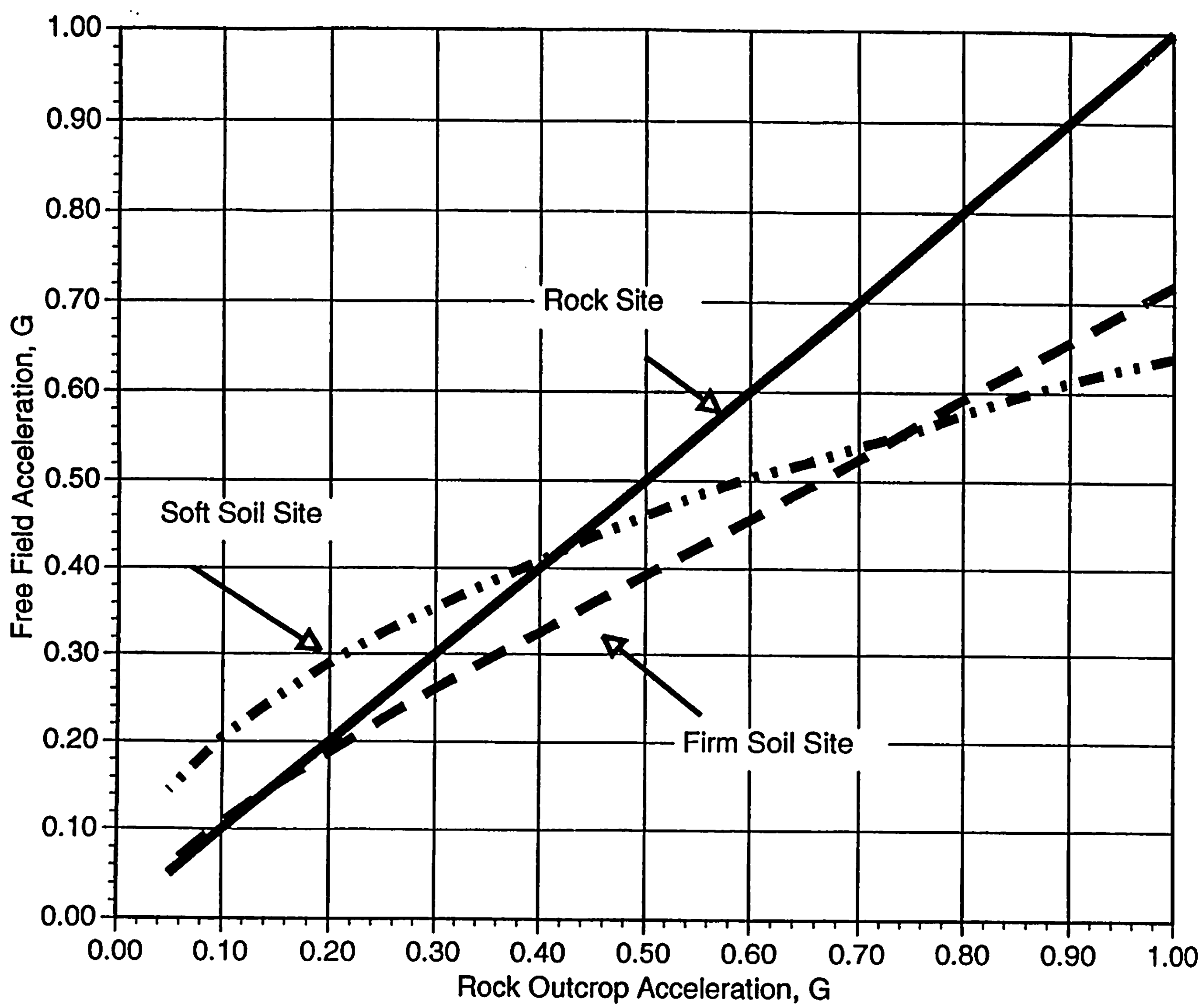

Figure 1.4
Rock - Firm - Soft Soil Acceleration Relationship

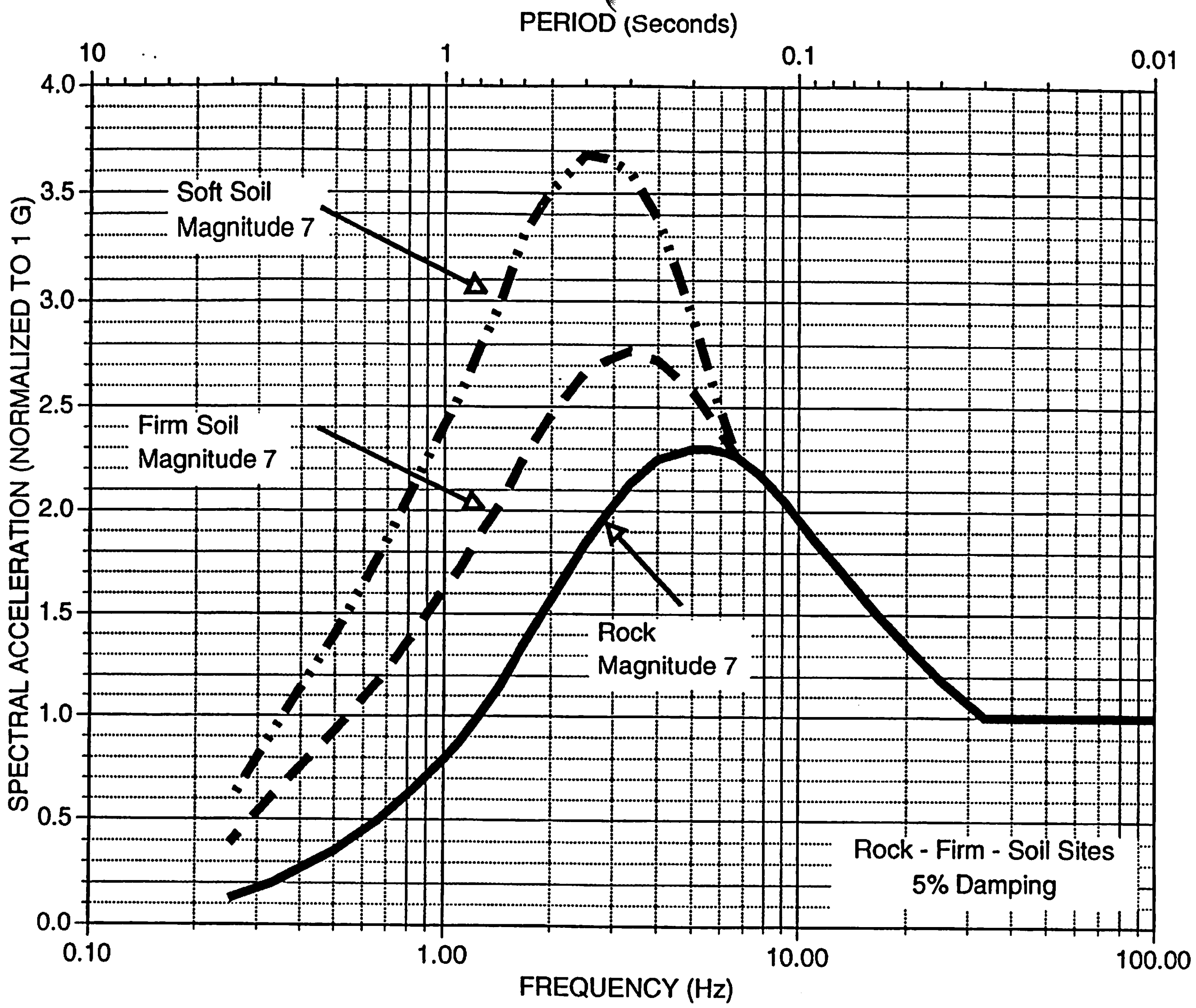

Figure 1.5
Free Field Response Spectra - Soil Effects

At lower frequencies such as 1.0 Hz or 0.5 hz (ground motion periods of 1 second and 2 seconds, respectively), the spectral accelerations on firm soil or soft soils are much higher than those on rock sites. These spectral effects, in combination with PGA effects, result in markedly different building damage patterns on rock, firm soil, and soft soil sites (see Technical Appendix 2).

