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RELATIONSHIPS BETWEEN SOIL CONDITIONS AND EARTHQUAKE GROUND MOTIONS IN MEXICO CITY IN THE EARTHQUAKE OF SEPT. 19, 1985

by

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A report on research sponsored by
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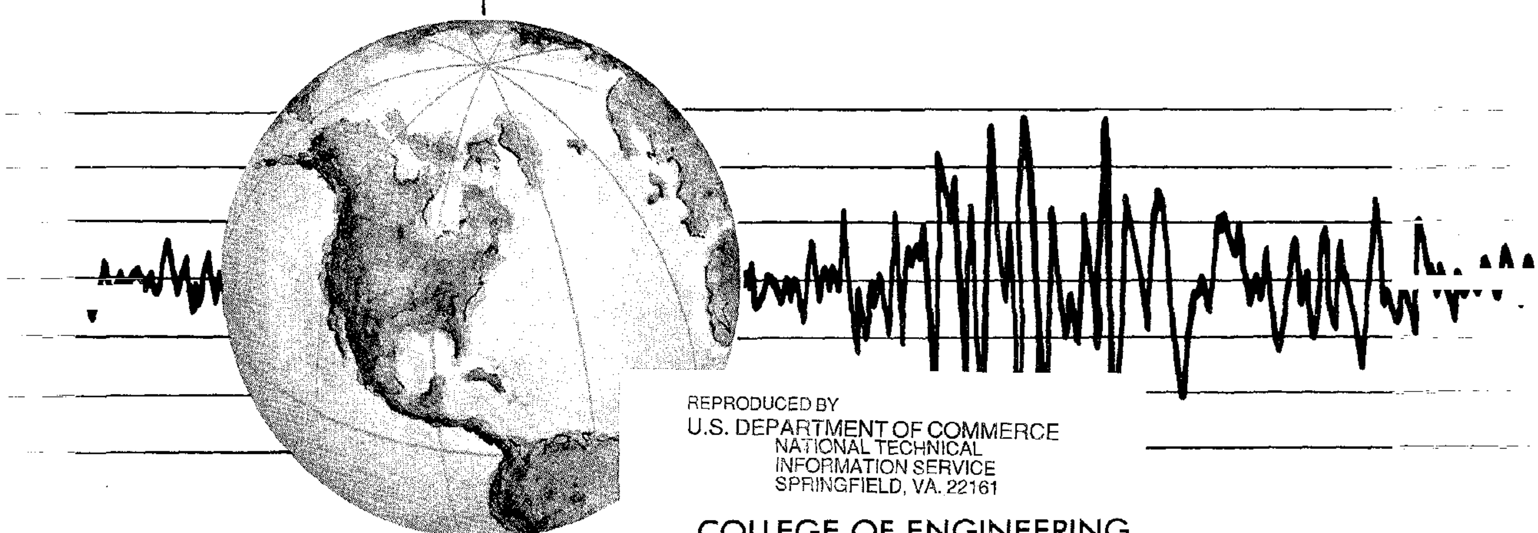

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One of the most dramatic aspects of the earthquake effects in Mexico City in the earthquake of September 19, 1985 was the enormous differences in intensities of shaking and associated building damage in different parts of the city. It is the purpose of this report to describe the soil conditions in Mexico City, present the results of special studies made since the earthquake to explore in detail the soil conditions at the sites of strong-motion recording stations and at other sites of interest in and near the city, and to present the results of some analytical studies of the extent to which the observed differences in shaking intensities can be predicted using simple analyses of ground response incorporating measured properties of the shear wave velocities of the soils.

The study is part of cooperative investigation of these and other aspects of ground response in the Mexico City earthquake of September 19, 1985 being undertaken by investigators at the National University of Mexico and the University of California at Berkeley.

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1. Introduction

One of the most dramatic aspects of the earthquake effects in Mexico City in the earthquake of September 19, 1985 was the enormous differences in intensities of shaking and associated building damage in different parts of the city. In the south-west part of the city ground motions were moderate and building damage was minor. However in the north-west part of the city, catastrophic damages occurred and a record of the earthquake motions near the southern end of this heavy damage area showed a very high intensity of shaking. Similar patterns of building damage intensities have been observed in previous earthquakes and the differences attributed to the differences in soil conditions in different parts of the city. In the 1985 earthquake these differences seem to be somewhat more accentuated than in other earthquakes in the past 40 years, and the availability of recordings of ground motions in different parts of the city makes it possible to explore, in greater detail than heretofore, the relationships between soil conditions and intensities of shaking.

It is the purpose of this report to describe the soil conditions in Mexico City, present the results of special studies made since the earthquake to explore in detail the soil conditions at the sites of strong-motion recording stations and at other sites of interest in and near the city, and to present the results of some analytical studies of the extent to which the observed differences in shaking intensities can be predicted using simple analyses of ground response incorporating measured properties of the shear wave velocities of the soils.

The study is part of cooperative investigation of these and other aspects of ground response in the Mexico City earthquake of September 19,

1985 being undertaken by investigators at the National University of Mexico and the University of California, Berkeley.

Soil Conditions in Mexico City

The soil conditions in Mexico City have been the subject of many investigations in the past 50 years and before the earthquake of September 19, 1985 they were already reasonably well-established. The city is located on the edge of an old lake bed; thus while the western part of the city is underlain by rock and hard soil deposits, the eastern part of the city is located on soft clay deposits filling the former lake bed. An east-west profile showing this variation in soil conditions (after Zeevaert, 1972) is shown in Fig. 1-1. Between the hard formations in the west and the deep clay deposits in the east, there is a "transition zone" where the soils have generally stiff characteristics but may also involve some limited depths of soft clay.

In the lake bed area, the soft clay deposits which have shear wave velocities ranging from about 40 to 90 m/sec, are underlain by very stiff and hard formations (the hard layer) with shear wave velocities of the order of 500 m/sec or greater; thus there is a very marked change in wave velocity at this boundary and this facilitates considerably the analyses of wave propagation effects in the Mexico City clays. Contours showing the approximate depths of soils (mostly involving a surface layer of sand fill and an underlying deep layer of soft clay with interbedded layers of sand and silt) which overly the hard layer are shown in Fig. 1-2 (modified after Resendiz et al., 1970).

