Design Response Spectra for Washington State Bridges

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This report presents site-dependent design response spectra which account for the effects of the soils and earthquakes that occur in Washington State. A base spectrum and soil amplification spectra are developed that are correlated with a mapped severity coefficient. The base spectrum is selected with consideration given to the special characteristics of the subduction zone earthquakes likely to occur in this area. The computer program SHAKE is used to develop the soil amplification spectra. Soil profiles from 123 boring logs from actual bridge sites in Washington are used in this research The results are intended to replace corresponding sections of the currently used AASHTO guidelines.

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DESIGN RESPONSE SPECTRA FOR

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DESIGN RESPONSE SPECTRA FOR WASHINGTON STATE BRIDGES

SUMMARY

Seismic guidelines currently used in Washington State for the design of highway bridges do not reflect the unique geology and seismicity of the area. The objective of this research is the development of site-dependent design response spectra which reflect the effects of the earthquakes and soils that occur in Washington State.

A base spectrum and soil amplification spectra are developed which are intended to replace the seismic response spectrum and site coefficients presented in the AASHTO guidelines. The base spectrum is developed using available data on ground motion from subduction zone earthquakes similar to those occurring in Washington State.These earthquakes generally have larger high-frequency components than shallow-focus earthquakes. Since the existing codes are based primarily on data from shallow-focus earthquakes, the base spectrum developed has a larger high-frequency content than the existing base spectrum. The soil amplification spectra are derived using 123 boring logs from actual bridge sites in Washington. Data from the boring logs are correlated to dynamic soil properties which are used in the computer program SHAKE to find the frequency-dependent amplification properties of the soil profiles. The profiles are grouped by depth and type of soils. Nine groups are identified. Mean amplification spectra are developed for each group. The results show good correlation with other site-dependent studies. Comparison with actual earthquake records from this

area is also good. A review of the damage from past large earthquakes in this area shows that effects not modelled in this study may be important in localized regions.

CONCLUSIONS AND RECOMMENDATIONS

While the base spectrum and soil amplification spectra developed in this study are in general agreement with the existing codes in terms of strengths of ground shaking, differences in spectral shapes are seen. These 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 less than about 0.4 seconds). 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 hopefully more reasonable) value of relative ground-shaking.

The base spectrum and soil amplification spectra developed are an improvement over the existing guidelines because the earthquakes and soils in Washington are represented in a more realistic way. These results, however, must be considered a first-order approximation of site response. Additional site-specific studies may be appropriate for unusual or critical bridges.

There are a few areas were future research may help improve the present results. The dynamic soil properties required for the computations were derived using empirical relationships from the data in the boring logs. It would be possible to improve the results by performing laboratory studies and taking down-hole velocity measurements. The question of focusing needs to be addressed as well, possibly by identifying potentially susceptible areas, or providing a method of modifying the spectral values for these areas. The program SHAKE was used for the analytical calculations. This program represents the best currently available tool for analyzing data in an area as large as the one covered by the present study. In case that new computational techniques are developed in the future, they could be used to eliminate some of the approximations involved in SHAKE. Finally, it is noted that the spectra developed here are to be used with an Acceleration Coefficient indicating the severity of ground shaking in the area. In light of new understanding of ground motion from subduction zone earthquakes, a step in improving the estimation of future ground motion would be the remapping of the Acceleration Coefficient.

INTRODUCTION

Background

Washington State is one of the major centers of earthquake activity in the country. Two recent earthquakes (1949, magnitude 7.1; 1965, magnitude 6.5) caused considerable structural damage in the highly populated Puget Sound basin. The estimated recurrence interval of magnitude 6 earthquakes in this area is between five and ten years (1,2). The possible occurrence of an earthquake with a magnitude greater than eight has been suggested (3).

Because of this high seismic hazard, there is a vital need for rational seismic design of highway bridges in this region. Accurate representation of earthquake forces is required for economic as well as safety reasons since seismic forces frequently control bridge design. The Washington State Department of Transportation (WSDOT) is currently using AASHTO's 1983 seismic guidelines (4). These guidelines were originally developed by the Applied Technology Council as seismic guidelines for buildings (5) and were later modified for bridges (6). The guidelines were developed for general U.S. use and are based on research relying largely on data from California earthquakes. Earthquakes occurring in Washington State differ significantly from those in California in terms of source characteristics, wave propagation paths, and site geology. For a better understanding of the differences and the uniqueness of seismicity in Washington State, a brief review of the geology and seismicity in this area is given.

Geology and Seismicity

The landmass of the western U.S. is a result of the activity along a convergent plate boundary parallel to the Rocky Mountains over the past 300 million years (7). The relative movement of the plates has shifted in time but these tectonic processes are still active, as evidenced by volcanic activity parallel to the present-day coastline. The operational plate boundaries in Washington State are shown in Figure 1. The subduction of the Juan de Fuca plate appears to be currently active (3) and the largest earthquakes occurring in the area are deep-focus events associated with this subduction process (7). There are also many smaller earthquakes at shallower depths that are believed to be associated with active north-south compression in this area. The reader is referred to Hopper et al. (8) for a more complete description of these tectonic processes. Much of the geology in the Puget Sound basin is dominated by the effects of the various advances and retreats of the Puget Lobe of the Cordillerian Ice Sheet. This ice sheet is associated with periods of global glaciation beginning over 40,000 years ago. During this period, the area was sometimes covered with up to 5000 feet of ice. As the ice retreated, thick layers of till were deposited and lakes and rivers formed. As the ice again advanced, these deposits were overridden, reworked and redeposited. These multiple periods of glaciation resulted in deep layers of heavily over-consolidated till interspersed with glaciofluvial and glaciolacustrine deposits in most of the Puget Sound Basin. These deposits hide much of the underlying bedrock structure in this area, making it very difficult to identify active faults or to understand their movements.

From this brief description of the geology of the area, it is realized that there are significant differences between the seismicity in California and the one in Washington State. California earthquakes are generally shallow-focus and associated with faults which often extend to the ground surface. Also, the soils in California are very different from those occurring in Washington. This makes using data from California earthquakes, for seismic considerations in Washington Sate, questionable.