The impact of earthquakes on buildings depends not only on the level of ground motion (PGA) and on spectral content, but also on the duration of ground motion. Longer duration shaking will subject buildings to more cycles of deformation and thus produce greater damage than will the same PGA level of shaking for shorter periods of time. Larger magnitude earthquakes produce much longer durations of strong shaking than do smaller earthquakes. On rock sites, small earthquakes (magnitudes <6) may produce only a few seconds of strong ground motion, whereas large earthquakes (magnitudes >7) may produce 20 or more seconds of strong ground motion. Furthermore, duration of shaking depends on site characteristics. The duration of shaking on soil sites will generally be 30% or more greater than the durations experienced on rock sites.

Because of these duration effects, a large subduction zone earthquake which results in 0.25 g on a rock site in Portland will result in more damage than a smaller crustal earthquake which also produces a PGA of 0.25 g on the same site. We include the effects of duration in considering the probabilities of damaging earthquakes in Portland (Section 1.4).

1.3 Earthquake Ground Motions: Deterministic Results for Five Earthquakes Affecting Portland

Deterministic calculations of ground motions predict the expected levels of ground motion for an occurrence of a specific earthquake. Deterministic calculations of ground motion may be for a single site or show the expected patterns of ground motion over an entire region. In either case, deterministic calculations only consider ground motions from specific earthquakes and do not consider the probability of such earthquakes.

The five earthquake sources most significant for Portland are the Cascadia subduction zone interplate earthquakes, the deep intraplate earthquakes, and three crustal faults near Portland (the Portland Hills, Lackamas Creek and Grand Butte faults). The maximum credible earthquake magnitudes for these five sources, the location of the source zone, and the closest distance to the interchange of I-5 and I-84 are summarized in Table 1.1. A map showing the locations of the three nearby crustal faults is shown as Figure 1.6.

Table 1.1
Maximum Credible Earthquakes for Five Earthquake Sources

Earthquake Source	Magnitude	Location	Closest Distance to I-5 / I-84
Portland Hills	6.9	Adjacent to Downtown	3 km
Lackamas Creek	6.5	N.E. of Downtown	20 km
Grant Butte	6.25	S.E. of Downtown	11 km
Intraplate	7.5	Beneath Downtown	70 km
Interplate	8.5	Under Pacific Ocean	119 km

Table 1.2
Ground Motions at I-5 and I-84 Interchange

Earthquake	Magnitude	Rock PGA (g) Median	Rock PGA (g) 84th	Soil PGA (g) Median	Soil PGA (g) 84th	Soft Soil PGA (g) Median	Soft Soil PGA (g) 84th
Portland Hills	6.9	0.61	0.93	0.46	0.68	0.51	0.63
Lackamas Creek	6.5	0.17	0.27	0.13	0.24	0.26	0.33
Grant Butte	6.25	4.2	0.41	0.22	0.32	0.31	0.40
Intraplate	7.5	.024	0.52	.022	0.40	0.32	0.47
Interplate	8.5	.019	0.37	0.18	0.30	0.29	0.39

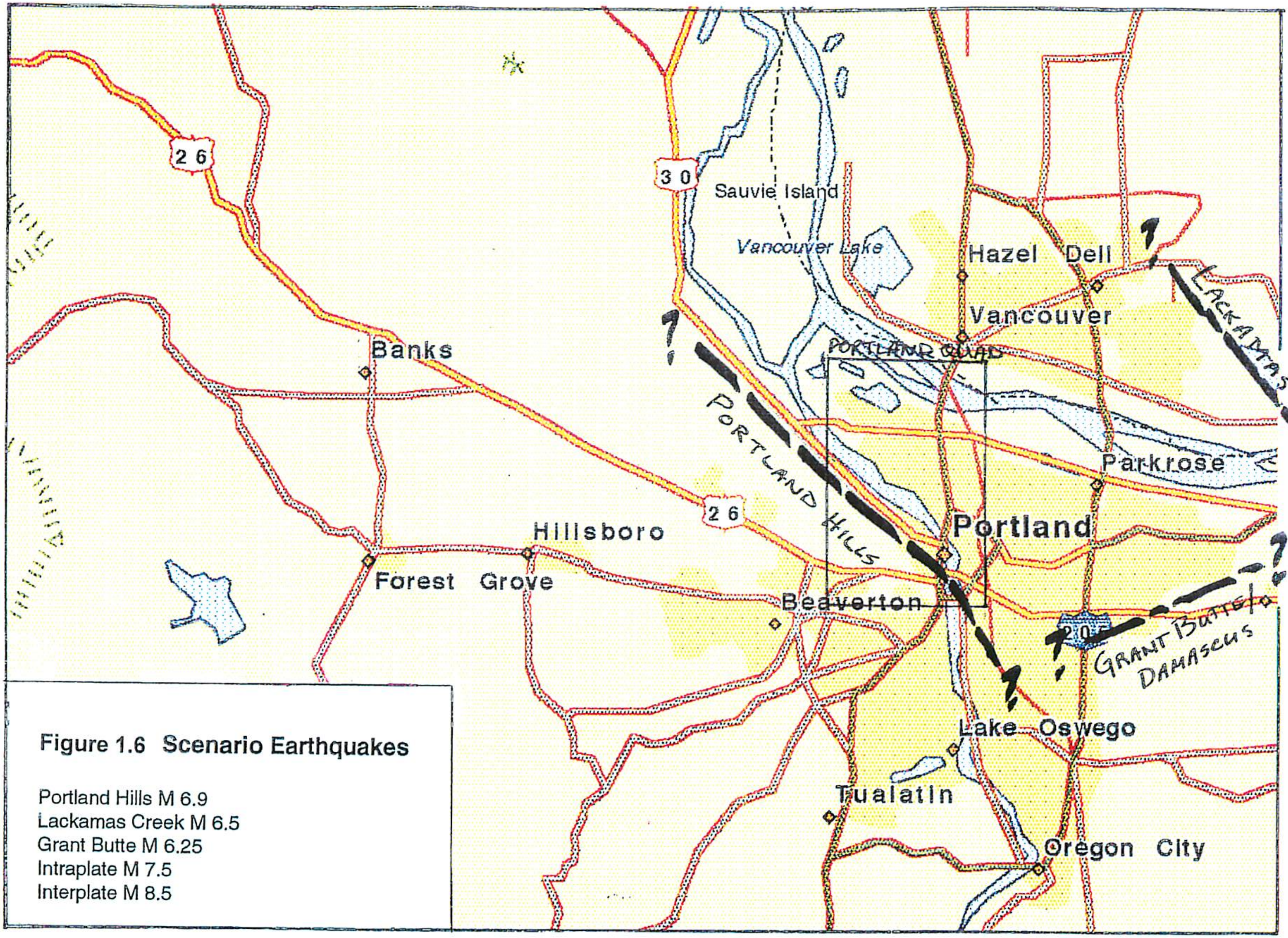

Figure 1.6 Scenario Earthquakes

Portland Hills M 6.9
Lackamas Creek M 6.5
Grant Butte M 6.25
Intraplate M 7.5
Interplate M 8.5

Table 1.2 shows the expected ground motions at the I-5 and I-84 interchange from these five earthquakes for three types of sites considered within Portland: rock, firm soil, and soft soil. The response spectra assumed for these model sites are as shown previously in Figure 1.5. The "median" values of horizontal peak ground acceleration (PGA, in % of g, the acceleration of gravity) represent the best guess or typical level of ground motion expected. The 84th percentile PGA values are one standard deviation above the median value; these values reflect uncertainties in attenuation relationships and the inherent randomness (variability) of earthquake mechanisms which may result in ground motions higher or lower than typical at any given site in any given earthquake. The 84th percentile (probability of non-exceedance) means that the probability that the ground motion exceeds these values in any one earthquake is about 16%.

