Seismic Highway Bridge Design Using Spectra Specific to Washington State

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The Washington State Department of Transportation adopted recommendations for seismic response spectra to replace the AASHTO guidelines. The replacement spectra were based on input and soil amplification representative of the geologic conditions of the Pacific Northwest. A deep subduction zone earthquake was used as the source event rather than a shallow strike-slip earthquake typical of that used in the development of the AASHTO guidelines. Soil data from 123 boring logs from actual bridge sites in Washington State were processed, and nine soil groups representative of the soil conditions in the region were identified, based on similarities of standard penetration test data. Soil amplification spectra were derived for the nine soil groups. These were compared with spectra provided by current guidelines and similar works. They were also correlated with damage from previous earthquakes in the area.

The Pacific Northwest of the United States is acknowledged as a major seismically active region. Two recent events in this region (1949, M 7.1; 1965, M 6.5) resulted in numerous ground failures and considerable structural damage in the heavily populated Puget Sound basin. The recurrence interval of M 6 events in this region has been estimated to be between 5 and 10 years (*1,2*). The potential occurrence of a greater than M 8 earthquake has been suggested (*3*).

The Washington Department of Transportation (WSDOT) is currently updating seismic guidelines for highway bridges. Before 1989, WSDOT used AASHTO's 1983 seismic guidelines (*4*). These guidelines were developed for general use on the basis of research relying on data from California earthquakes. Source mechanisms, wave propagation paths, and site geology of Washington State earthquakes differ significantly from those of California earthquakes.

Seismic activity in Washington State is produced by subduction of the Juan de Fuca plate under the North American plate producing deep focus events (*3*). Overlying the thick base rock are sizable deposits of glacial material left during the multiple advances and retreats of the Cordilleran ice sheet. These deposits are often heavily overconsolidated with a mixture of grain sizes. On the contrary, California earthquakes generally result from lateral strike-slip of the Pacific plate and the North American plate. These earthquakes tend to have shallow foci ($\leq$ 20 km). The Quaternary deposits overlying the intact rock are often lacustrine, marine, or alluvial. These deposits tend to be thinner and less overconsolidated than the glacial deposits of Washington State. As a result, WSDOT commissioned research to develop seismic response spectra that more accurately represented ground motion resulting from a Washington State earthquake. Soil amplification spectra for nine characteristic soil profiles were derived using 123 boring logs from bridge sites throughout Washington State.

The base spectrum developed using available data on ground motion from Japanese subduction zone earthquakes similar to those occurring in Washington State is shown in Figure 1. These earthquakes generally have larger high-frequency components than do shallow-focus earthquakes. For comparison, the current AASHTO base (Soil Group I) is superimposed on Figure 1. Figures 2 through 4 show the response spectra normalized by input acceleration for the nine soil groups developed. The curves show the base spectrum multiplied by the soil amplification spectra for 0.1, 0.2, and 0.3 scaled input. These are the most likely values of the acceleration coefficient in Washington State. The curves should be multiplied by the corresponding acceleration coefficient to obtain the design spectra. Table 1 gives the nine soil groups that are considered to be representative of the soil types in Washington State. The soil groups were based on standard penetration test (SPT) data because of extensive use in site investigations. This table can be used to characterize any site in Washington State on the basis of this commonly used in situ test; a zonation map is not needed. The specifics on the development of these spectra are described elsewhere (*5,6*).

EVALUATION OF SPECTRA

The products of the base spectrum and the soil amplification spectra were compared with the appropriate AASHTO guideline curves and the spectra developed by Seed et al. (*7*). The products were also compared with the curves generated by predictive equations for subduction zone earthquakes and the response from the existing strong ground-motion records from

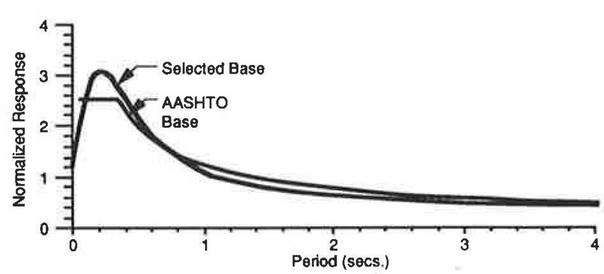

FIGURE 1 Selected base spectrum and AASHTO Soil Type I curve.