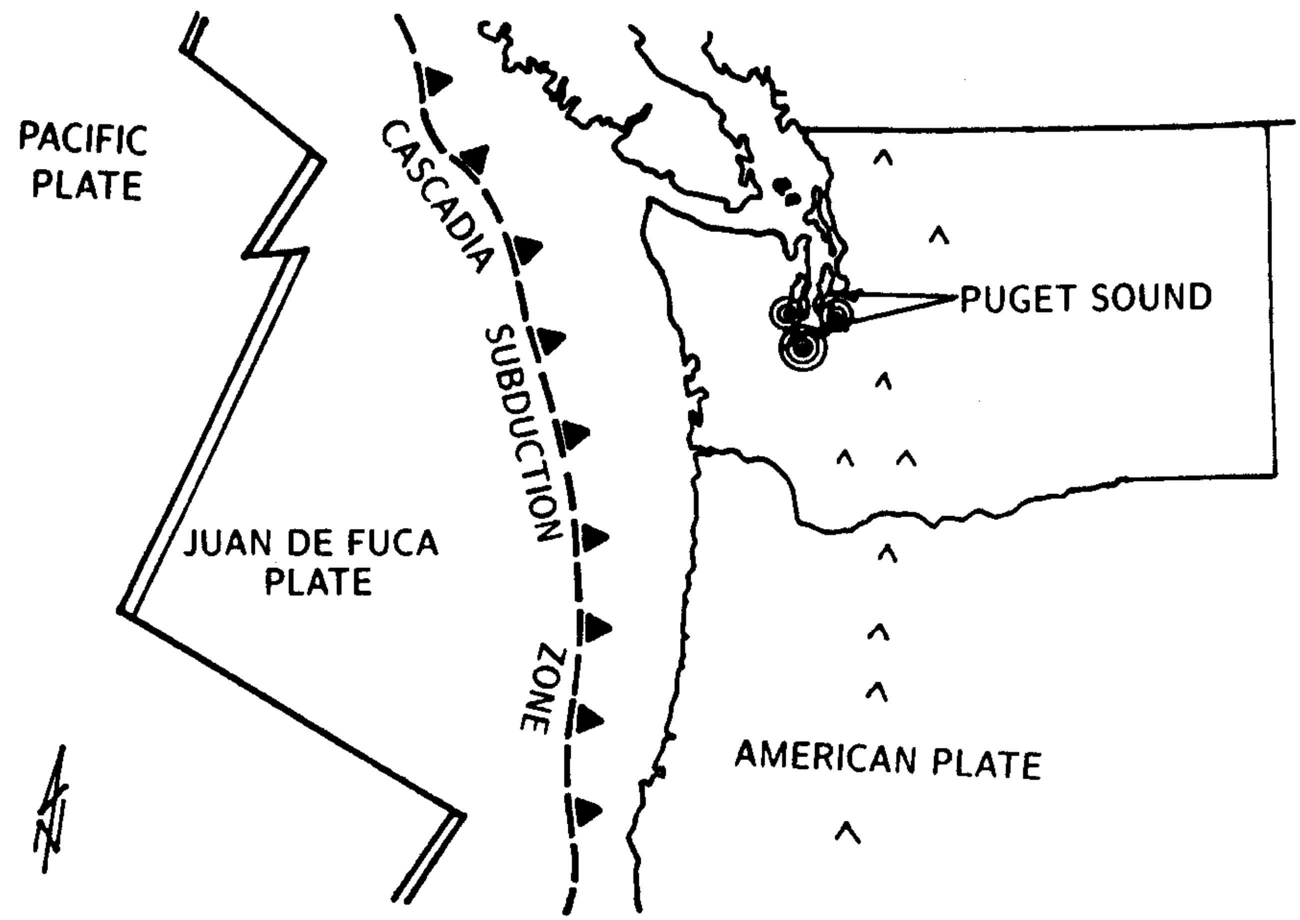


Figure 1. Active plate boundaries in the Pacific Northwest.

Research Objectives

The objective of this study is to develop design response spectra which reflect the unique seismicity and geology of the region. To achieve this objective, the following tasks were accomplished:

1. A literature search of the geology and hazard analyses studies in Washington State was conducted and the findings were summarized.
2. Different computational tools were investigated. The program SHAKE was selected for the analysis.
3. Soil data from around the state were collected.
4. The soil data were correlated with the soil dynamic properties required for the computations. Appropriate input for the program was formulated.
5. A classification of the soil profiles within the state into nine groups was made and soil amplification spectra showing the amplification/attenuation properties of these profiles were developed.
6. A base spectrum which reflects the properties of the earthquakes likely to occur in Washington State was determined.

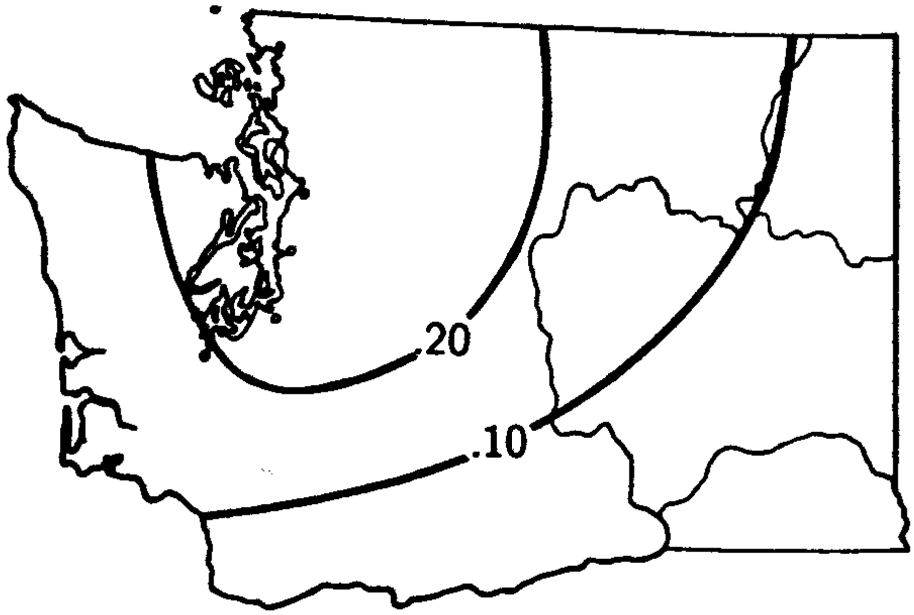
REVIEW OF PREVIOUS WORK

The objective of this research is to improve the AASHTO guidelines to reflect ground shaking values consistent with the earthquakes and soils that occur in Washington State. The results must be easy to use by the bridge designer, and be based on available information about the bridge site. The particular section of the AASHTO guidelines includes the zoning maps, the base spectrum, and soil amplification factors.

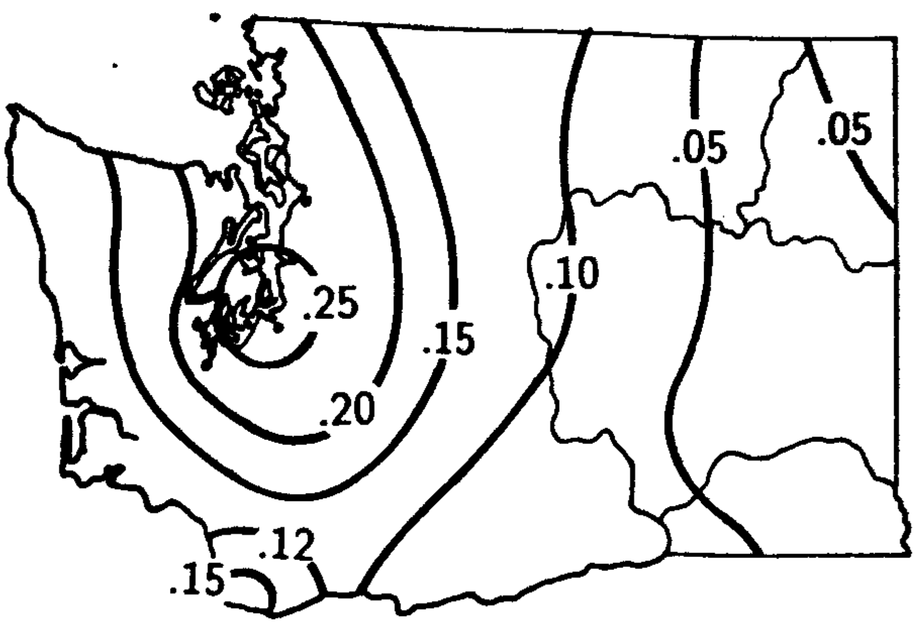
Figure 2a shows the AASHTO zoning map for Washington State (4). The map depicts contours of effective ground acceleration which is an Acceleration Coefficient developed, by the Applied Technology Council, specifically as a response spectrum scaling factor. It is important to note that the AASHTO maps show contours of an Acceleration Coefficient, and not expected peak ground acceleration as determined by others. Several studies of the seismicity in Washington State have already been performed which have resulted in improved seismic maps for the area. Algermissen and Perkins in 1976 studied the expected peak ground acceleration in the contiguous United States (9). They developed maps of expected peak ground acceleration on rock for a return period of 500 years. These maps were based primarily on an analysis of historic seismicity and, in general, geologic evidence was not considered. Source zones were identified and recurrence relationships were determined for each zone. The assumption made in these analyses was that future seismic activity would be similar to historic seismic activity, but would affect a larger area. Appropriate regional attenuation relationships were established and the extreme cumulative probability of acceleration during the return period was calculated and mapped. Perkins et al. in 1980 developed new zoning maps for Washington State which are an improvement over the 1976 study by Algermissen and Perkins because geologic factors were considered along with historic seismicity (10) . Perkins used attenuation factors from Schnabel and Seed's 1973 study of California earthquakes (11). In Perkins' analysis of the deep-focus earthquakes likely to occur in Washington, the assumption was made that the attenuation would be the same for equivalent hypocentral distances; in other words, the attenuation in the horizontal direction would be the same as the attenuation in the vertical direction. It should be noted that the maps developed by Algermissen and Perkins in 1976 and by Perkins in 1980 depict contours of expected peak ground acceleration and not of the Acceleration Coefficient as used in the AASHTO guidelines.