PGAs expected in Portland (median values) for the five earthquakes are shown in Figures 1.7 through 1.11. The site characterizations as rock, firm soil or soft soil are based on the generalized geologic map of Portland (Figure 1.12).

For the three crustal earthquakes, the geographic pattern of PGAs depends on the location of the fault (PGAs are highest near the fault) and on site characteristics. Thus, for the Portland Hills earthquake, ground motions are strongest in the southwest portion of Portland. For the Lackamas Creek earthquake, ground motions are strongest in the northeast portion of Portland. For the Grand Butte earthquake, ground motions are strongest in the southeast portion of Portland.

For the Cascadia subduction zone (interplate) earthquake and the deep intraplate earthquake, the source zones are quite distant from Portland and thus the variation in ground motions because of differences in distance to the fault is minor. For these earthquakes, the variation in expected ground motions is due almost entirely to variations in site characteristics. Thus, the areas of high PGAs correspond closely to the areas of "soft soil" shown on the geologic map (Figure 1.12).

The PGA patterns shown in Figures 1.7 through 1.11 dramatically illustrate the importance of site conditions in determining seismic risk to the existing building inventory in Portland. The PGA levels expected depend not only on the magnitude and location of the earthquakes but also on the site characteristics. These important differences between rock, firm soil, and soft soil sites in Portland are further amplified by the effects of duration and spectral content of ground motions. The building fragility curves, discussed in Technical Appendix 2, reflect all of these important differences between rock, firm soil and soft soil sites.