It is important to recognize that the clay beds extend considerably to the north and south of the main part of Mexico City. The city itself is

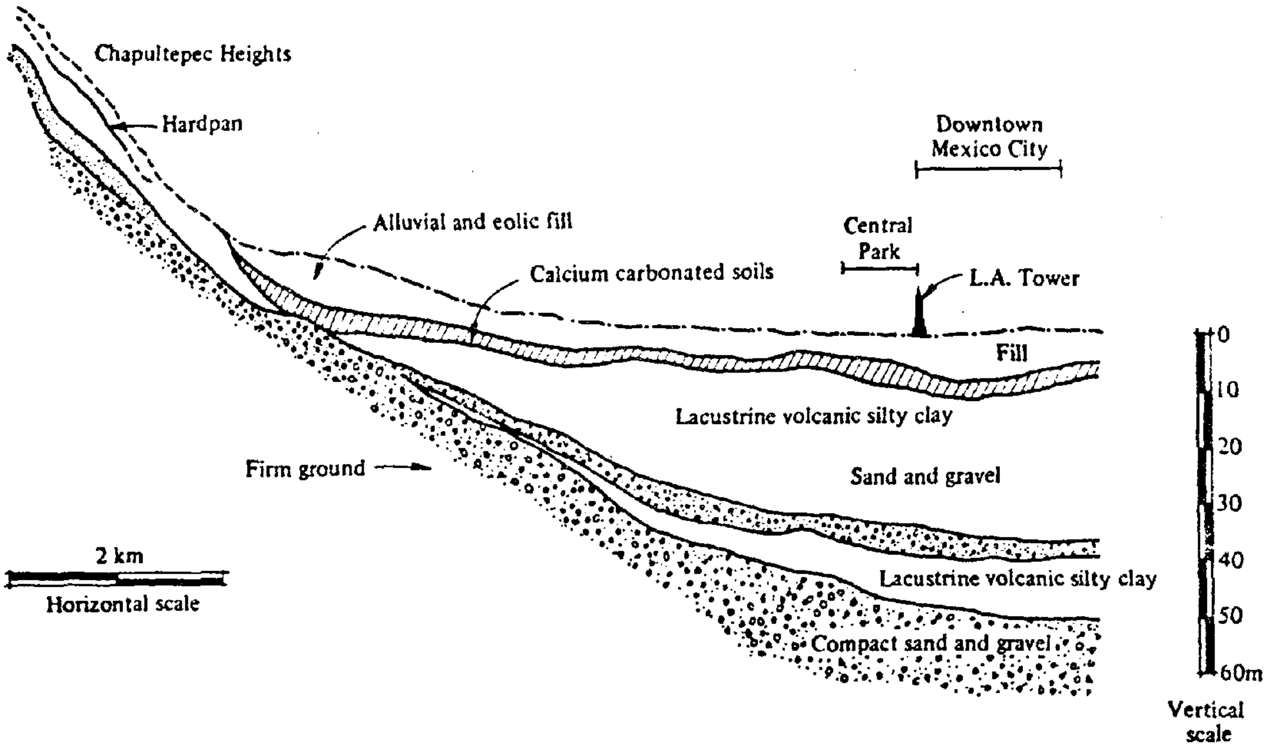


Fig. 1-1 EAST-WEST SOIL PROFILE - BASIN OF VALLEY OF MEXICO (after Zeevaert, 1972)

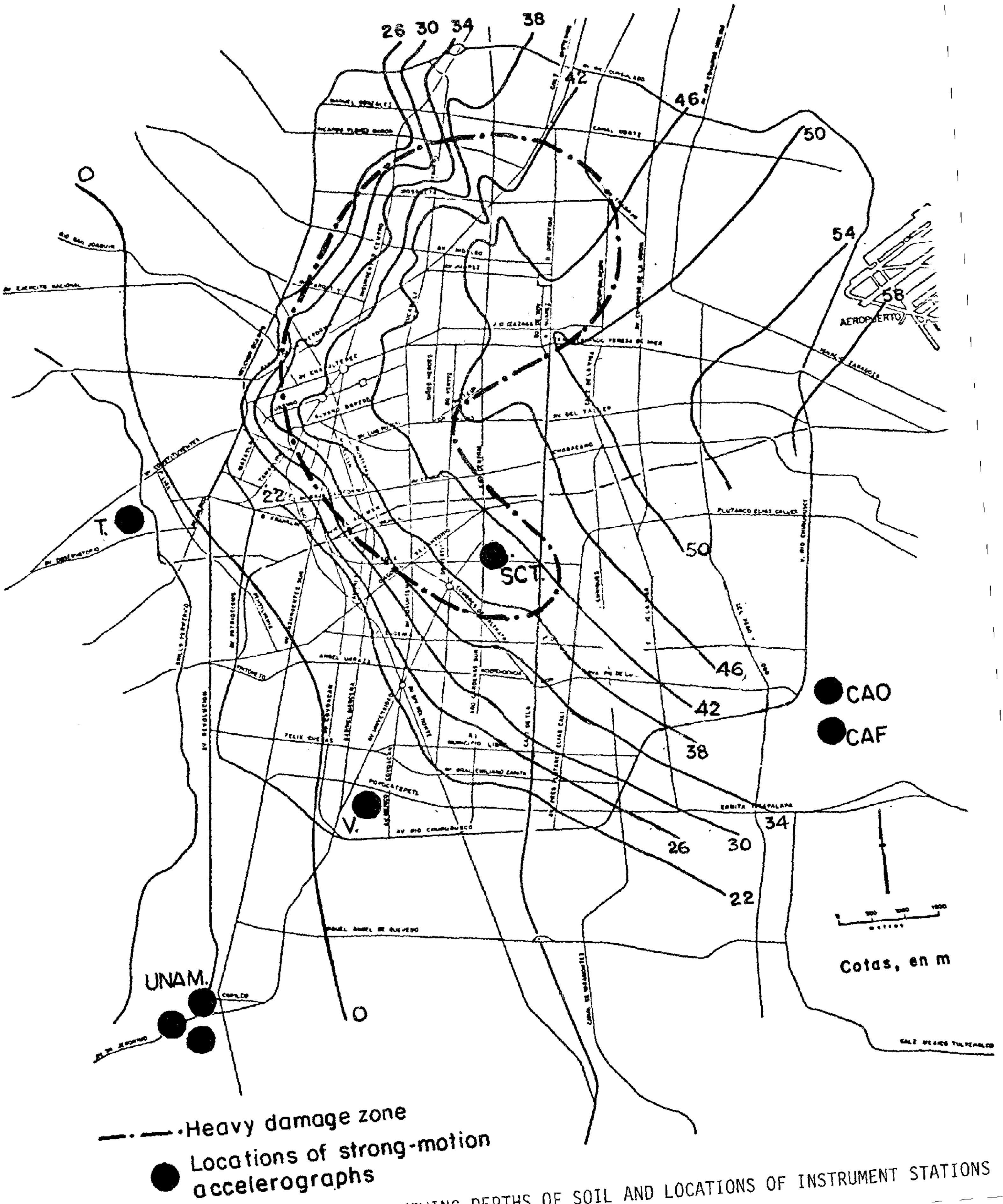


Fig. 1-2 PLAN OF MEXICO CITY SHOWING DEPTHS OF SOIL AND LOCATIONS OF INSTRUMENT STATIONS

located on the edge of the former Texcoco Lake which extends about 35 kms to the north. This lake was separated by a ridge of hills across the southern part of the city, from a second lake, the Xochimilco-Chalco Lake as shown in Fig. 1-3. Both of the lake beds are now essentially filled with clay deposits, but the clays have somewhat different characteristics, the Xochimilco-Chalco Lake clays being somewhat stiffer and stronger than the Texcoco Lake clays.