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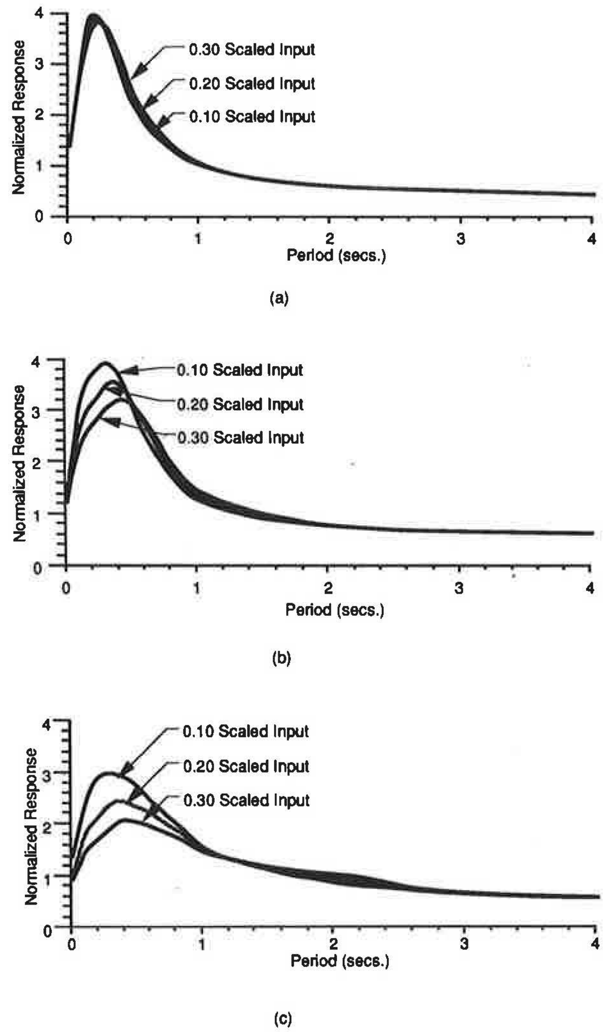

FIGURE 2 Base spectrum multiplied by soil amplification spectra for Groups 1, 2, and 3 (a, b, and c) soils for 0.1, 0.2, and 0.3 scaled input.

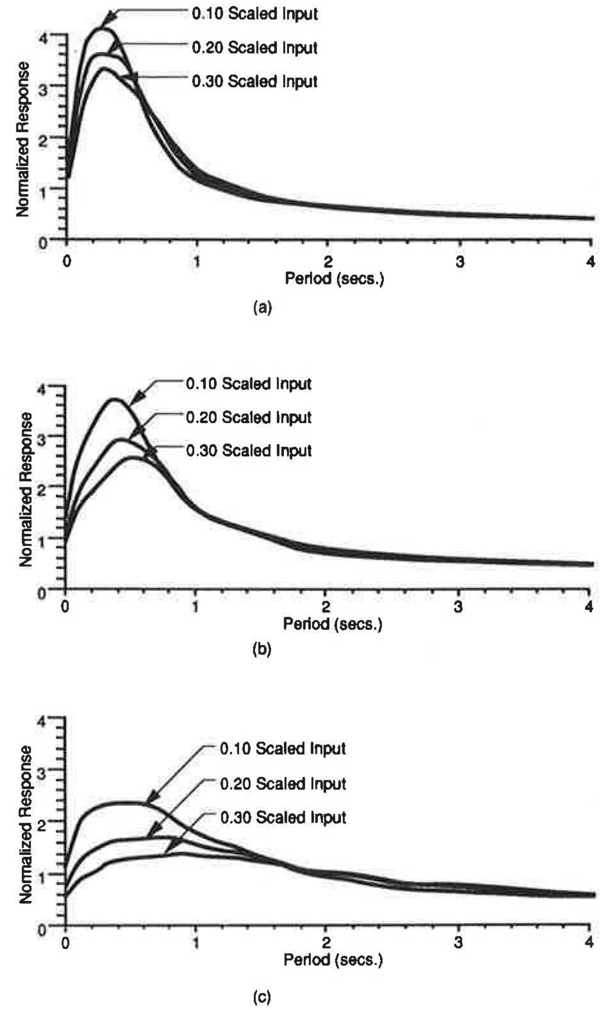

FIGURE 3 Base spectrum multiplied by soil amplification spectra for Groups 4, 5, and 6 (a, b, and c) soils for 0.1, 0.2, and 0.3 scaled input.

the Puget Sound area. Damage from the 1949 and 1965 earthquakes was investigated to determine the correlation between earthquake damage and site soils and to see whether the spectra developed would predict that damage.