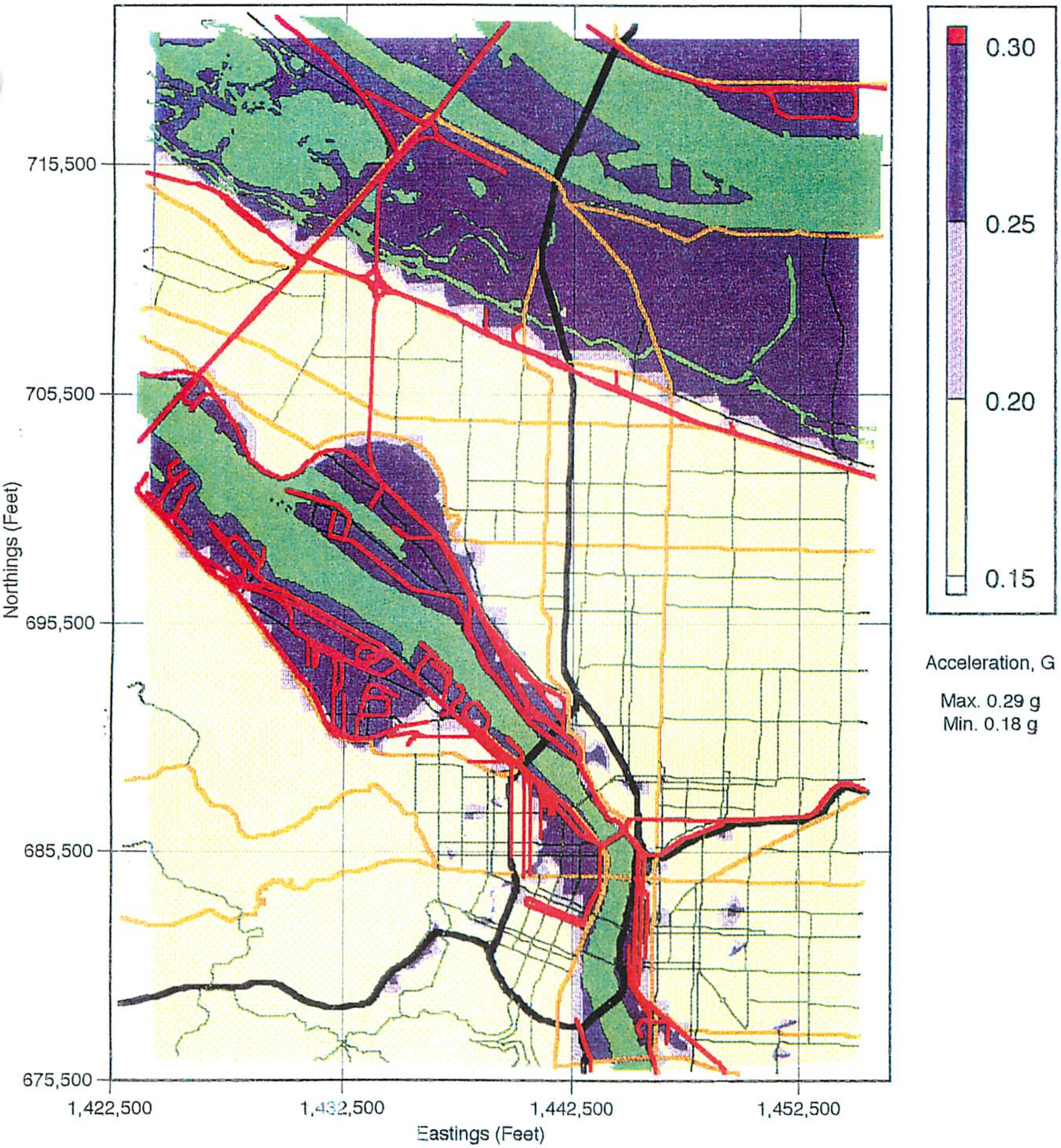

Figure 1.7 PGA Contour Map
Cascadia Interplate Magnitude 8.5

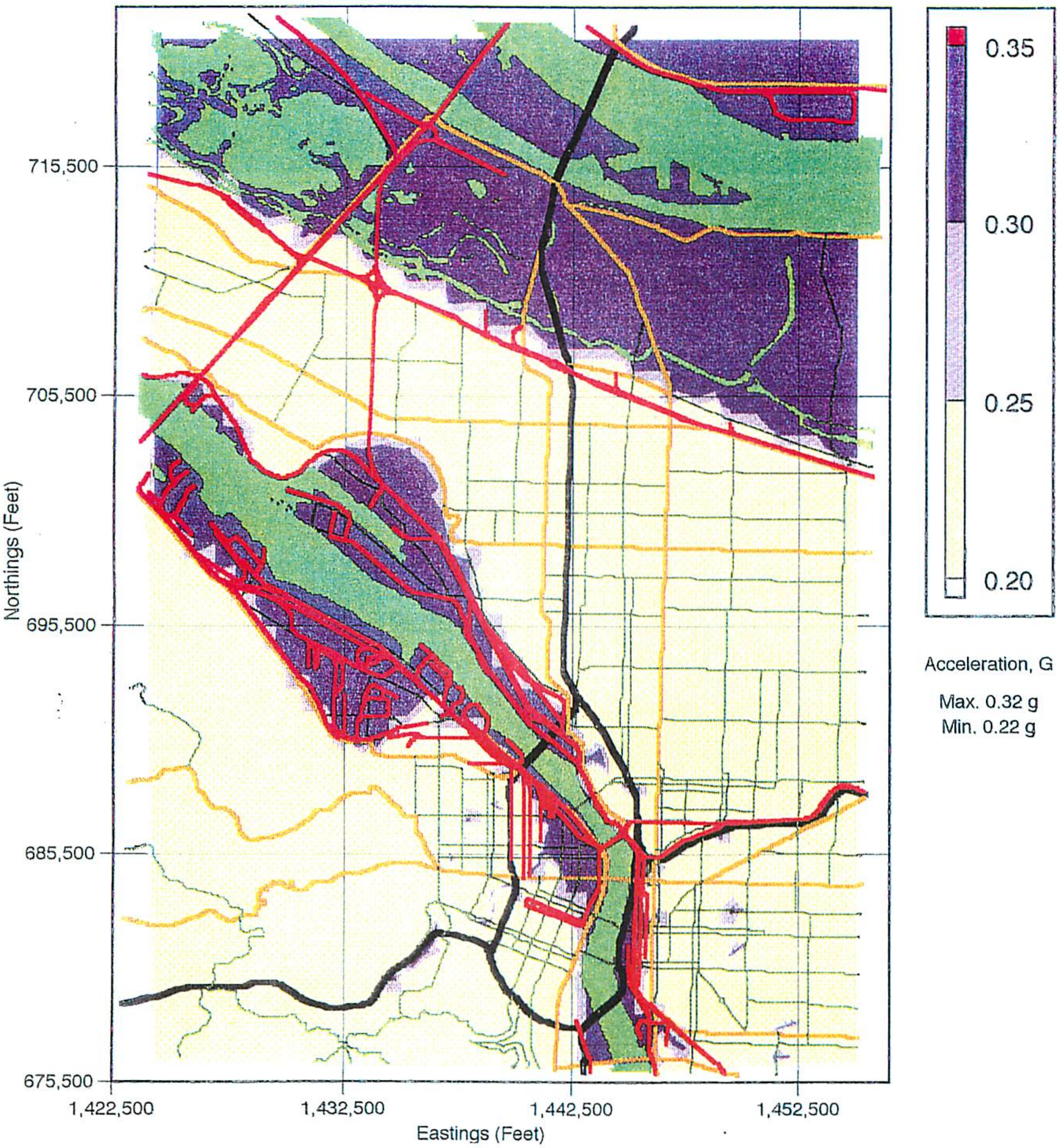

Figure 1.8 PGA Contour Map
Intraplate Magnitude 7.5

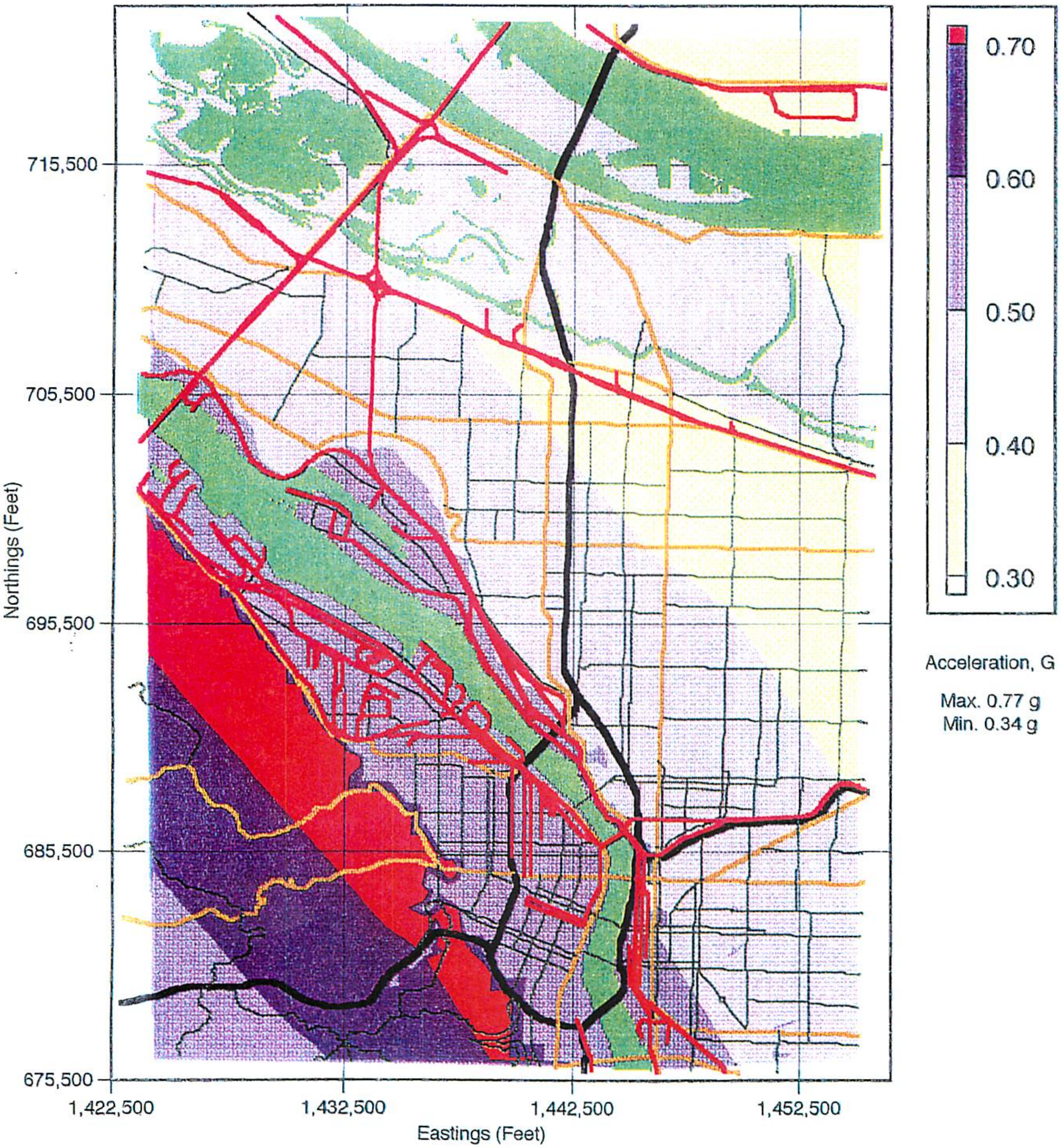

Figure 1.9 PGA Contour Map
Portland Hills Magnitude 6.9

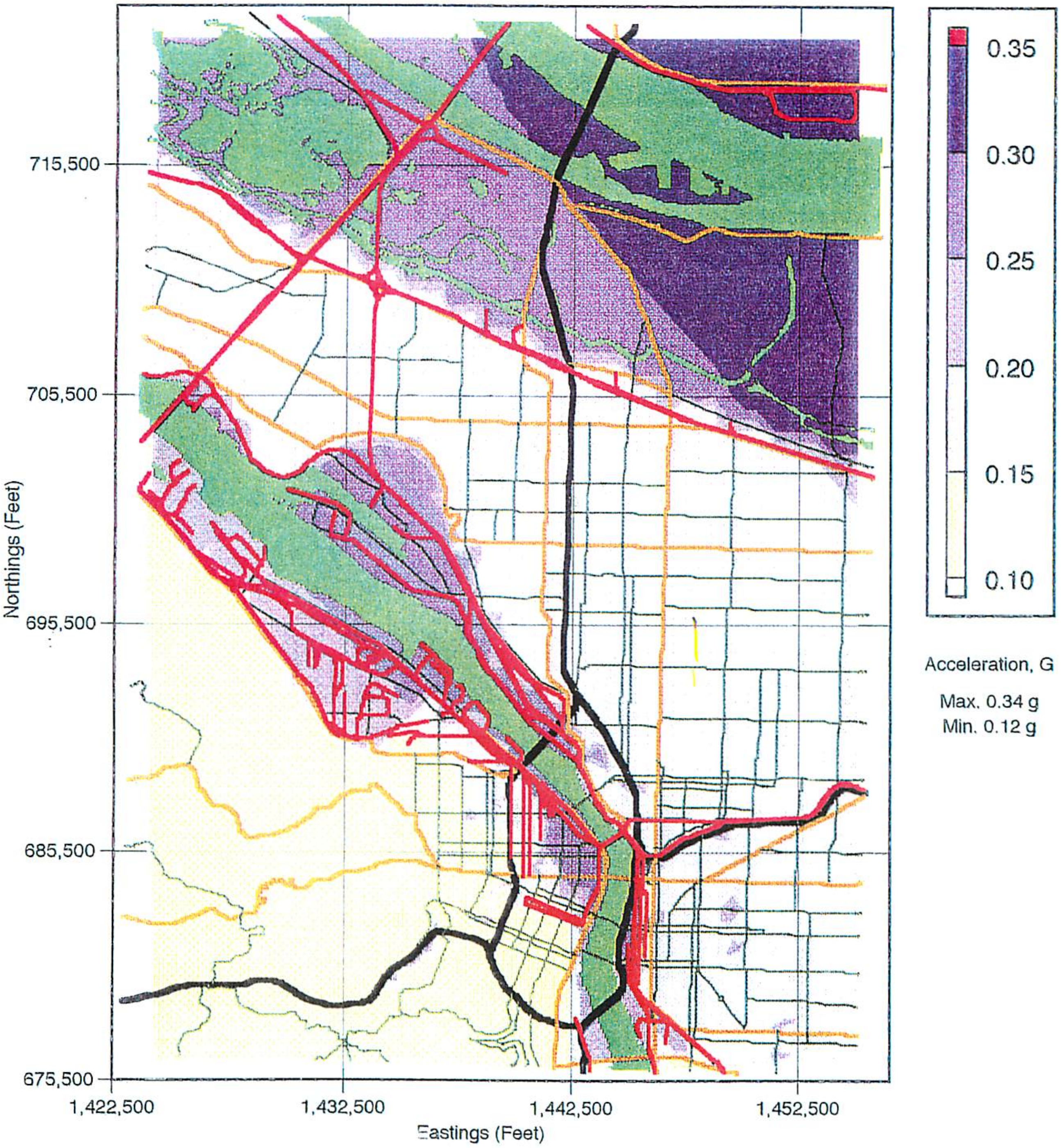

Figure 1.10 PGA Contour Map
Lackamas Creek Magnitude 6.5

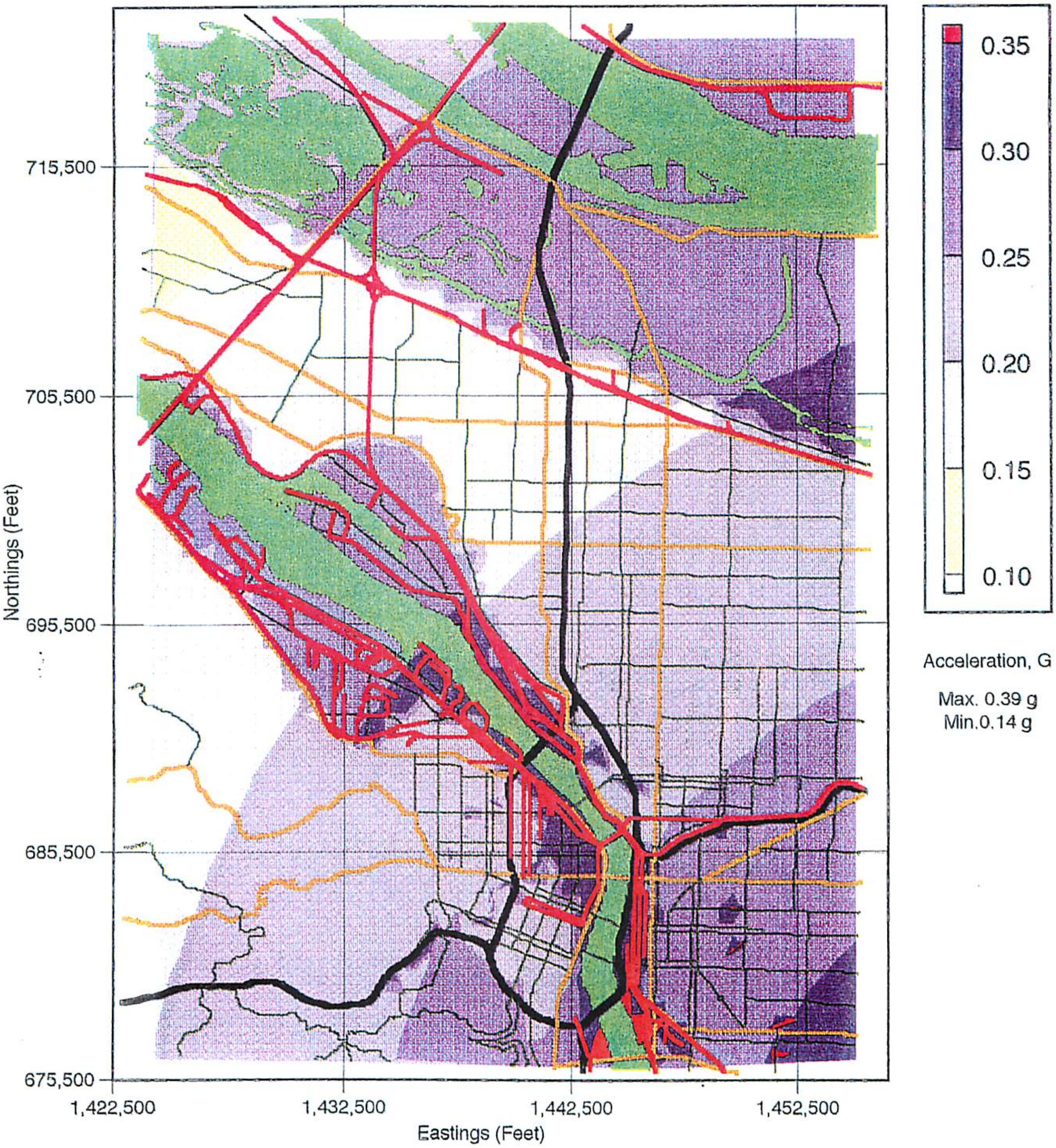

Figure 1.11 PGA Contour Map
Grant Butte Magnitude 6.25

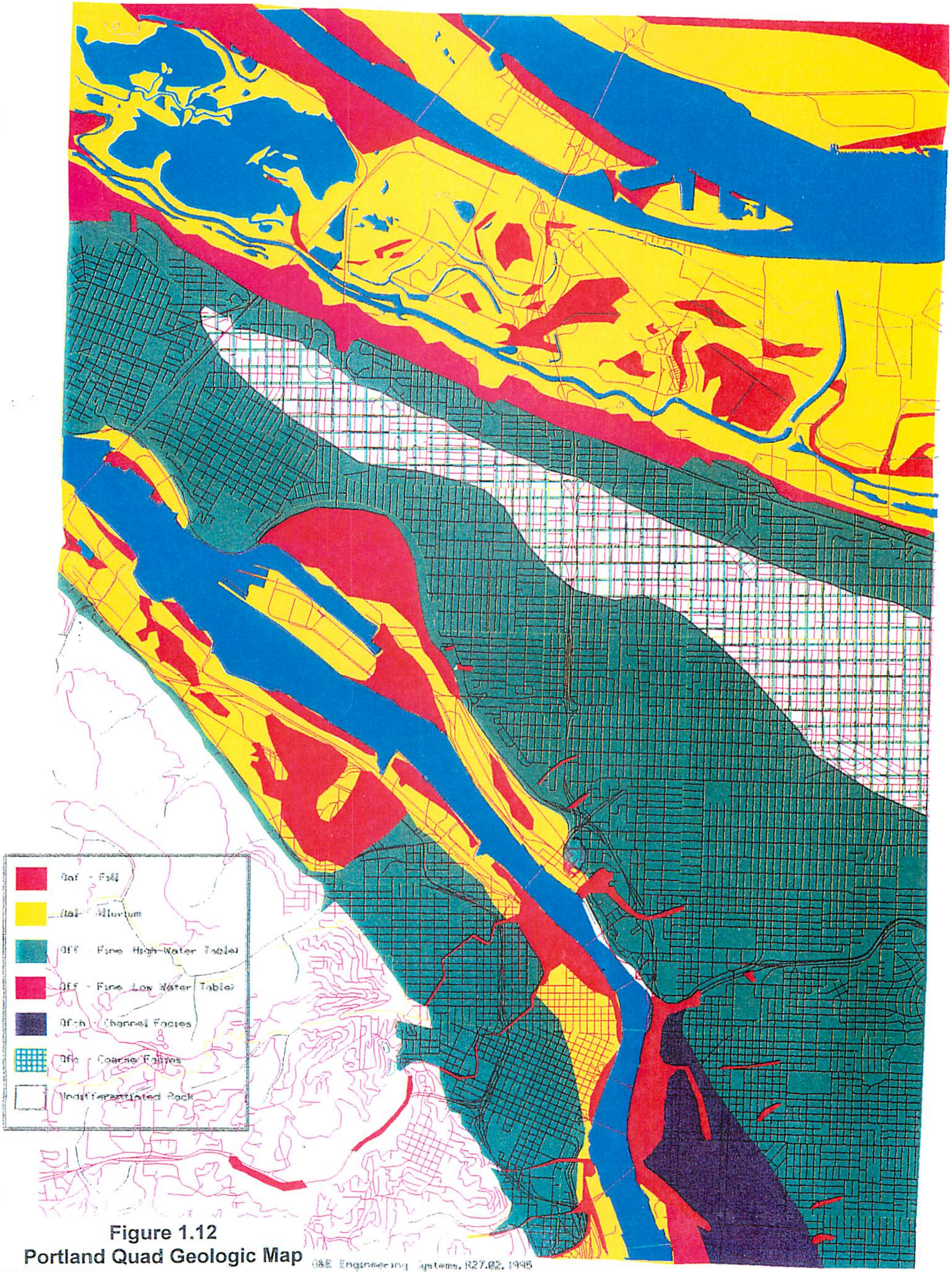

Figure 1.12
Portland Quad Geologic Map

G&E Engineering Systems, R27.02, 1995

1.4 Earthquake Ground Motions: Probabilistic

1.4.1 Assumptions

Evaluation of seismic risk for public policy decision-making requires not only an understanding of the deterministic ground motions expected from particular faults but also a probabilistic analysis. Whether a given earthquake is expected to recur every 50 years, every 500 years, every 5,000 years or every 50,000 years profoundly affects how both the public and private sectors may choose to address the seismic risk.