Damage surveys show that virtually all the structures which collapsed or suffered major damage in the earthquake of September 19, 1985 lie within the zone bounded by the chain-dot line in Fig. 1-2. The soil depth contours in Fig. 1-2 indicate that within this zone, the depth to the hard layer typically ranges from about 26 to 44 meters. On the shallow soil deposits to the west and south, and on the deeper clay deposits to the east and north, damage was relatively minor. Surveys show that the major damage in the heavy damage area occurred to structures with story heights ranging from about 6 to 18 stories.

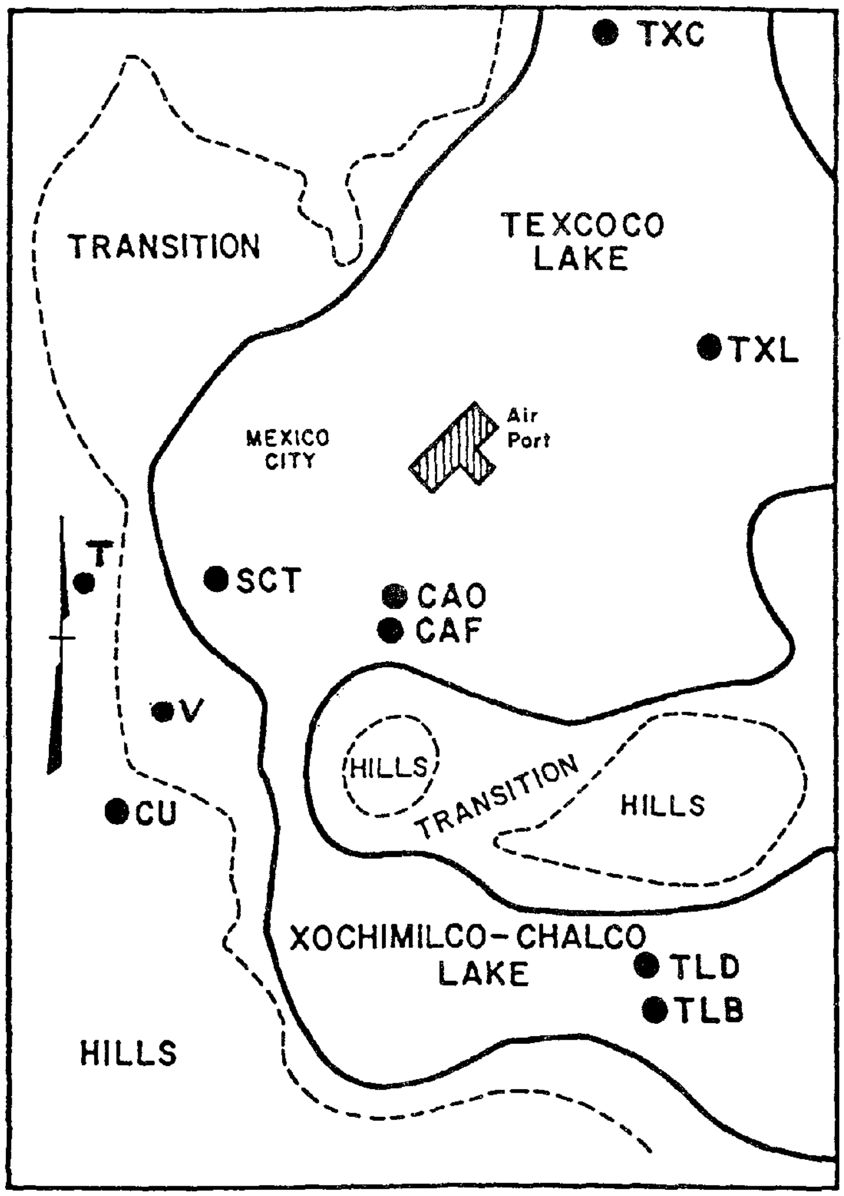


Fig. 1-3 LAKE DEPOSITS NEAR MEXICO CITY AND LOCATIONS OF RECORDING STATIONS

2. Ground Motions in the Sept. 19, 1985 Earthquake

Strong motion records of the earthquake of Sept. 19, 1985 were obtained at a number of sites in and around Mexico City including:

1. Three sites located on the rock and stiff soil area at the University of Mexico (UNAM).
2. One site on the rock and stiff soil area at Tacubaya (T).
3. One site located on the transition zone at Viveros (V).
4. One site (the SCT Building site) on the clay deposits near the southern boundary of the heavy damage area; the depth of soils overlying the hard formations at this site is about 37 m. Acceleration response spectra for the two components of motion at this site are shown in Fig. 2-1.
5. Two sites about 0.5 km apart on the deeper clay deposits in the Central Market area; at one site (CAF) the soil depth was about 45 m and at the other site (CAO) the soil depth was about 56 m. Acceleration response spectra for the motions recorded at each of these sites are shown in Figs. 2-2 and 2-3.
6. Two sites about 3 kms apart to the south of the city on the clay deposits formed in the Xochimilco-Chalco Lake. At one of these sites (TLD) the depth of soil was about 65 m and at the other site (TLB) the depth to the hard layer was about 105 m. Acceleration response spectra for the motions recorded at these sites are shown in Figs. 2-4 and 2-5.
7. Two sites on the Texcoco Lake clay deposits to the north or east of Mexico City, designated TXC and TXL in Fig. 1-3. No detailed