A comparison of the spectra developed in this study with the spectra developed by Seed et al. (*7*) (Figure 5) demonstrates the general trends of the difference of subduction versus shallow earthquakes: larger high-frequency components and smaller long-period components with increasing depth or softness of the deposits, or both. These same trends can also be seen in the spectra developed by Hayashi et al. (*8*) for Japanese sites (see Figure 6). The Japanese earthquakes that their analysis was based on are subduction zone earthquakes, where larger high-frequency content can be expected. The higher frequencies can be seen in these spectra in the stiff soil category.

The AASHTO curves scaled by the soil factors for three soil conditions are similar to the spectra developed in this study in terms of strengths of records. In that respect, the developed spectra are consistent with the existing codes. The differences in spectral shapes are from two sources. There are differences in frequency content because deep-focus earthquakes have larger high-frequency content than do shallow-focus earthquakes. There are also differences because of the unique types of soils in Washington State and because of the refinement of the soil groupings. These differences should be expected because the AASHTO curves are based primarily on spectra developed using California earthquakes and soils, which are different from the soils and earthquakes in Washington State.

When comparing the spectra developed in this study with the existing AASHTO curves, it must be noted that the depths specified in this analysis are generally to hard soils (blow counts above 100) and not to bedrock, which is the depth prescribed by the AASHTO guidelines. The depth from hard soils to bedrock soils varies from zero to around 900 ft in Washington State. The AASHTO curves and corresponding spectra from this analysis are shown in Figure 7. The AASHTO spectrum for still soil sites (Group I) very generally corresponds to the base spectrum and Group 1 of this study. There

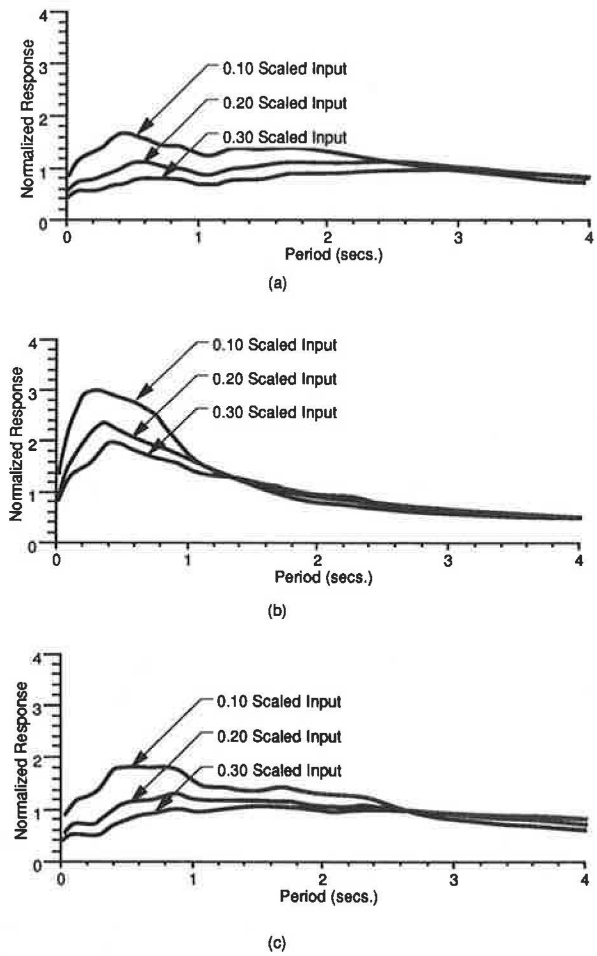

FIGURE 4 Base spectrum multiplied by soil amplification spectra for Groups 7, 8, and 9 (a, b, and c) soils for 0.1, 0.2, and 0.3 scaled input.