The seismic hazard curve shown in Figure 1.13 shows the annual exceedance probabilities for ground motions **on rock sites** arising from four types of earthquakes: the Cascadia subduction zone interplate earthquakes, the deep intraplate earthquakes, crustal earthquakes on known faults (including the three discussed previously) and, crustal earthquakes from "zones." Figure 1.13 also shows the cumulative (total) hazard curve summing all of these possible earthquakes.

Crustal "zones" are included to reflect the fact that earthquakes frequently occur, in any seismically active area, from faults previously unrecognized. Thus, the total expected crustal seismic activity affecting Portland is adjusted to reflect the estimated activity from "zones" as well as from currently mapped faults.

The seismic hazard curve depends on assumptions about the recurrence intervals or frequencies of earthquakes within the various source zones. In compiling this curve we have used the recurrence intervals estimated by Geomatrix.[1,2] The hazard curve depends not only on the estimated magnitudes and recurrence intervals of earthquakes on the sources, but also on the attenuation relationship which governs how ground motions diminish with increasing distance from the fault. In compiling this hazard curve, we have used the attenuation relationships proposed by Crouse[3] specifically for Cascadia subduction zone interplate and deep intraplate earthquakes. The Crouse attenuation relationships predict less attenuation and thus somewhat higher ground motions in Portland than do other attenuation relationships.

These seismic hazard curves are for rock sites. Similar curves for firm soil and soft soil sites may be obtained from Figure 1.13 and the ratios of PGAs shown in Figure 1.4.

For similar sites (i.e., rock, firm soil, or soft soil), the seismic hazard for Portland is relatively homogeneous - that is, the seismic hazard is quite uniform across the City. This homogeneity of seismic hazard arises because ground motions from distant subduction zone earthquakes vary only slightly across Portland and the cumulative ground motions expected from crustal faults and zones approximately average out across Portland. In more detail, seismic hazard is slightly higher for locations near one of the mapped crustal faults, but this difference is small compared to the overall seismic hazard for Portland. For the purposes of this study, we assume that the cumulative seismic hazard curve is uniform throughout Portland, except for site effects.