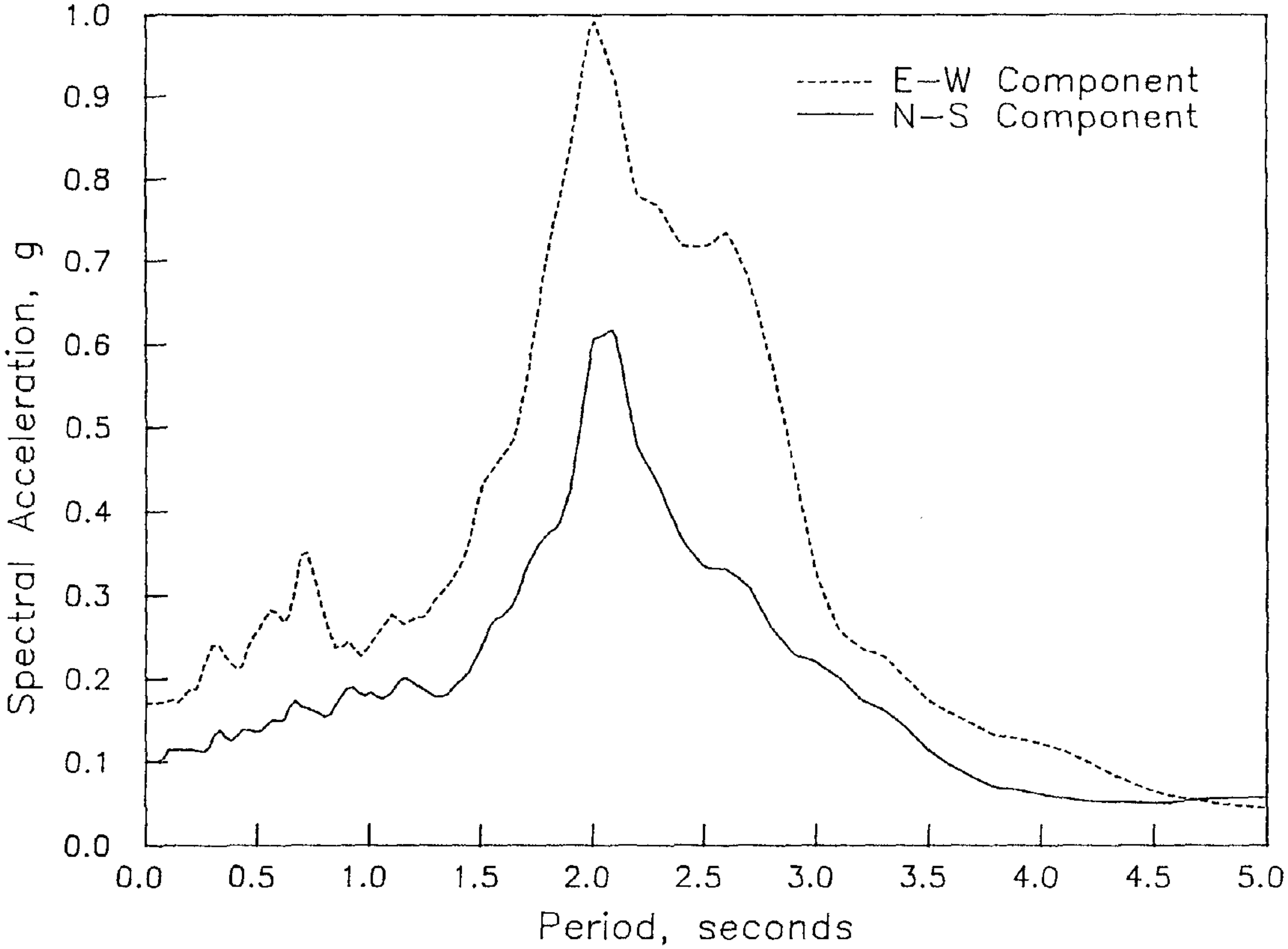


Fig. 2-1 ACCELERATION RESPONSE SPECTRA FOR GROUND MOTIONS RECORDED AT SCT SITE

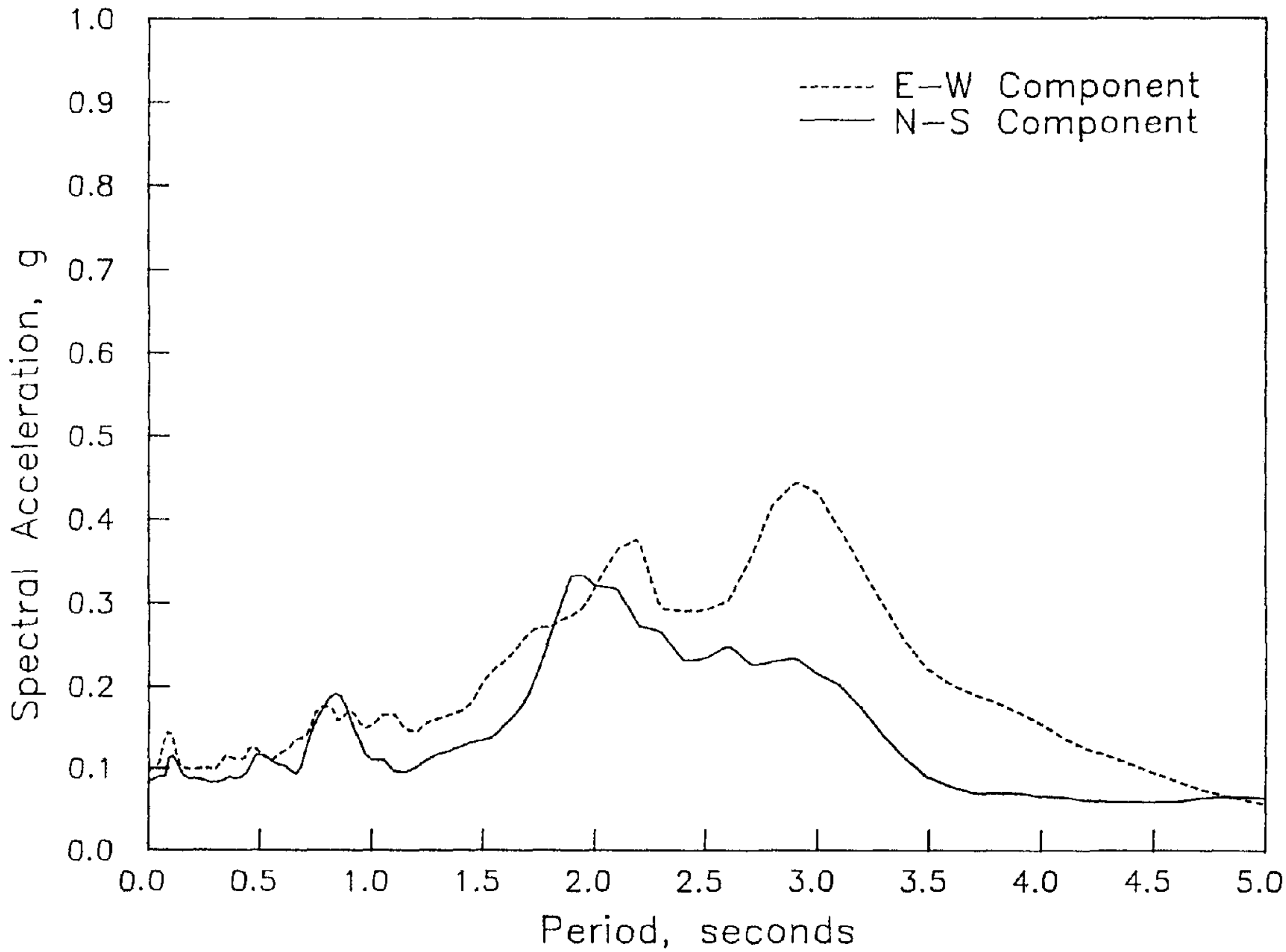


Fig. 2-2 ACCELERATION RESPONSE SPECTRA FOR GROUND MOTIONS RECORDED AT CAF SITE