The zoning maps were recalculated by J. Higgins (12) in 1986. Higgins' work is based on the 1980 study by Perkins with the difference that Higgins modified the acceleration data to account for velocity attenuation effects so the resulting velocity-related acceleration coefficients would be more nearly like the Acceleration Coefficient used in the AASHTO codes. Figure 2b shows the map developed by Higgins.

The base spectrum and modification factors for local soil conditions in AASHTO were developed using a study by Seed, Ugas, and Lysmer (13), who found significant differences in spectral shapes for four different generalized soil conditions: (a) rock, (b) stiff soil, (c) deep cohesionless soil, and (d) soft to medium clays and sands. An ensemble of 104 strong-motion records were used in this analysis, the majority from California earthquakes. The rock and stiff soil categories were combined into one category and simplified to represent the base spectrum in the AASHTO guidelines. For other site conditions, the base spectrum is multiplied by a scaling factor (1.2 for stiff clays and deep cohesionless soils and 1.5 for soft to medium-stiff clays and sands) to duplicate the general effects of these soils as indicated by Seed et al. The curves developed by Seed et al. and the corresponding AASHTO curves are shown on Figure 3. The resulting response values are then used to obtain either an elastic seismic

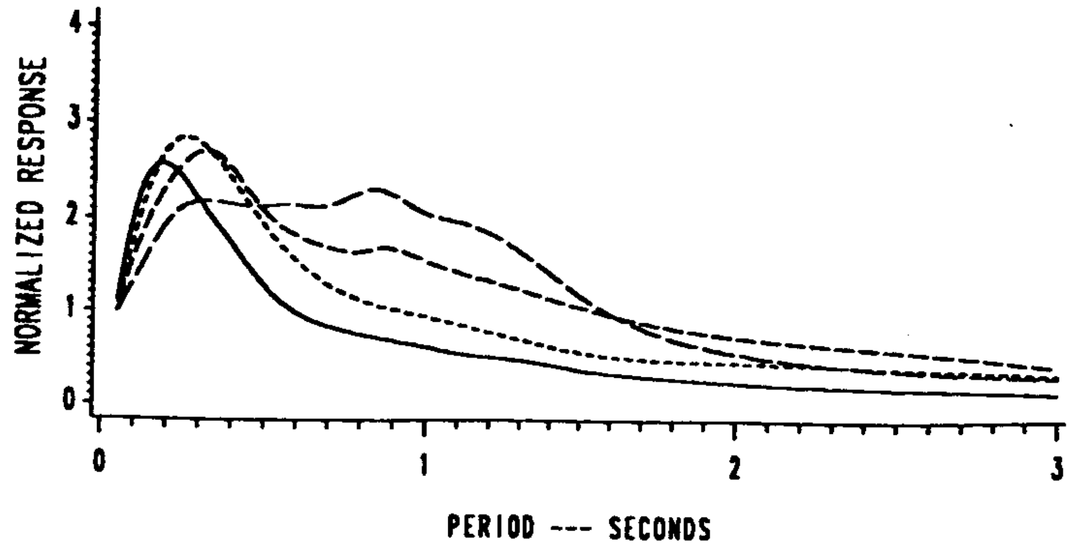


(a)

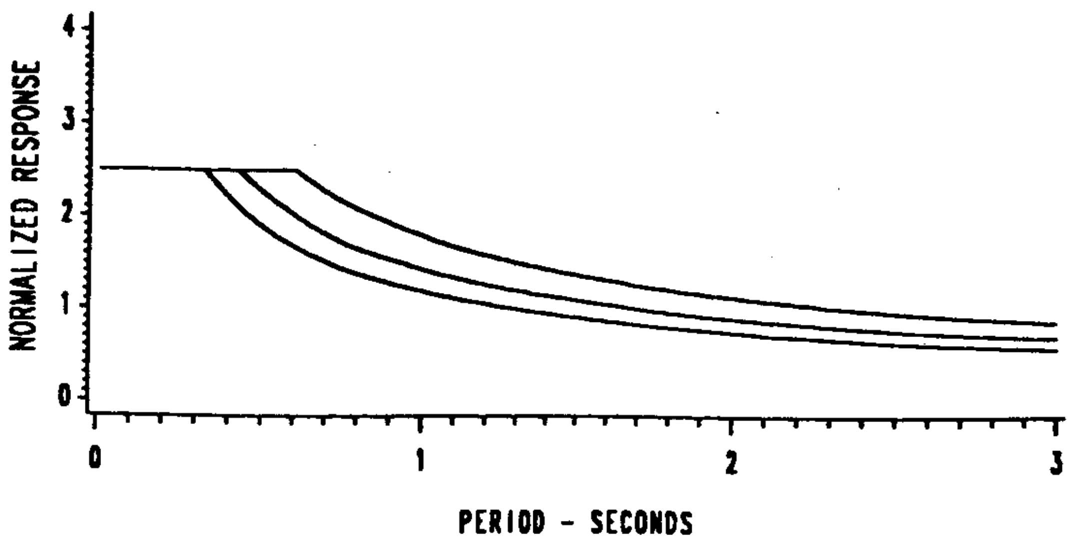


(b)

Figure 2. (a) AASHTO's and (b) Higgin's Seismic Maps of Washington State



(a)



(b)

Figure 3. (a) Site-Dependent spectra developed by Seed et al.
(b) AASHTO curves for three soil conditions

response coefficient, which is then used to find an equivalent static force, or an elastic seismic response spectrum, which can be used in a dynamic modal analysis.

The objective of this research is to replace the AASHTO spectra with ones based on local seismicity. The spectra will be used in conjunction with the map of the Acceleration Coefficient. The most recent mapping of the area is the one developed by Higgins which is actually based to the study by Perkins. Perkins' study, and hence Higgins' report, may not represent the best estimate of relative ground shaking in light of very recent developments in the understanding of subduction zone earthquake ground motion. Recent studies on subduction zone ground motion indicate definite differences in attenuation properties between shallow-focus and deep-focus earthquakes (14). There are also distinct differences in frequency content. Because of these recent developments, it is anticipated that the zoning may need to be reconsidered in the near future.