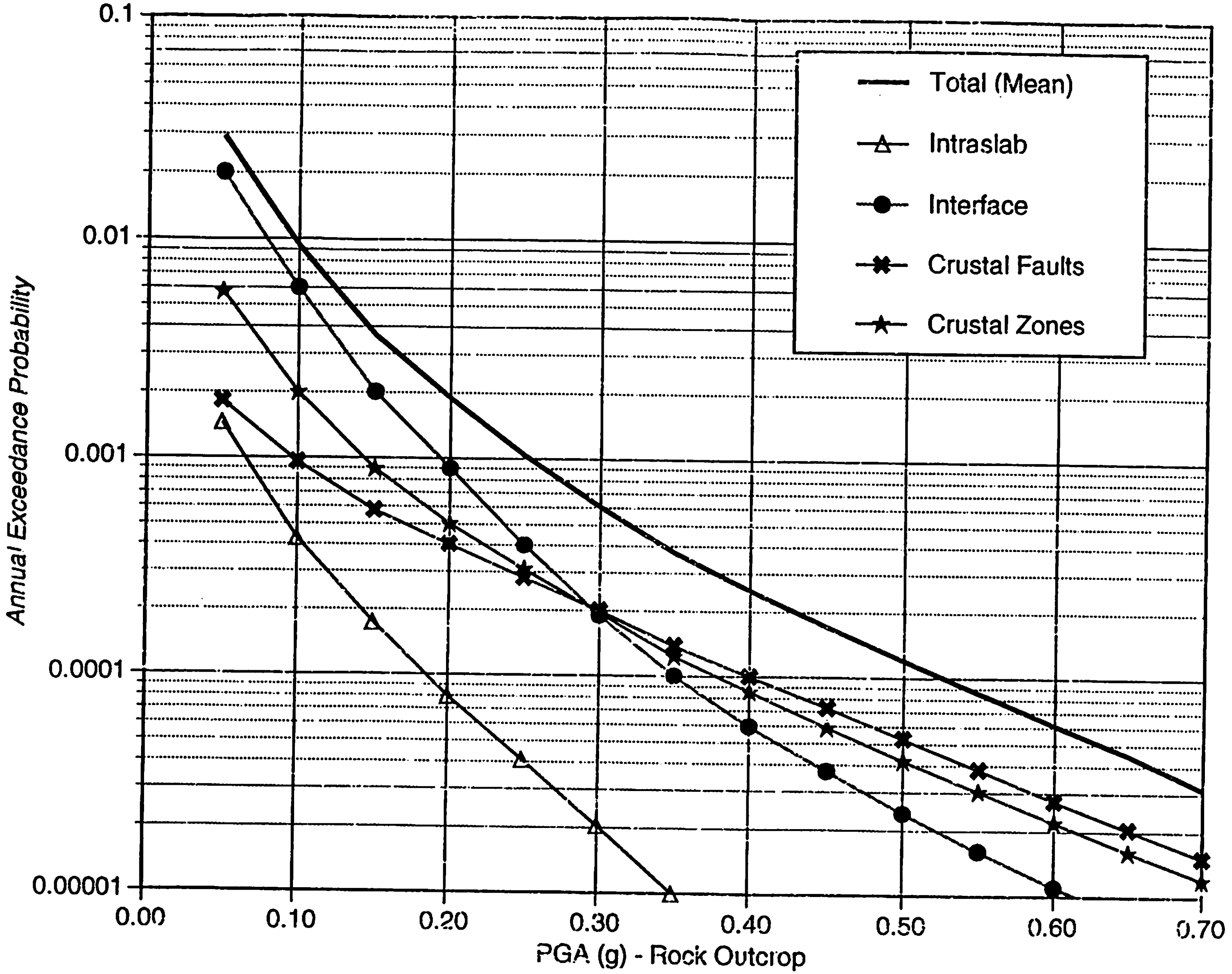

Figure 1.13 **Portland City Area - Probabilistic Hazards**

R27.02 Rev. B

1.4.2 Two Types of Earthquakes: Subduction Zone and Crustal

For Portland, subduction zone and crustal earthquakes may have substantially different impacts on buildings because of the differences in their duration and spectral (frequency or period) content of their ground motions. Therefore, the probabilities of damaging ground motions are evaluated separately for these two major types of earthquakes. For subduction zone earthquakes, the annual exceedance probabilities are obtained from the seismic hazard curve (Figure 1.13) as the sum of the exceedance probabilities for the interplate and intraplate earthquakes. For crustal earthquakes, the annual exceedance probabilities are obtained from the seismic hazard curve as the sum of the exceedance probabilities for the crustal zone and crustal fault earthquakes.

Estimated building damages as a function of ground motions are based on duration-adjusted PGAs, as discussed in Technical Appendix 2. PGA values for subduction zone and crustal earthquakes are adjusted separately for duration. Then, the exceedance probabilities for a given duration-adjusted PGA level are combined. This duration-adjustment calculation was done modified from an empirical relationship developed by John Eidinger of G&E Engineering Systems, Inc. Duration adjusted PGA (PGA^{dur}) is the product of PGA and an adjustment factor, a, so that $\mathbf{PGA^{dur} = PGA * a}$, where $a = 1.0/(1.9 - 0.35*\ln(time))$, ln is the natural log, and time is the length of strong shaking. For typical earthquakes, shaking time is estimated as follows:

Table 1.3
Earthquake Shaking Time vs. Magnitude

	Shaking Time (Seconds)	
Magnitude	**Rock Site**	**Soil Site**
$M \leq 6$	6	8
$6 < M \leq 6.5$	9	12
$6.5 < M \leq 6.75$	12	16
$6.75 < M \leq 7.0$	15	20
$7.0 < M \leq 7.5$	18	24
$7.5 < M$	21	28

The following table shows values of the duration adjustment factor, a, as a function of shaking time in seconds.

Table 1.4
Duration Adjustment Factor for PGA

Time (Seconds)	Duration Adjustment Factor
6	0.786
8	0.853
9	0.884
12	0.971
15	1.050
16	1.076
18	1.126
20	1.174
21	1.198
24	1.270
28	1.363

For rock sites, the combined annual exceedance probabilities (and corresponding recurrence intervals) for duration-adjusted PGAs from subduction zone and crustal earthquakes are shown in Table 1.5; these estimates used a duration adjustment factor of 0.971 for crustal earthquakes and 1.198 for subduction zone earthquakes. These estimates are derived from the hazard curves (Figure 1.13), and the duration adjustment factors discussed above. The duration factor of 1.198 for subduction zone earthquakes has a substantial effect on estimated building damages. For example, if a given subduction zone earthquake would result in ground motions of 0.25 g, then the duration adjusted ground motion level is about 0.3 g. This 20% increase in effective PGA level has much more than a 20% increase in building damages, because building damages increase sharply with increasing PGA levels (see Technical Appendix 2).

Table 1.5
Portland Seismic Hazard: Rock Sites

Duration Adjusted PGA (%)	Annual Exceedance Probability	Recurrence Interval (years)	Recurrence Interval, Rounded (years)
4	0.029019	34	34
8	0.010701	93	93
16	0.004376	229	230
32	0.000651	1,536	1,500
55	0.0000982	10,183	10,000
80	0.00001941	51,520	50,000
100	0.00000433	230,947	230,000

Table 1.5 shows our best estimate of the **duration-adjusted** seismic hazard curve for rock sites in Portland. The PGA values shown in Table 1.5 above correspond to the steps used in the benefit-cost program (see Technical Appendix 5).

The **duration-adjusted** seismic hazard curve shown in Table 1.5 is conceptually different from the conventional seismic hazard curve, as shown in Figure 1.13. This duration-adjusted hazard curve is provided as a convenience to the reader in assessing the relative risks to certain types of buildings on rock, firm soil, and soft soil sites in Portland. Because we have combined part of the building's response characteristics to duration with the ground shaking PGA level, the resulting duration-adjusted hazard curve should be used **only** within the context of this report. Using the duration-adjusted hazard curve for very brittle structures, elastic structures, and many classes of equipment would be incorrect.

There is a significant uncertainty in all of these recurrence interval estimates, especially for the very long recurrence intervals shown at very high PGA levels. The estimates for the very high PGA levels are formal results from the hazard curve; these very long recurrence intervals should not be interpreted literally. Rather, such intervals indicate that it is possible, albeit very rarely, that such high PGAs may occur. Very high PGAs would be experienced in Portland very near moderate size earthquakes. Because the seismology of the Portland area is not completely understood, we assume that there is a small probability of such events from unknown faults which could be located anywhere in the Portland area (i.e., the crustal earthquake "zones" discussed on page A1-18). However, because of the very low probabilities, these improbable events have virtually no impact on benefit-cost analyses.

1.3.4 Site Characteristics: Rock, Firm Soil and Soft Soil Sites

As discussed earlier in this appendix, site characteristics profoundly affect seismic hazards. Softer sites (firm soil and soft soil) may amplify or deamplify ground motions experienced on rock sites. Softer sites will also experience longer durations of shaking than will rock sites. Softer sites will have higher ground motions at lower frequencies (longer periods) and thus experience somewhat different damage patterns than rock sites.

Because of these important differences, the probabilities of damaging ground motions and building damage estimates (fragility curves) are substantially different on rock, firm soil and soft soil sites (see Technical Appendix 2). The annual exceedance probabilities for duration adjusted ground motions also differ for rock, firm soil and soft soil sites. In a manner similar to that described above for rock sites, the PGA values for subduction zone and crustal earthquakes are adjusted separately for duration. Then, the exceedance probabilities for a given duration-adjusted PGA level are combined and separate seismic risk tables are calculated for rock, firm soil, and soft soil sites in Portland.

Annual exceedance probabilities and recurrence intervals for rock sites were given in Table 1.5. For firm soil and soft soil sites, the combined annual exceedance probabilities (and corresponding recurrence intervals) for duration-adjusted PGAs from subduction zone and crustal earthquakes are given in Tables 1.6 and 1.7. These estimates used duration adjustment factors of 1.076 for crustal earthquakes and 1.363 for subduction zone earthquakes. However, duration adjustment factors of less than one were used for low PGA values because the predominant source of such low levels of ground motion is small crustal earthquakes which have very short durations of shaking and thus little potential for causing damages.

Table 1.6
Portland Seismic Hazard: Firm Soil Sites

Duration Adjusted PGA (%)	Annual Exceedance Probability	Recurrence Interval (years)	Recurrence Interval, Rounded (years)
4	0.0435285	23	23
8	0.014355	70	70
16	0.0065433	153	150
32	0.000607	1,647	1,600
55	0.0001211	8,258	8,000
80	0.00000476	210,084	210,000
100	0.0000005481	1,824,485	1,800,000

Table 1.6 shows our best estimate of the **duration-adjusted** seismic hazard curve for firm soil sites in Portland. The PGA values shown in Table 1.6 above correspond to the steps used in the benefit-cost program (see Technical Appendix 5).