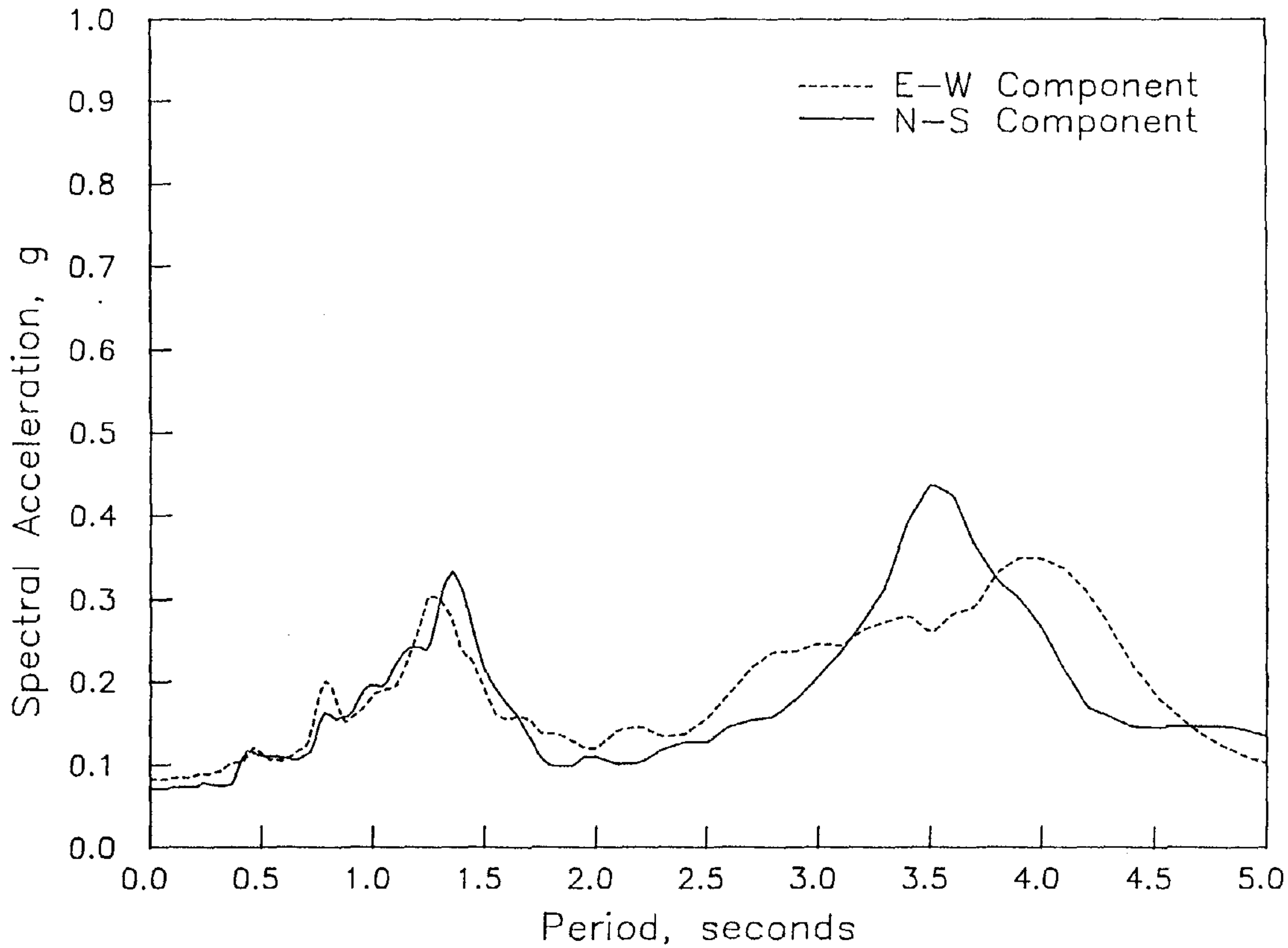


Fig. 2-3 ACCELERATION RESPONSE SPECTRA FOR GROUND MOTIONS RECORDED AT CAO SITE

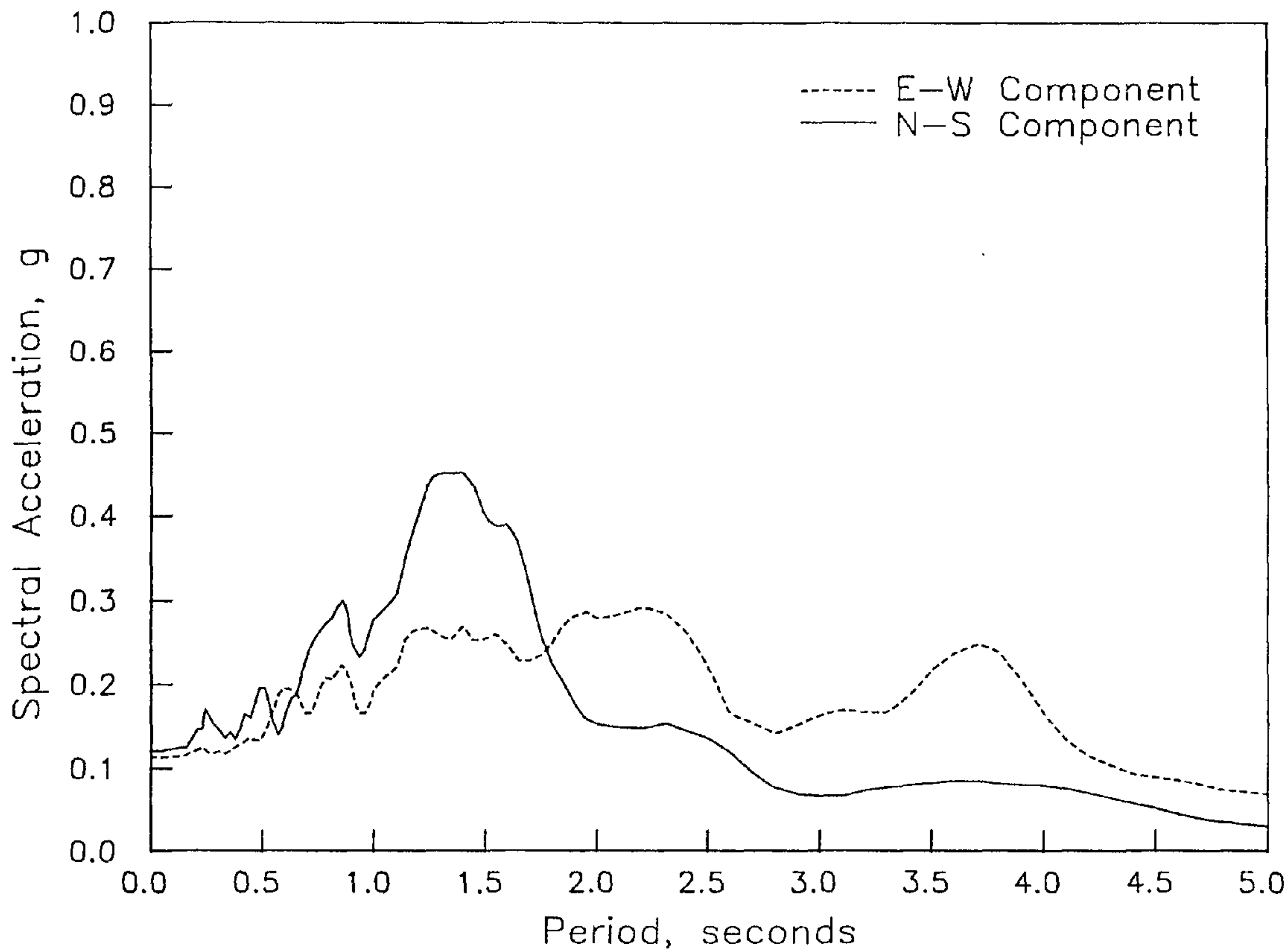


Fig. 2-4 ACCELERATION RESPONSE SPECTRA FOR GROUND MOTIONS RECORDED AT TLD SITE