Because of these on going improvements in the seismic zoning of the area, this research establishes appropriate base spectra and soil amplification factors forWashington State that are essentially independent from the zoning currently used. This independence requires assessing possible levels of ground motion in the area with consideration given to recent developments in the understanding of subduction zone earthquake ground motion. It should be emphasized that following the AASHTO guidelines, the zoning maps to be used with the results of this research should depict contours of the Acceleration Coefficient or Effective Ground Acceleration and not peak ground acceleration. It is expected that the zoning map developed by Higgins will be used but if future improvements in the zoning map are made, there is no need for change of the base spectrum and the soil amplification coefficients developed here.

PROCEDURES

Soil amplification factors were developed using the program SHAKE (15). Required program input consists of a soil profile (with depths and types of soil layers), strain-dependent damping and moduli curves for the types of soils, and an acceleration time history used as input at the base of the profile.

Soil Profiles

The soil profiles used were developed from 123 boring holes from bridge sites in Washington State. This large study group was used in an attempt to include the range of soil types and variations encountered in this area. The soils were categorized as clays or sand depending on their predominant behavior, as required for the input to SHAKE. Since the type of information available on the logs is limited, it was necessary to use empirical relations between the available data (usually Standard Penetration Tests (SPT) and undrained shear strength) and dynamic properties of the soil. Ohsaki and Iwasaki's relationship (16) between shear modulus and SPT blow counts was used on cohesionless soils. Undrained shear strength was correlated to shear modulus using relationships developed by Seed and Idriss (17) and modified using curves developed by Egan and Ebeling (18). Average damping ratio versus strain curves, developed by Seed and Idriss (17), were used in the analysis.

Input Time History

The acceleration time history required as base input to SHAKE was developed with consideration of the following: expected magnitudes of earthquakes in the area, variations in frequency content and amplitude in light of new data on subduction zone earthquakes, and limited depths of soil profiles to be used. Several methods were considered in selecting appropriate time histories, including using actual time histories, deconvoluting Puget Sound strong ground motion records, and simulating time histories based on predictive equations. Sensitivity studies were preformed to determine the effects of variability in the time histories chosen. From these investigations, it was finally decided to use simulated records.

The average spectrum corresponding to stiff soils, developed by Seed, was selected as the target spectrum for the generation of records. The spectrum was scaled by 0.1, 0.2 and 0.3 in order to encompass the range of strengths of ground motion expected in Washington State. The program SIMQUAKE, (19), was used to produce four acceleration time histories to be used in SHAKE.

Soil Amplification Spectra

SHAKE was used to determine the five percent damped acceleration response of the soil profiles to the time history input. This response was then divided by the response of the time history at a rock outcropping. The result is a soil amplification spectrum which shows the amplification (or attenuation) effects of the profile on the underlying base motion.

The soil amplification spectra were grouped according to type and depth of soils, with consideration given to ease of classification by the design engineer. Mean curves were developed for each group. Sensitivity studies were performed to analyze the effects of changes in the soil profiles and dynamic properties assumed. Studies were performed to determine the effects of soft and clay layers in the profile, and at what depths these layers had the most effect on the response. Effects of changes in water table and assumptions made about the base were also tested. Dynamic properties were varied to determine the effect for different types of soils. The results of these studies were compared to the results of other site-response studies.

Base Spectrum

The base spectrum was selected based on the following considerations: correlation with base input to SHAKE (with factors such as ground response of subduction zone earthquakes considered there) and AASHTO's conservatism at longer periods. Consideration was given to using more that one base spectrum to account for differences in spectral shape between near and far earthquakes.

The results of the base spectrum plus soil amplification factors were compared to appropriate theoretical and empirical studies including the AASHTO specifications, and studies from ground motions from subduction zone earthquakes. The results were also compared to the existing strong-motion records from the 1949 and 1965 events. The reported damage from these earthquakes was also examined to determine if effects other that those modeled in this study are critical in this area.

DISCUSSION

The useful results of this analysis are:

1) A classification of the soil profiles within the state into nine groups and the determination of soil amplification spectra which show the amplification/attenuation properties of these nine soil profiles.

2) A base spectrum which reflects the properties of the earthquakes likely to occur in Washington State.

Soil Groups

The soil groups were determined from the spectra developed with the 0.2 scaled simulated records. The assumption made was that groupings obtained using the 0.1 and 0.3 scaled records would be the same as those developed using the 0.2 records. Peak spectral amplification for each site was plotted as a function of period and preliminary groupings were made. Sites within each group were analyzed for similarities. The results appeared to be primarily functions of depth and types of soils in the profiles. Some slight shifting between the preliminary groups allowed categorization by easily identifiable traits. The final groups are shown on Table 1.

Coastal sites, with very loose, silty deposits, were grouped separately because of the great variability in response for minor variations in G_{max} values calculated from blow counts. Because of the small number of coastal sites available, sites with variations in depths and G_{max} values were simulated to find a probable range of responses.

TABLE 1 - SOIL GROUPS

1. 20-50 feet to blow counts of 100 or greater of medium to dense cohesionless soils with up to 5 feet 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 feet.

2. 51-100 feet to blow counts of 100 or greater of medium to dense cohesionless soils with up to 20 feet of loose soils at the surface. Variable layers of medium and dense soils, with no layers of loose soil beneath the top 20 feet.

3. 100-300 feet to blow counts of 100 or greater of medium to dense cohesionless soils with up to 30 feet of loose soils at the surface. Variable layers of medium and dense soils, with no layers of loose soil beneath the top 30 feet.

4. 10-50 feet to blow counts of 100 or greater of all other soils not in group 1.

5. 50-100 feet to blow counts of 100 or greater of all other soils not in group 2.

6. 100-300 feet to blow counts of 100 or greater of all other soils not in groups 3 or 7.

7. 100+ feet to blow counts of 100 or greater of soils consisting primarily of clays or clays and loose sands.

8. COAST SITES, 10-50 feet of loose silt and sand (not necessarily to SPT=100)

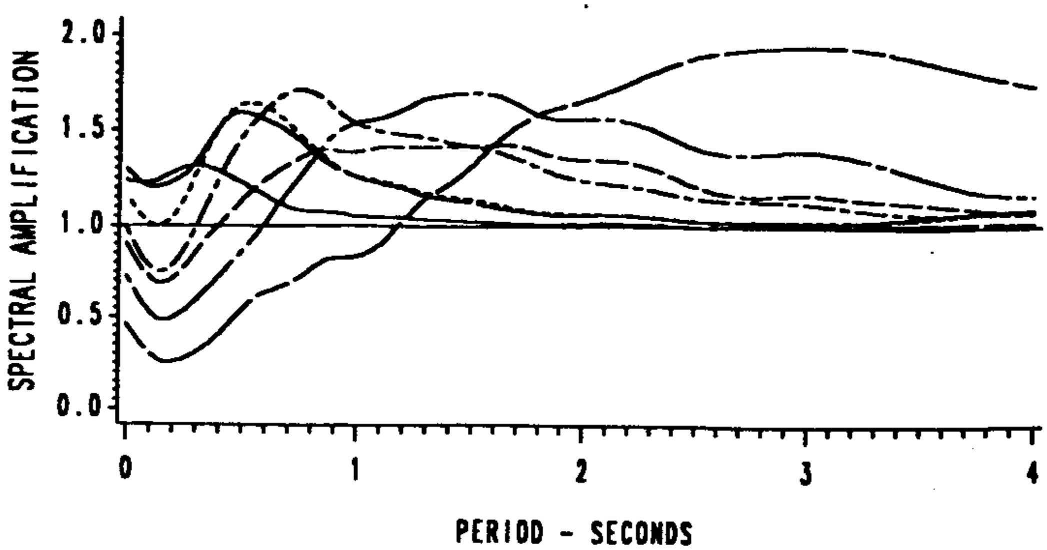
9. COAST SITES, 50+ feet of loose silt and sand (not necessarily to SPT=100)