The **duration-adjusted** seismic hazard curve shown in Table 1.6 is conceptually different from the conventional seismic hazard curve, as shown in Figure 1.13. This duration-adjusted hazard curve is provided as a convenience to the reader in assessing the relative risks to certain types of buildings on rock, firm soil, and soft soil sites in Portland. Because we have combined part of the building's response characteristics to duration with the ground shaking PGA level, the resulting duration-adjusted hazard curve should be used **only** within the context of this report. Using the duration-adjusted hazard curve for very brittle structures, elastic structures, and many classes of equipment would be incorrect.

There is a significant uncertainty in all of these recurrence interval estimates, especially for the very long recurrence intervals shown at very high PGA levels. The estimates for the very high PGA levels are formal results from the hazard curve; these very long recurrence intervals should not be interpreted literally. Rather, such intervals indicate that it is possible, albeit very rarely, that such high PGAs may occur. Very high PGAs would be experienced in Portland very near moderate size earthquakes. Because the seismology of the Portland area is not completely understood, we assume that there is a small probability of such events from unknown faults which could be located anywhere in the Portland area (i.e., the crustal earthquake "zones" discussed on page A1-18). However, because of the very low probabilities, these improbable events have virtually no impact on benefit-cost analyses.

Table 1.7
Portland Seismic Risk: Soft Soil Sites

Duration Adjusted PGA (%)	Annual Exceedance Probability	Recurrence Interval (years)	Recurrence Interval, Rounded (years)
4	0.087057	11	11
8	0.03588875	28	28
16	0.019629	51	52
32	0.003639	275	275
55	0.0001139	8,780	9,000
80	0.000000688	1,453,488	1,500,000
100	n/a	n/a	n/a

The "n/a" for PGAs of 100 % g indicate that such PGA levels are not expected on soft soil sites because these sites deamplify ground motions at high PGA levels.

Table 1.7 shows our best estimate of the **duration-adjusted** seismic hazard curve for soft soil sites in Portland. The PGA values shown in Table 1.7 above correspond to the steps used in the benefit-cost program (see Technical Appendix 5).

The **duration-adjusted** seismic hazard curve shown in Table 1.7 is conceptually different from the conventional seismic hazard curve, as shown in Figure 1.13. This duration-adjusted hazard curve is provided as a convenience to the reader in assessing the relative risks to certain types of buildings on rock, firm soil, and soft soil sites in Portland. Because we have combined part of the building's response characteristics to duration with the ground shaking PGA level, the resulting duration-adjusted hazard curve should be used **only** within the context of this report. Using the duration-adjusted hazard curve for very brittle structures, elastic structures, and many classes of equipment would be incorrect.

There is a significant uncertainty in all of these recurrence interval estimates, especially for the very long recurrence intervals shown at very high PGA levels. The estimates for the very high PGA levels are formal results from the hazard curve; these very long recurrence intervals should not be interpreted literally. Rather, such intervals indicate that it is possible, albeit very rarely, that such high PGAs may occur. Very high PGAs would be experienced in Portland very near moderate sized earthquakes. Because, the seismology of the Portland area is not completely understood, we assume that there is a small probability of such events from unknown faults which could be located anywhere in the Portland area (i.e., the crustal earthquake "zones" discussed on page A1-18). However, because of the very low probabilities, these improbable events have virtually no impact on benefit-cost analyses.

To compare directly the Seismic Hazard in Portland for rock, firm soil and soft soil sites, we summarize the rounded recurrence intervals for these three site characteristics in Table 1.8.

At low to moderate duration-adjusted PGAs, the recurrence intervals for a given PGA level are significantly lower for firm soil and lower again for soft soils, relative to rock sites. These shorter recurrence intervals (e.g., higher annual exceedance probabilities) arise because of two effects: amplification of PGAs on softer sites and greater duration on the soil sites. At higher PGA levels, the softer sites deamplify ground motions and the duration factor is overtaken by the deamplification. Thus, at very high PGA levels the recurrence intervals are shorter for rock sites (higher annual exceedance probabilities)

The shorter recurrence intervals on firm soil sites and especially on soft soil sites, compared to rock sites, reflect a considerably greater seismic hazard on these sites for the levels of ground motion most likely to cause major damages in Portland. At extremely high levels of ground shaking (55% g or higher), recurrence intervals are similar or shorter on rock sites than on the soil sites. However, earthquakes causing these levels of ground shaking are so rare (recurrence intervals of approximately 10,000 years or longer) than they contribute very little to seismic hazard in Portland.

These differences in recurrence intervals reflect part of the differences in seismic risk between these three types of sites. Further differences arise because of differences in the spectral response curve (Figure 1.5); the softer sites experience stronger ground motions at the lower frequencies which are, in many cases, more damaging to buildings. Thus, there are also differences in the fragility curves (building damage vs. duration-adjusted PGA) for buildings on the three types of sites. These very important differences, which generally increase damages on soil sites compared to rock sites, are discussed in Technical Appendix 2.

Table 1.8
Portland Seismic Hazard: Rock, Firm Soil and Soft Soil Sites

Duration Adjusted PGA (%)	Recurrence Interval (years)		
	ROCK	FIRM SOIL	SOFT SOIL
4	34	23	11
8	93	70	28
16	230	150	51
32	1,500	1,600	275
55	10,000	8,000	9,000
80	50,000	210,000	1,500,000
100	230,000	1,800,000	n/a

The "n/a" for PGAs of 100 % g indicate that such PGA levels are not expected on soft soil sites because these sites deamplify ground motions at high PGA levels.

Table 1.8 shows our best estimate of the **duration-adjusted** seismic hazard curve for rock, firm soil and soft soil sites in Portland. The PGA values shown in Table 1.8 above correspond to the steps used in the benefit-cost program (see Technical Appendix 5).

The **duration-adjusted** seismic hazard curve shown in Table 1.8 is conceptually different from the conventional seismic hazard curve, as shown in Figure 1.13. This duration-adjusted hazard curve is provided as a convenience to the reader in assessing the relative risks to certain types of buildings on rock, firm soil, and soft soil sites in Portland. Because we have combined part of the building's response characteristics to duration with the ground shaking PGA level, the resulting duration-adjusted hazard curve should be used **only** within the context of this report. Using the duration-adjusted hazard curve for very brittle structures, elastic structures, and many classes of equipment would be incorrect.

There is a significant uncertainty in all of these recurrence interval estimates, especially for the very long recurrence intervals shown at very high PGA levels. The estimates for the very high PGA levels are formal results from the hazard curve; these very long recurrence intervals should not be interpreted literally. Rather, such intervals indicate that it is possible, albeit very rarely, that such high PGAs may occur. Very high PGAs would be experienced in Portland very near moderate sized earthquakes. Because, the seismology of the Portland area is not completely understood, we assume that there is a small probability of such events from unknown faults which could be located anywhere in the Portland area (i.e., the crustal earthquake "zones" discussed on page A1-18). However, because of the very low probabilities, these improbable events have virtually no impact on benefit-cost analyses.

1.5 References

1. Cornforth Consultants, "Seismic Ground Response Evaluation, Portland Groundwater Pump Station," prepared for the Portland Water Bureau, Feb., 1993.

2. Cornforth Consultants, "Seismic Hazard Evaluation for Bull Run Dam Sites near Sandy, Oregon," technical report prepared for the City of Portland, Oregon, Hydroelectric Power Section, Bureau of Water Works, November, 1992.

3. Crouse, C.B., "Ground-Motion Attenuation Equations for Earthquakes on the Cascadia Subduction Zone," **Earthquake Spectra**, Vol 7, No. 2, May 1991.