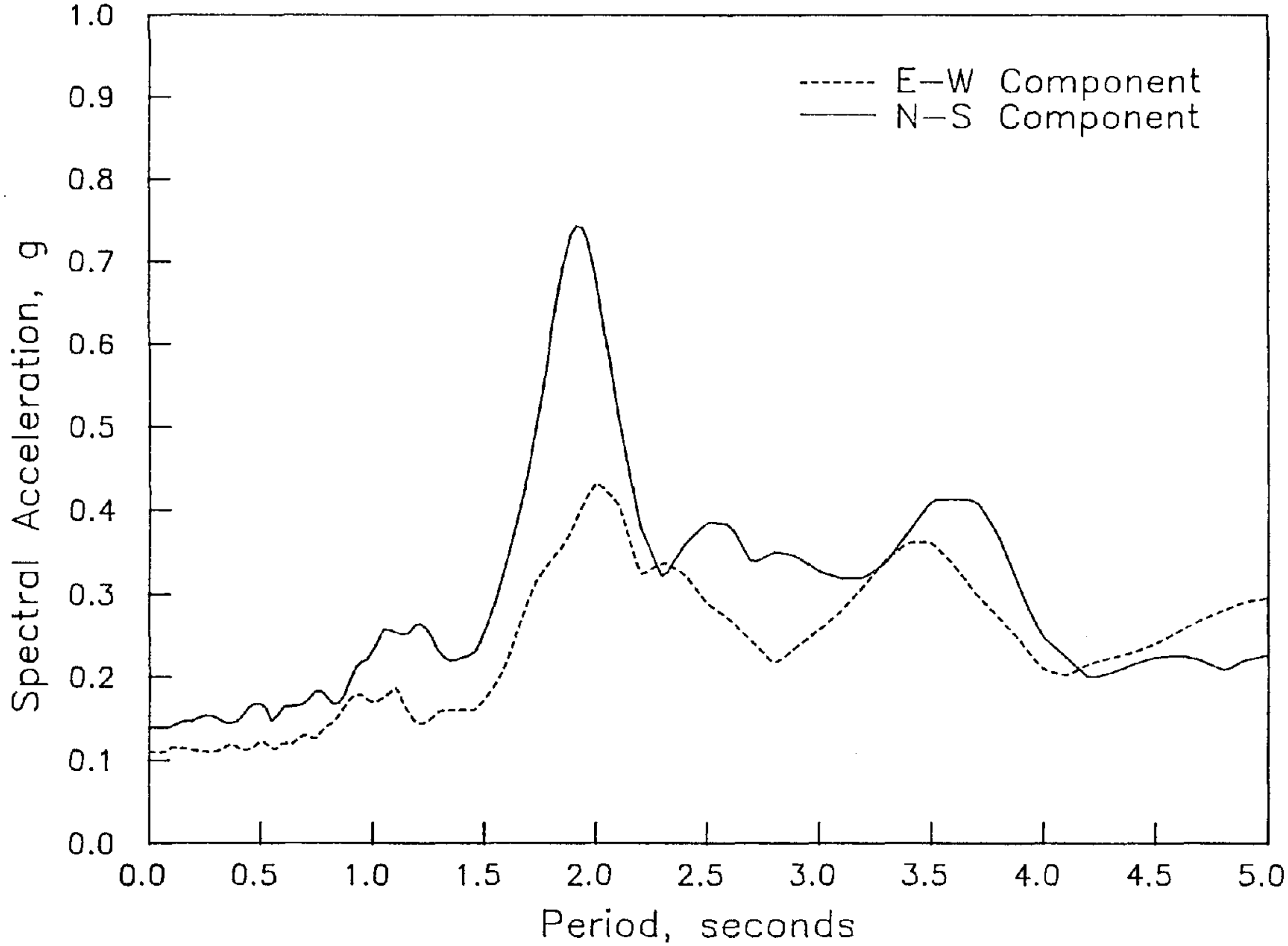


Fig. 2-5 ACCELERATION RESPONSE SPECTRA FOR GROUND MOTIONS RECORDED AT TLB SITE

information is available concerning the soil conditions at these sites.