Soil Amplification Spectra

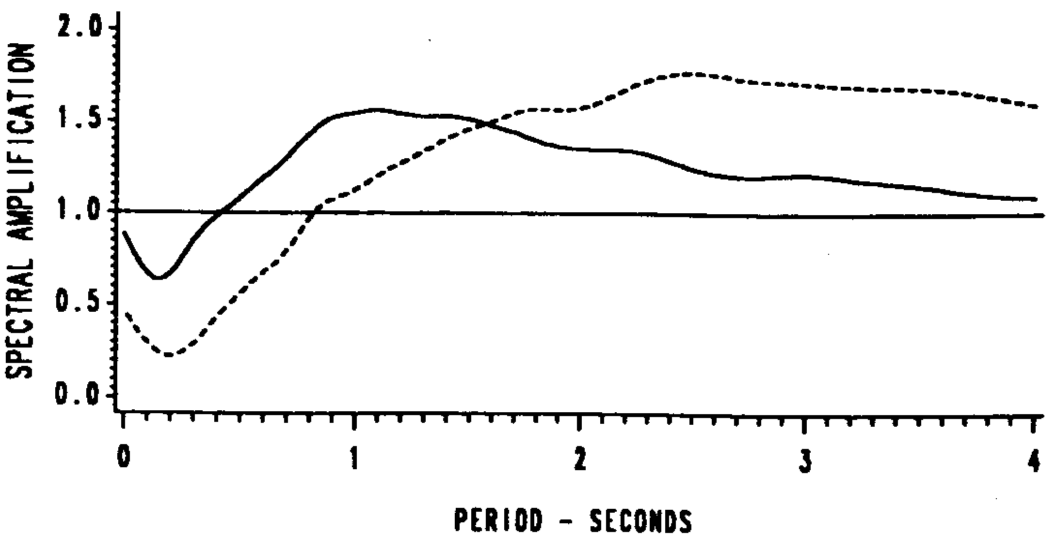
For each of the 9 soil groups soil amplification spectra were developed corresponding to values 0.1, 0.2, and 0.3 of the severity coefficient (Acceleration Coefficient). The amplifications were analyzed statistically at 38 periods. Finally, the mean amplification spectra were determined. Figure 4 compares the mean amplification spectra for all nine groups developed using the 0.2 scaled record. Similar curves were obtained for the 0.1 and 0.3 scaled spectra. Hard copies of the spectral ordinates can be found in the Final Technical Report (20). From the figure it can be seen that groups one, two and three represent well-behaved sites and conservative amplifications are allowed. The groups of the same depths with clays and/or loose soils in general show higher amplitudes and greater ranges in frequency content.

Base Spectrum

The base spectrum developed by modifying the Seed stiff spectrum, is shown in Figure 5. In the same figure, the AASHTO base (soil group I) is also shown for comparison. Ordinates for the base spectrum curve can be found in the Final Technical Report (20). Figures 6-14 show the base spectrum times the soil amplification spectra for the nine soil groups formulated in this study.



(a)



(b)

Fig. 4 Soil amplification spectra for 0.2 scaled records for (a) groups 1-7 and b) coastal sites; groups 8 and 9.