are larger high-frequency components in the spectra from this study. This is consistent with studies showing subduction zone ground motions having larger high-frequency content (*9*). The spectra are very similar above a period of about 1 sec. The AASHTO spectrum for stiff clays and deep cohesionless soils (Group II) corresponds to Groups 2 and 3 spectra in this

TABLE 1 SOIL GROUPS

Group	Description
1	20-50 ft to blow counts of 100 or greater of medium to dense cohesionless soils with up to 5 ft of loose soils (blow counts less than or equal to 10) at the surface. Variable layers of medium and dense soils, with no layers of loose soils beneath the top 5 ft.
2	51-100 ft to blow counts of 100 or greater of medium to dense cohesionless soils with up to 20 ft of loose soils at the surface. Variable layers of medium and dense soils, with no layers of loose soil beneath the top 20 ft.
3	100-300 ft to blow counts of 100 or greater of medium to dense cohesionless soils with up to 30 ft of loose soils at the surface. Variable layers of medium and dense soils, with no layers of loose soil beneath the top 30 ft.
4	10-50 ft to blow counts of 100 or greater of all other soils not in group 1.
5	50-100 ft to blow counts of 100 or greater of all other soils not in group 2.
6	100-300 ft to blow counts of 100 or greater of all other soils not in groups 3, 7.
7	100+ ft to blow counts of 100 or greater of soils consisting primarily of clays or clays and loose sands.
8	COAST SITES, 10-50 ft of loose silt and sand (not necessarily to SPT=100)
9	COAST SITES, 50+ ft of loose silt and sand (not necessarily to SPT=100)

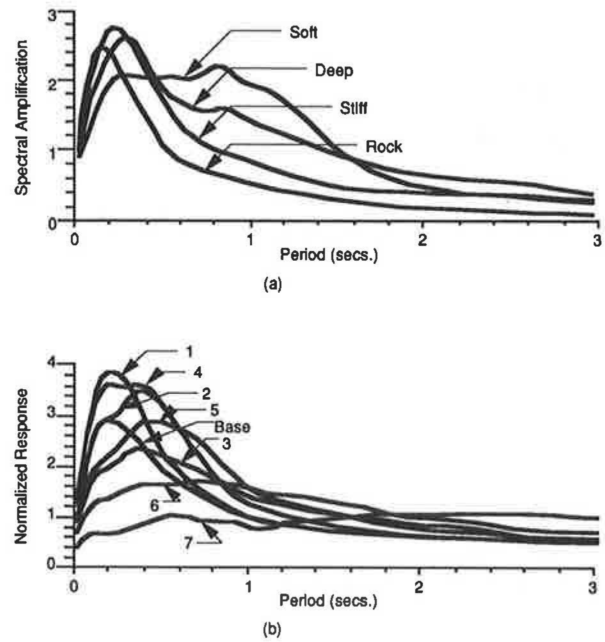

FIGURE 5 Comparison of spectra developed by Seed et al. (*7*) for four soil conditions (a) and spectra developed in this study for seven soil groups and base accelerations (b).

study. These groups do not include clays, which would generally reduce the higher-frequency response. The AASHTO spectrum for soft to medium-stiff clays and sands includes Groups 5, 6, and 7 in this study. The average of these spectra is very close to the AASHTO guideline curves. These comparisons indicate that the results of this analysis are generally consistent with existing spectra in terms of strengths. The comparisons also address the soil and earthquake factors in Washington State in a more realistic manner.

The spectra developed in this study can also be compared with the predictive equations for subduction zone earthquake ground response. Group 3 spectra are most similar in spectral shape to the Crouse et al. (*10*) and Vyas et al. (*11*) spectra for a magnitude 8 earthquake at a depth of 50 km, as shown in Figure 8.