The locations of all these recording sites are shown in Figs. 1-2 and 1-3.

The records of the earthquake motions obtained at the various sites indicate that:

1. Motions recorded at the University sites and at Tacubaya on the rock and hard soil deposits had generally similar characteristics with peak ground accelerations of the order of 0.04 g, peak spectral accelerations (5% damping) of about 0.11 g, and a predominant period of about 2 seconds.
2. There was a major amplification of the motions by the soft clay deposits underlying the SCT and Central Market sites. At the SCT site, where the soil conditions are more closely comparable to those in the heavy damage area to the north, the peak ground acceleration was about 0.17 g and the peak spectral acceleration for 5% damping was about 1.0 g at a period of about 2 seconds.
3. There were significant differences in the ground motions recorded at the SCT building site and at the Central Market sites, with the Central Market sites showing lower peak accelerations and maximum spectral amplifications at higher periods than at the SCT site. Thus at the CAO site, where the depth of soil was about 56 m, the peak ground acceleration was about 0.09 g, and the peak spectral acceleration (5% damping) was about 0.35 g at a period of about 3.5 seconds.

A comparison of representative average spectra for the SCT Building site, the Central Market site (CAO) and for sites in the rock and stiff soil zones is shown in Fig. 2-6. It is readily apparent from this comparison

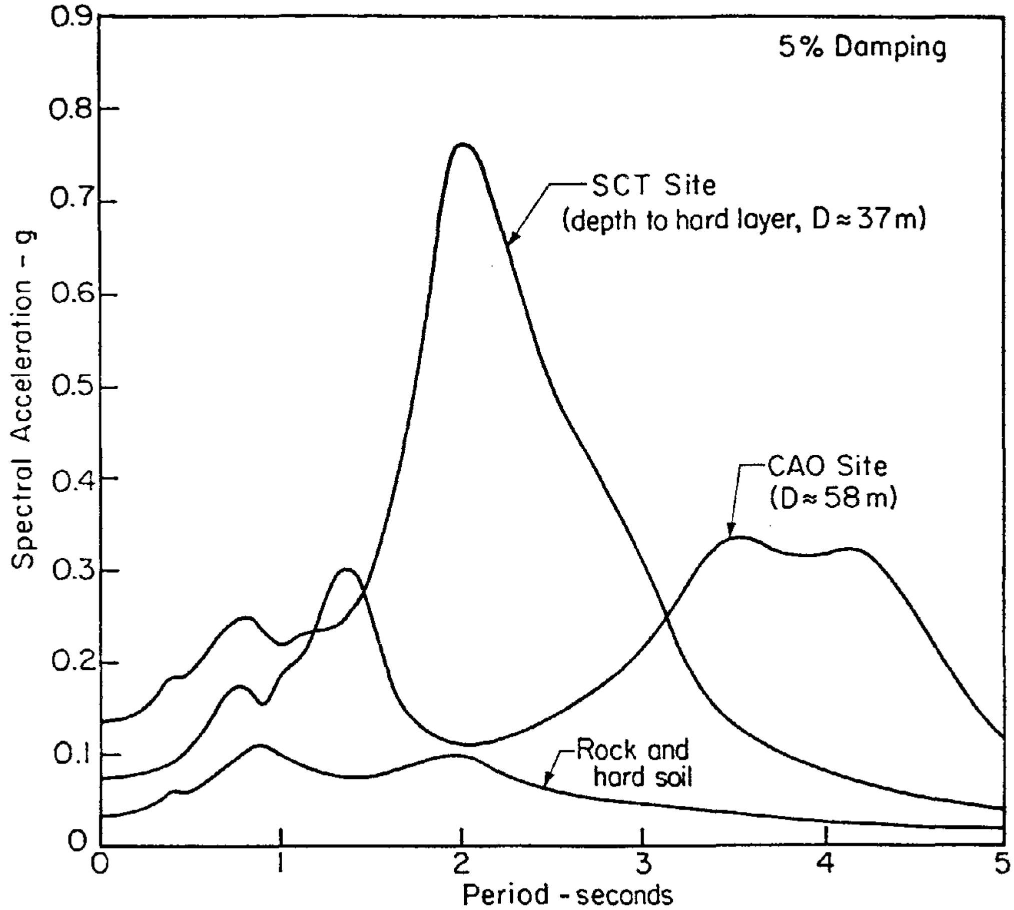


Fig. 2-6 AVERAGE ACCELERATION RESPONSE SPECTRA FOR MOTIONS RECORDED ON DIFFERENT SOIL CONDITIONS

why damage was negligible in the rock and stiff soil zones but very severe in the central part of the city underlain by clay layers with depths ranging between about 30 to 45 m.

It is interesting to note that one day after the main shock, the city was subjected to a major aftershock of Magnitude 7.5. Ground motions were recorded at some of the same stations in the aftershock; the motions were somewhat lower in intensity during the aftershock, as evidenced by the comparison between the response spectra for main shock and aftershock motions at the CAO site shown in Fig. 2-7. It is noteworthy that the forms of the response spectra at this site were remarkably similar for the two events, although the spectral peaks occurred at slightly lower periods in the aftershock, suggesting that the strains induced during the September 19 event were high enough to produce some small non-linear effects in the ground response (Romo and Seed, 1986).