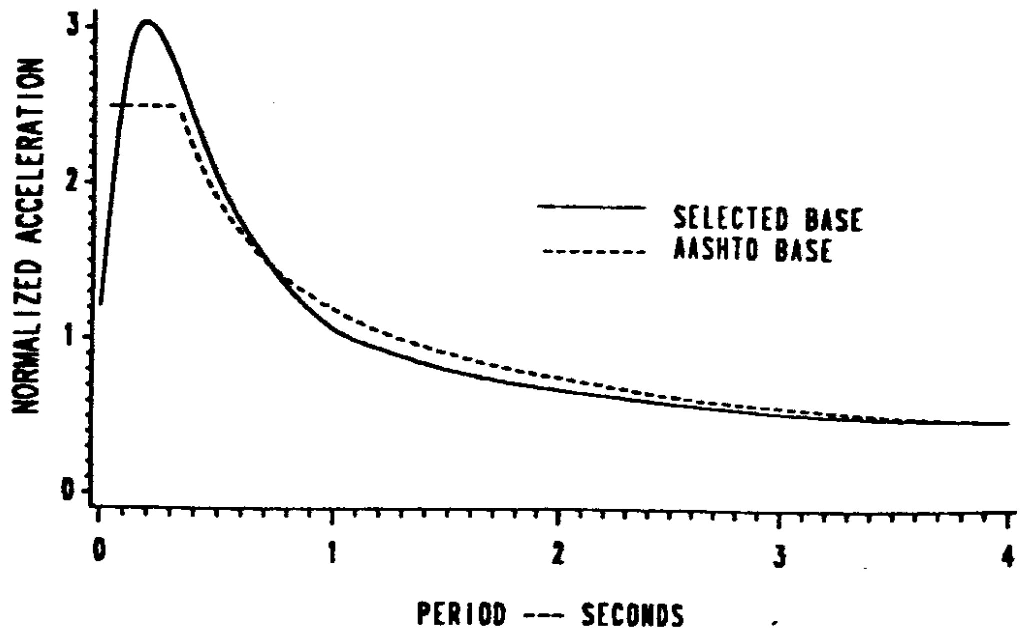


Figure 5. Selected base spectrum and AASHTO Soil Type I curve

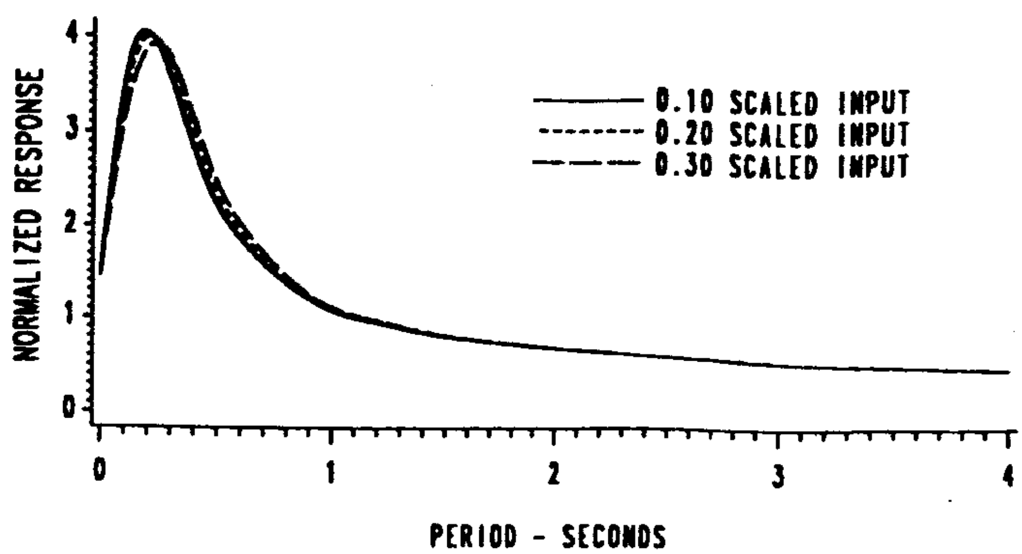


Figure 6. Soil amplification spectra times base spectrum for Group 1 soils

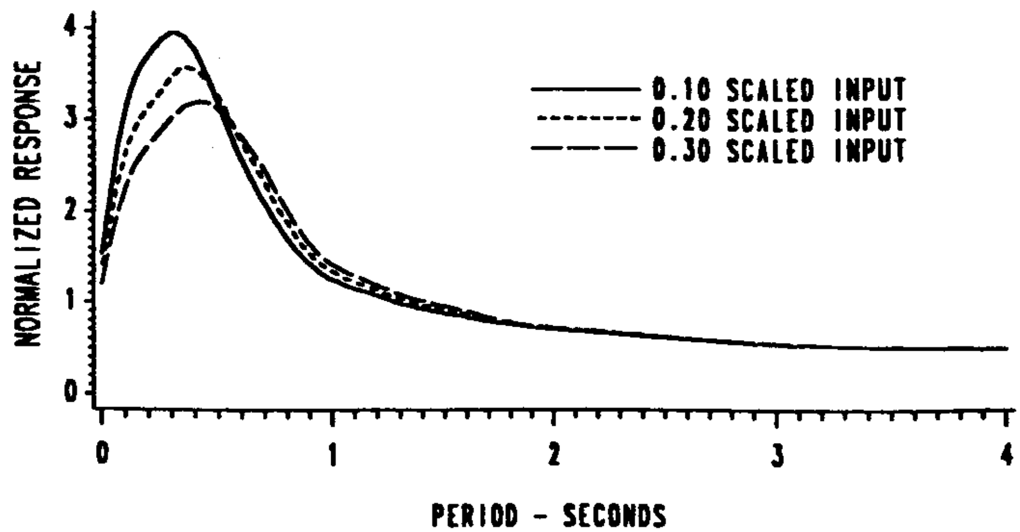


Figure 7. Soil amplification spectra times base spectrum for Group 2 soils

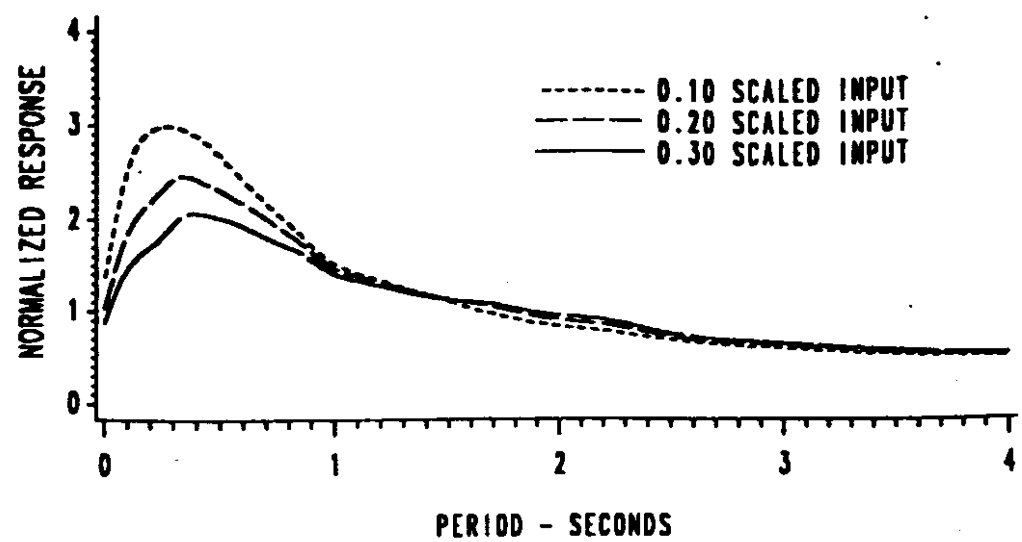


Figure 8. Soil amplification spectra times base spectrum for Group 3 soils

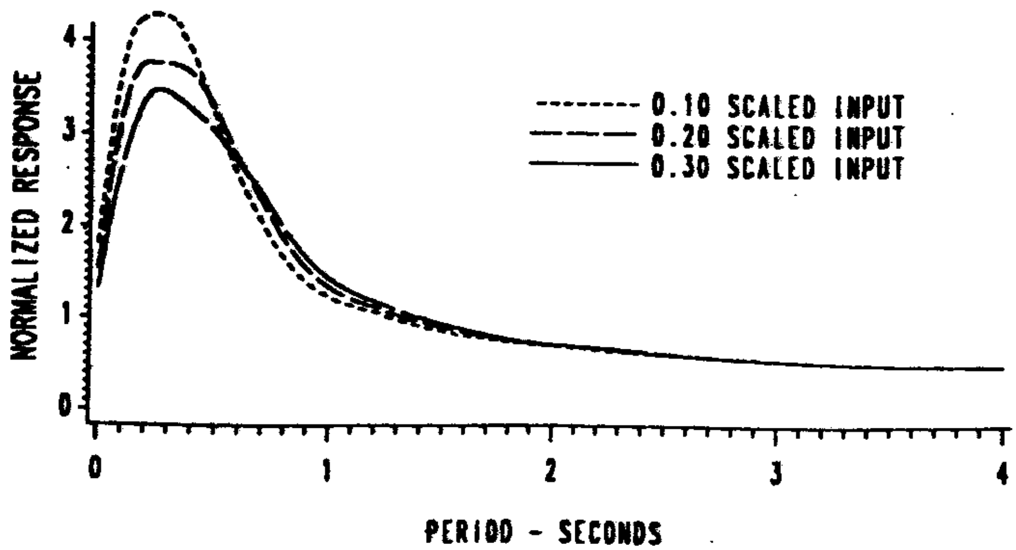


Figure 9. Soil amplification spectra times base spectrum for Group 4 soils

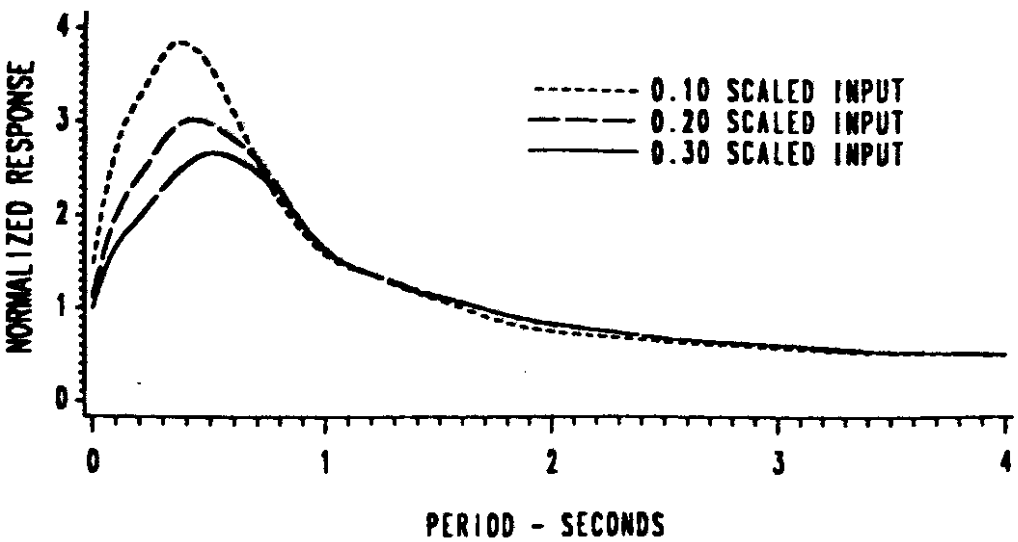


Figure 10. Soil amplification spectra times base spectrum for Group 5 soils

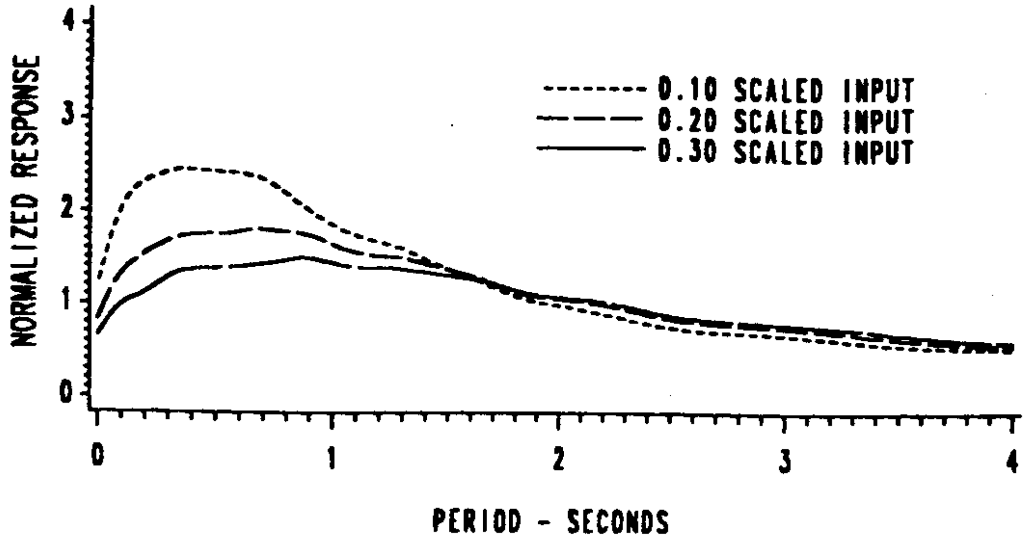


Figure 11. Soil amplification spectra times base spectrum for Group 6 soils

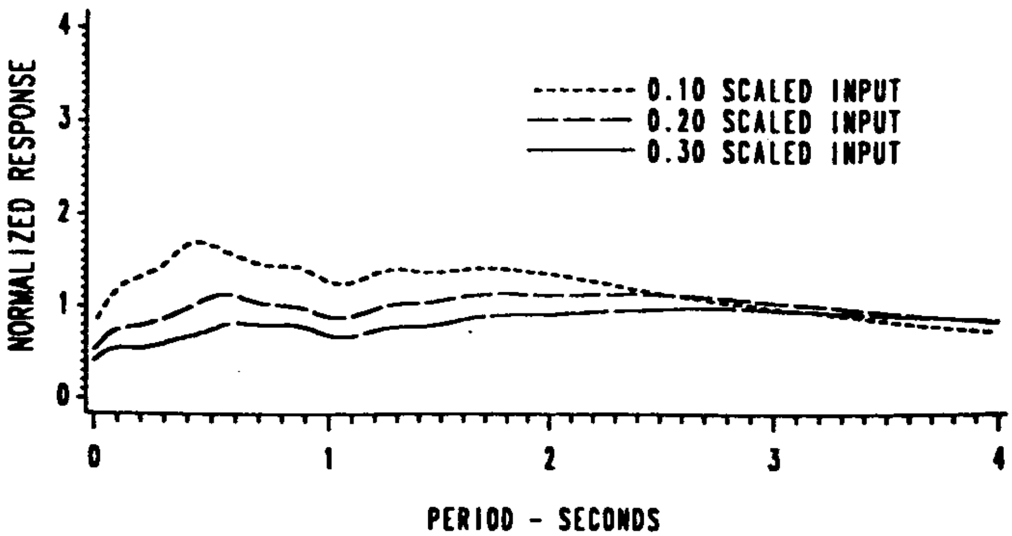


Figure 12. Soil amplification spectra times base spectrum for Group 7 soils

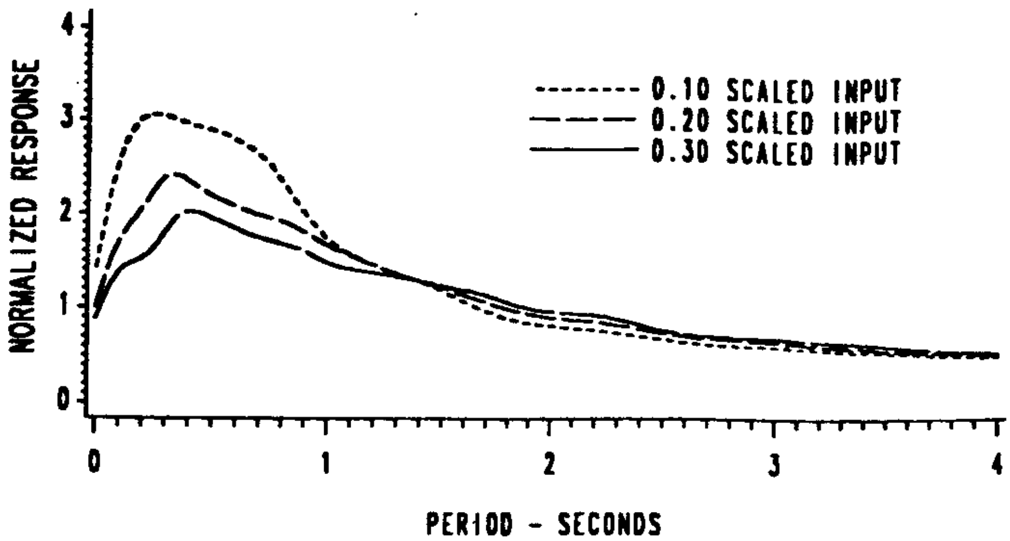


Figure 13. Soil amplification spectra times base spectrum for Group 8 soils

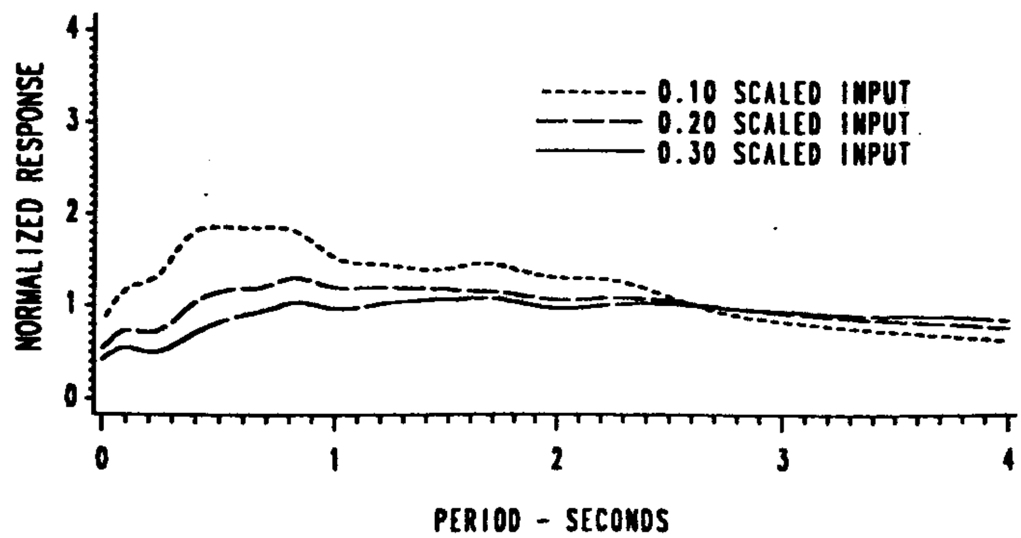


Figure 14. Soil amplification spectra times base spectrum for Group 9 soils

APPLICATIONS AND IMPLEMENTATION

The base spectrum and soil amplification spectra developed are intended to replace corresponding sections of the AASHTO guidelines (4). The applicable sections of the code are sections 3.5, which presents the soil profile types, and section 5.2, which gives the response spectrum equations. The soil profiles and associated