The spectra can also be compared with the responses of the 1949 and 1965 Puget Sound earthquakes. The recording site in Olympia for the 1949 and 1965 events can be classified as a Group 3 site (*12*). Scaled Group 3 spectra are compared

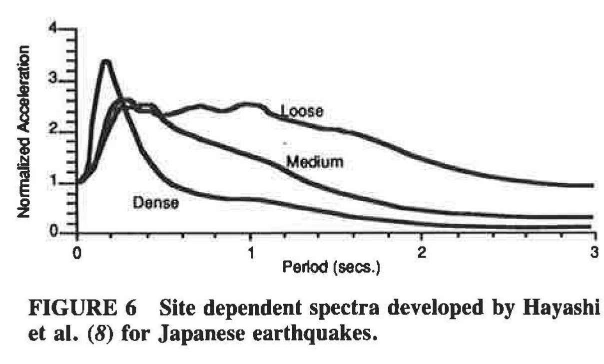

FIGURE 6 Site dependent spectra developed by Hayashi et al. (*8*) for Japanese earthquakes.

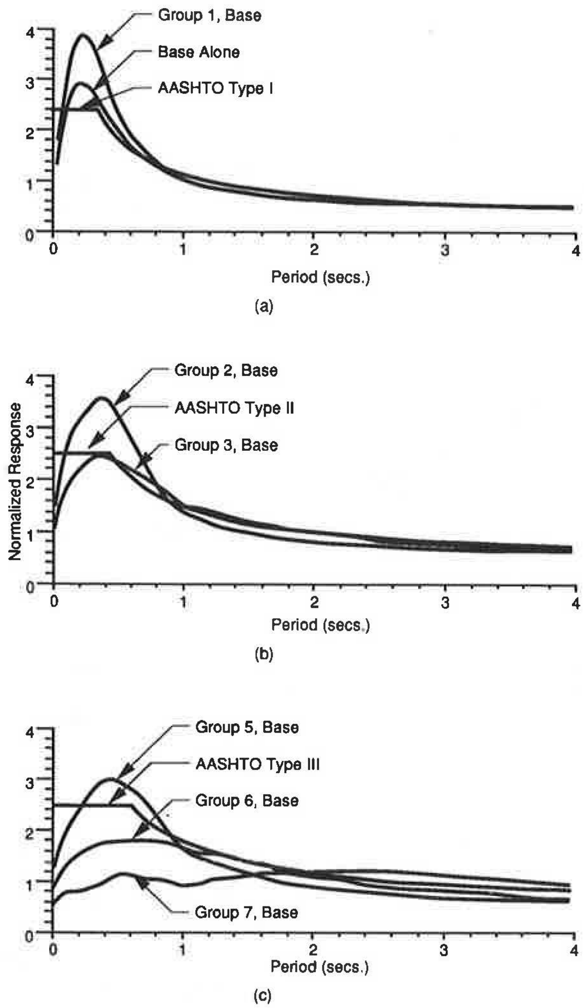

FIGURE 7 Comparison of AASHTO curves with spectra developed in this study: (*a*) AASHTO Type I with Group 1, (b) AASHTO Type II with Groups 2 and 3, (c) AASHTO Type III with WSDOT 5, 6, and 7.

with the responses from these two events in Figure 9. This actual response is enveloped fairly well by the Group 3 spectra except for the high-frequency response of the 1965 record. This event was almost directly under the recording station. Because of this, the time history may be rich in high-frequency components that would not be seen elsewhere. The recording

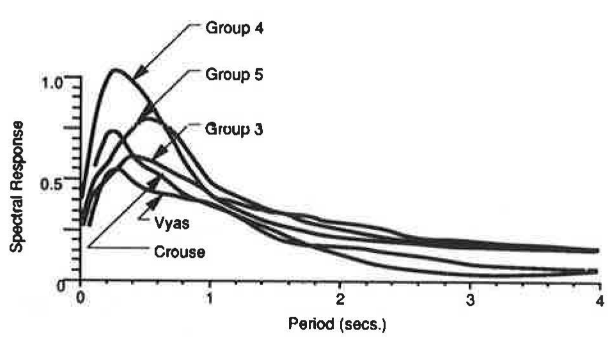

FIGURE 8 Comparison of spectra developed from predictive equations of Crouse et al. (*10*) and Vyas et al. (*11*) and spectra developed in this study scaled by 0.3.