soil factors presented in section 3.5 would be replaced by the amplification spectra for the soil groups developed in this study. In section 5.2, equations for C_s and C_{sm} would be replaced by values obtained from the base and soil amplification spectra. Specifically, for any period of interest, the base spectrum ordinate multiplied by the appropriate soil amplification ordinate for that period and the severity coefficient at the site would give the value of C_s to be used in place of the value obtained from equation (5-1) or C_{sm} in equation (5-2). The appropriate soil amplification spectra would be chosen based on the type of soils at the site and the selected severity coefficient. A schematic of this process is shown on Figure 15. For sites on rock or very hard soils (blow counts greater than 100 within the top 20 feet), the base spectrum would be used alone. Equation (5-3), which reduces the spectral ordinates at soft soil sites is unnecessary because the soil amplification spectra show this reduction.

In summary, the following steps are required to use the present results while performing manual calculations:

a) Determine the soil profile and the Acceleration Coefficient for the site.

b) Find base spectrum ordinate for period of interest.

c) Find the soil amplification ordinate for period of interest from the spectrum corresponding to the selected soil profile and Acceleration Coefficient.

d) Seismic coefficient C_s = Acceleration coefficient x base spectrum ordinate x soil amplification ordinate.

The appropriate severity coefficient could be taken from the map of velocity-related accelerations developed by Higgins (12) until the remapping is accomplished. Although the Higgins' map may not represent the best possible estimate of relative ground shaking, it does represent an improvement over the AASHTO maps because it shows a higher level of ground shaking anticipated, which is consistent with current knowledge of seismicity in this area. The user is cautioned against using peak ground accelerations developed from other sources to scale for reasons mentioned in the section on Review of Previous Work.

When the results of the present study are used in conjunction with a computer program, such as SEISAB, for earthquake analysis of bridges, a library of design response spectra must be introduced into the program. The base spectrum ordinates should be multiplied by all derived spectra. Twenty seven design response spectra will result, which correspond to the nine soil profiles and the three severity coefficients for each soil profile. The digitized data included in the Technical Report (20) can be easily used for this purpose. Again, the soil profile and the Acceleration Coefficient for the specific site must be identified and the program must be directed to use the corresponding design spectrum scaled by the Acceleration Coefficient.

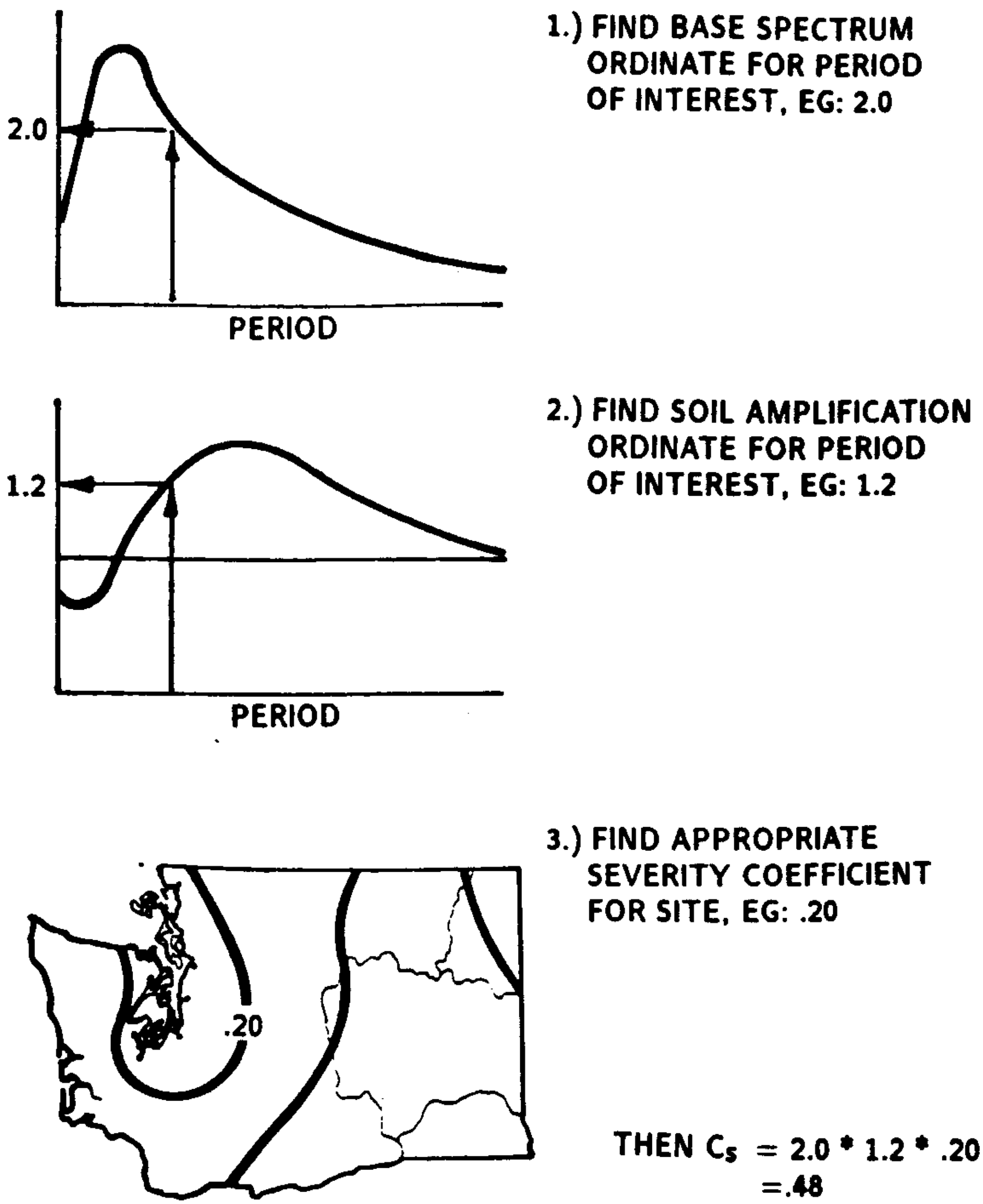


Figure 15. Use of base spectrum and soil amplification spectra developed.

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