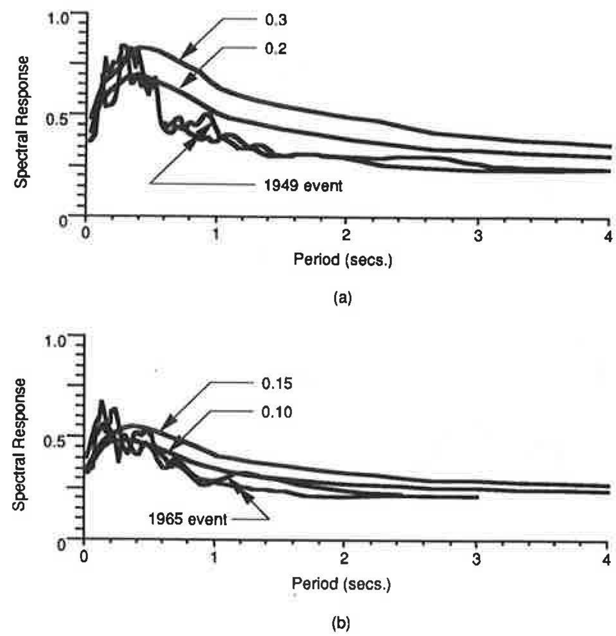

FIGURE 9 Comparison of Group 3 soil spectra developed in this study with horizontal response of Puget Sound earthquakes recorded in Olympia: (a) scaled by 0.3 and 0.2 and the 1949 event, (b) scaled by 0.1 and 0.15 and the 1965 event.

site in Seattle for the 1965 event would be classified as a Group 1 site. The response at this site is enveloped fairly well by the predicted spectra scaled by 0.10 as shown in Figure 10.

It is of value to examine the reported damage in the Puget Sound basin caused by the 1949 and 1965 events and how that damage has been correlated to geologic conditions. The results of this examination can be compared with the spectra developed in this analysis to see if they reflect greater ground shaking for those conditions. Most researchers found some correlation between damage and relative density of soils. Many structures built on artificial fill overlying tidal flats experienced high levels of ground shaking in both the 1949 and 1965 earthquakes (*13*). Damage was especially severe in the Duwamish River Valley (including Harbor Island) in the Seattle area. In Tacoma and Olympia, settlements of up to 25 cm occurred in the 1949 earthquake. It is not clear if this damage was because of subsidence or vibrational effects because there was evidence of both. Vibrational damage is a function of the period of ground shaking. When the natural period of a struc-

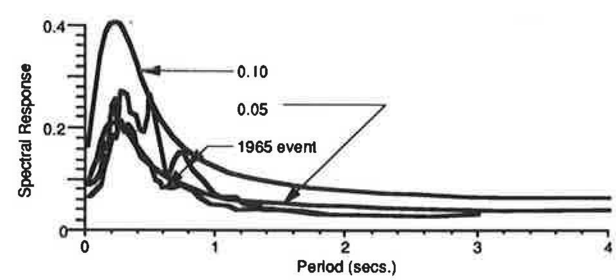

FIGURE 10 Spectra for Group 1 soils scaled by 0.01 and 0.05 and horizontal response of 1965 earthquake recorded in Seattle.

ture coincides with the period of the ground shaking, the probability of damage greatly increases. A general estimate of the natural period of 30- to 50-ft-high buildings in this area is 0.25 to 0.40 sec. Most of these softer sites fall into Groups 4, 5, or 6 depending on the depth to more compact material. Except for the Group 4 spectrum, these spectra have reduced frequency content in the 0.25 to 0.40 sec range compared with more compact sites. There are several possible reasons for the discrepancy between the reported damage and the ground shaking predicted by the spectra in this study. One possible explanation is that the damage in these areas was primarily caused by subsidence (*14*). Another is that the statistical averaging of the individual sites in the groups necessarily reduces the ordinates of extreme occurrences; in other words, the effects may be modeled in an individual site study but are averaged in a group. A third possibility is that effects other than surficial soils contributed to the damages observed.

The last possibility, that effects other than soils contribute to the severity of ground shaking in this area, has been suggested by several researchers. Anomalies in ground shaking not associated with surficial soils were found in other areas with denser, more stable ground conditions and in areas with artificial fill and unconsolidated natural deposits. Localized destruction on compact Pleistocene deposits occurred on the West Seattle Hill during the 1965 earthquake (*15*). In Tacoma and Olympia, the worst damage occurred in filled tidal flat areas, but there was also substantial damage on hard gravel uplands (*13*). Abnormally high intensities occurred in the Chehalis/Centralia area during both the 1949 and 1965 events (*15*). The severe damage seen in the Duwamish River Valley also varied considerably between areas with apparently similar site characteristics (*14*).

Various explanations have been forwarded to explain the capricious aspect of ground shaking in these areas. Yount (*16*) suspects that more severe ground shaking on compact Pleistocene deposits in Seattle was caused by low impedance units overlying bedrock at shallow depths. This explanation would generally be consistent with the results of this study for Group 1 sites. Hawkins and Crossen (*13*) indicated that clay layers underlying filled river basins might be suspected of causing damage. This analysis indicates a reduction in the amplitude of destructive frequencies on those types of soils.

Another explanation for these anomalies in relative ground shaking is that the highly variable stratigraphy of the underlying bedrock may influence the transmission of earthquake waves. Reflection and refraction may focus energy in certain areas. This idea was forwarded in 1942 by Coombs and Barksdale (*17*) for damages observed during a 1939 earthquake in the Puget Sound. This concept has received more attention recently with the introduction of sophisticated modeling techniques. Langston and Lee (*18*) showed the possible effects of focusing in the Duwamish River Valley using a three-dimensional ray-tracing algorithm. They suggested that focusing may be a primary agent in differential ground shaking in this area. This could produce an increase in ground shaking of up to an order of magnitude.

CRITICAL ANALYSIS

The results of this analysis must be examined in the context of the assumptions inherent in the AASHTO guidelines. One assumption was that ground shaking could be represented by a base spectrum multiplied by a severity coefficient and modified by a soil factor. The severity coefficient map indicates only very general spatial relationships with respect to identified source zones. The earthquake parameters accounted for in the maps are (very generally) source-to-site distance and crustal attenuation. The soil modifiers indicate only the frequency dependent attenuation/amplification properties of the soil column directly beneath the site. The base spectrum, if that assumption is correct, must represent the effects of all other factors that can affect ground shaking at a site, including source characteristics, directivity, and focusing. A broadband spectrum is typically used to account for these variations, but, as was noted in a previous section, effects of focusing alone may cause an order-of-magnitude increase in ground shaking. To specify a base spectrum that would encompass those effects would mean that for most sites the base spectrum would be unreasonably conservative. The solution is to neglect the effects of focusing, directivity, and other parameters that are earthquake- and site-specific and that could (but usually do not) cause more intense ground shaking and to use instead a reasonable average value. This is not outside the intent of the formulators of ATC 3-06 (who produced the AASHTO guidelines) who state, "It is possible that the design earthquake ground shaking might be exceeded during the lifespan of the structure—although the probability of this happening is quite small" (*19*). The broadband spectrum should encompass most, but not necessarily all, of the anticipated ground response.

Another assumption is that the design response spectrum at a site is directly correlated with the damage an earthquake can cause. Many factors contribute to damage that cannot be represented by this simple frequency-response diagram. The duration of an earthquake is not represented in the response spectrum, except in a very general sense—long-duration earthquakes typically have a broader range of frequency components (*20*). The duration of an earthquake is a critical factor in structural response in terms of cyclic loading effects. Subduction zone events may have durations up to 4 min. This may be a critical concern and it is addressed in the AASHTO guidelines by suggesting a standard duration of ground shaking of 20 to 30 sec. It was seen in the section on correlation with damage from past earthquakes that on softer sites, ground failure (subsidence) may cause as much damage as do vibrations. Increasing the design coefficient in these areas may result in an increase in the structure's ability to resist lateral motions but does not specifically address damage due to differential settlement.

With the limitations in the AASHTO guidelines in mind, the validity of the assumptions made in this analysis can be examined. The first assumption to consider is that ground response can be modeled by vertical shear waves propagating through horizontal soil layers. Studies comparing down-hole data with analytic response using SHAKE (*21*) indicate that near surface motions may contain components not predicted with this simple model (*22*). Wave theory predicts that shear waves become more vertical as they pass through increasingly less-dense materials on their way to the surface (*23*). For deep focus earthquakes this assumption of vertical shear waves seems reasonable. Nonhorizontally layered bedrock can affect the propagation of earthquake waves through reflection and refraction, which results in nonvertical propagation near the ground surface. Focusing effects in sedimentary basins can produce long-period surface waves (*24*) that may be critical in terms of differential movement between bridge piers (*25*). These long-period effects are accounted for in the AASHTO guidelines in a general way by increasing the base spectrum ordinates at longer periods. Although the effects of focusing can be large, they are very much site- and earthquake-specific and will not affect most sites. Not accounting for them appears consistent with the AASHTO philosophy. The assumption of horizontal soil layers is not unreasonable. Softer soils, which have a greater impact on attenuation/amplification of base motion, are typically horizontally (or nearly horizontally) layered.

A second assumption is that dynamic properties of soils are directly correlated with blow counts and static laboratory test results. Using these correlations requires caution. There are many factors that can affect the blow counts recorded and undrained shear strength test results (*26,27*). There is significant variability in the values observed in the boring logs, even in apparently homogeneous deposits. Sensitivity studies have been performed in an attempt to bracket the possible response, and it appears that the profile responses are not sensitive to 30 percent variations in calculated shear modulus values except at very soft sites. These soft sites fall into groups that incorporate a wide range of frequency amplification, so this greater variation is accounted for.

Even with consideration of the uncertainties related to these assumptions, the results are consistent with the findings of more sophisticated analyses and give a reasonable first-order estimation of soil amplification effects.

There is some uncertainty related to each of the components of this analysis. It may appear prudent when considering these compounding uncertainties to use mean plus one (or even two) standard deviations in assigning soil amplification multipliers. It is necessary, however, to consider the other parameters that can affect the response and the uncertainties related to each of these. Taking mean plus one standard deviations for all of the parameters that can affect ground shaking would lead to unreasonably large design forces. It seems more rational to use average values for all parameters; if a standard deviation is taken, it should be taken for the entire spectral response. A very rough estimate of the ratios between the response spectrum coefficients and mean plus one standard deviation coefficients might be 1.3 to 1.4 (*28*).

There is some concern that the very high frequency components (periods less than about 0.2 sec) have not been adequately represented in the selected base spectrum. The 1965 Olympia records contain significant components in this range as indicated in Figure 9. Comparison of spectra developed using shallow-focus and subduction zone earthquakes shows significant differences in this frequency range on rock and stiff soil sites. The spectra developed in this study, however, appear to be consistent with most of the available data. For this reason, the higher-frequency components were not increased. Studies were done to determine what effect these higher frequencies would have on the amplification spectra. There appeared to be no significant effect from including larger high-frequency components (Figure 10).

The results of this study (combined with the generalities involved in the mapping of the severity coefficient) must be considered as a first-order approximation of site response. Site-specific studies should be considered for critical or unusual structures so that other factors, such as susceptibility to focusing, can be considered in the analysis.

CONCLUSIONS

Response spectra for nine soil groups, developed for the particular conditions of Washington State, have been compared with the existing guidelines, spectra developed from predictive equations, spectra developed from subduction zone earthquakes, and site-specific spectra developed by Seed et al (*7*). In addition, the response spectra were correlated with damage caused by the recent strong earthquakes in Washington State.

Whereas the base spectrum and soil amplification spectra developed specifically for Washington State are in general agreement with the existing codes in terms of strength of ground shaking, differences in spectral shapes are observed. The differences are consistent with expected differences in frequency content between shallow- and deep-focus earthquakes. The soils in Washington State are diverse, making it logical to divide the types into more groups than those identified by the existing codes. The spectral amplification/attenuation characteristics of these soil groups, however, correspond fairly well with the site-response characteristics of less-refined groupings.

The most substantial differences between the existing codes and the results of this study are at the higher frequencies (periods of less than 0.4 sec). This means the greatest changes in design forces calculated will be to very stiff structures or in the transverse direction in long-span bridges. For other periods of interest, the spectra developed here may provide a slightly higher or lower (but more reasonable) value of relative ground shaking.

This approach should be applied to other regions with subduction zone events. Similar conditions in Northern California, Oregon, and British Columbia warrant its use, if it is not already being done.

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