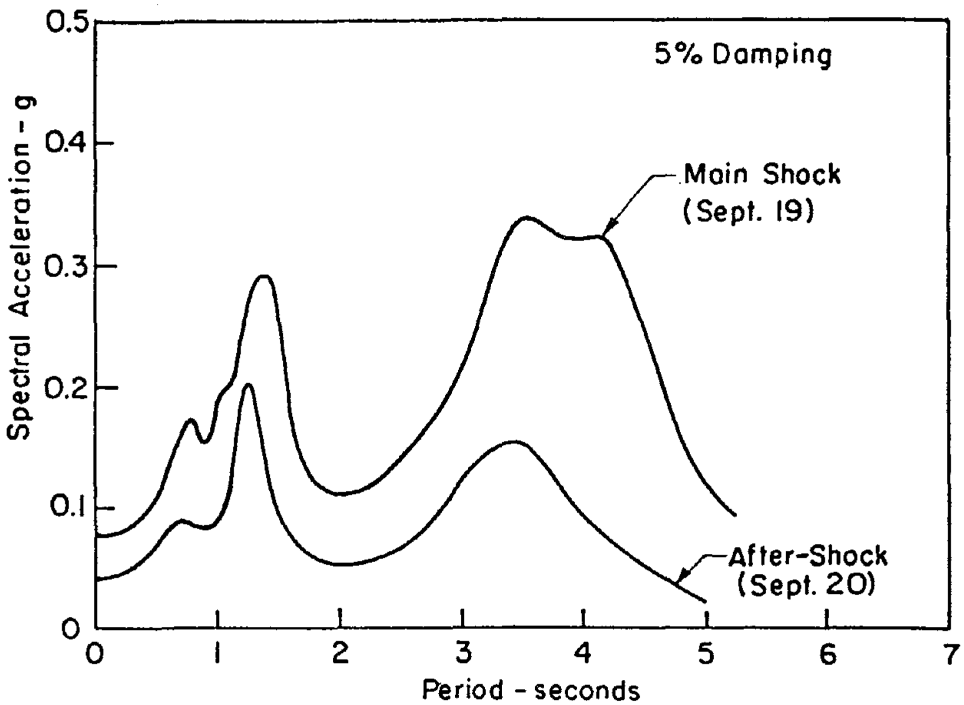


Fig. 2-7 AVERAGE RESPONSE SPECTRA AT CAO SITE FOR MAIN SHOCK AND STRONGEST AFTERSHOCK

3. Ground Motions on Rock and Hard Soil at UNAM

Of particular interest in studying the effects of local soil conditions on the ground motions throughout the city are the characteristics of the motions recorded on the rock and hard soil formations at the 3 stations located at the National University of Mexico. A shear wave velocity profile for one site in this area is shown in Fig. 3-1. At this site there is a layer of fractured lava about 12 m deep overlying soft rock with a shear wave velocity ranging from 450 to 600 m/sec at depths between 12 and 21 m. However the depth of the lava cover varies and outcrops of soft rock are readily apparent in the area. It is believed that the conditions in this area are thus reasonably representative of the "hard layer" which underlies the clay deposits throughout Mexico City.

In all, six horizontal components of motion were obtained at the three recording stations at UNAM. The response spectra for these six components are shown in Fig. 3-2. While the motions show some variations, they have some general characteristics in common, most showing spectral peaks at periods of the order of 0.9 second and about 2 seconds. The mean spectral shape for the six records is shown in Fig. 3-3, together with the upper and lower bounds of the spectral values determined from the six records. The mean value can presumably be considered to provide a good general characterization of the motions developed on the hard layer in the University area and at any similar outcropping of the hard layer in the Mexico City area.

For ground response analysis purposes it is necessary to select a ground motion record which can be considered representative of the motions on the hard foundation. Fig. 3-4 shows a comparison of the average

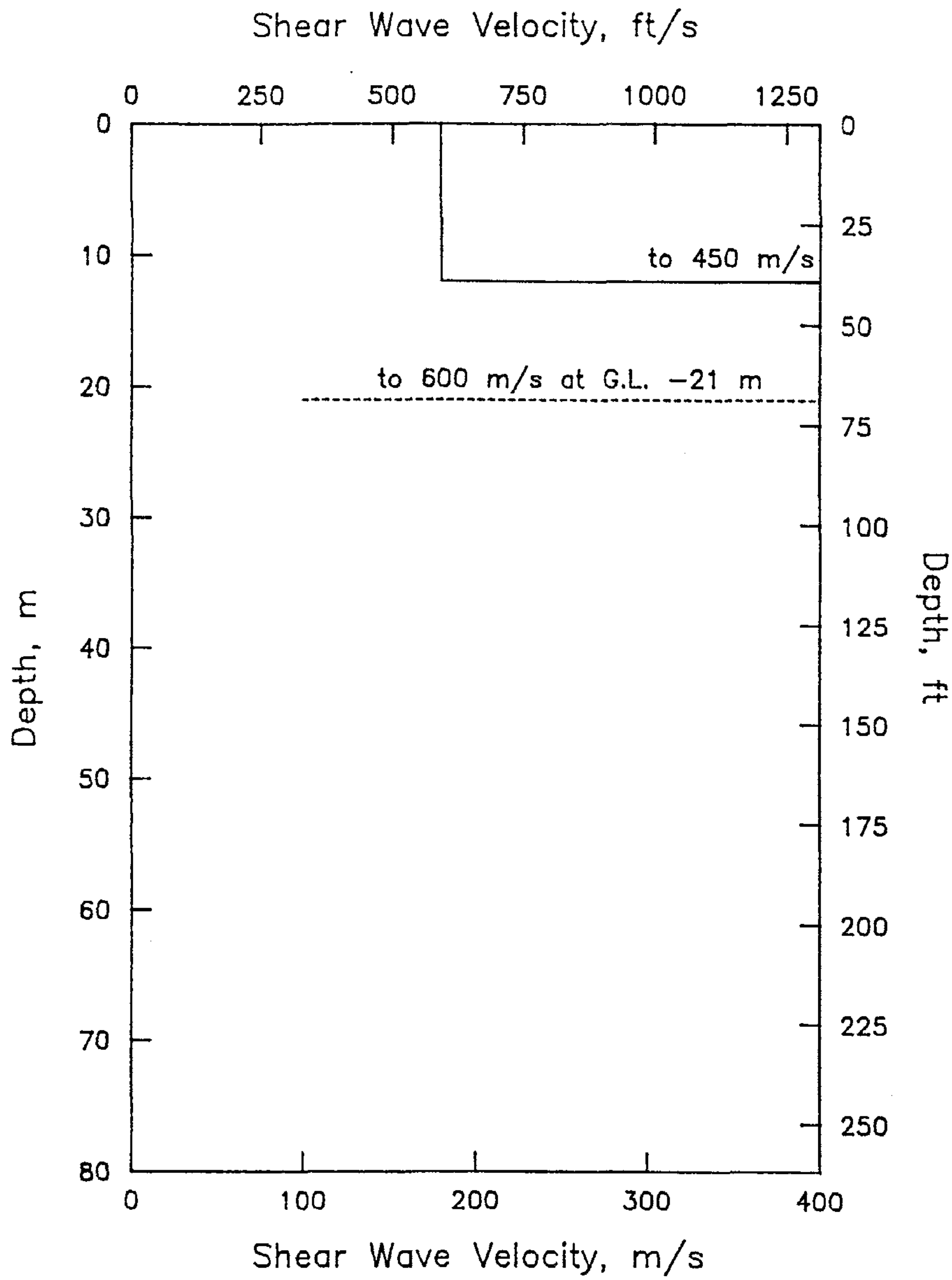


Fig. 3-1 SHEAR WAVE VELOCITY PROFILE AT UNAM SITE

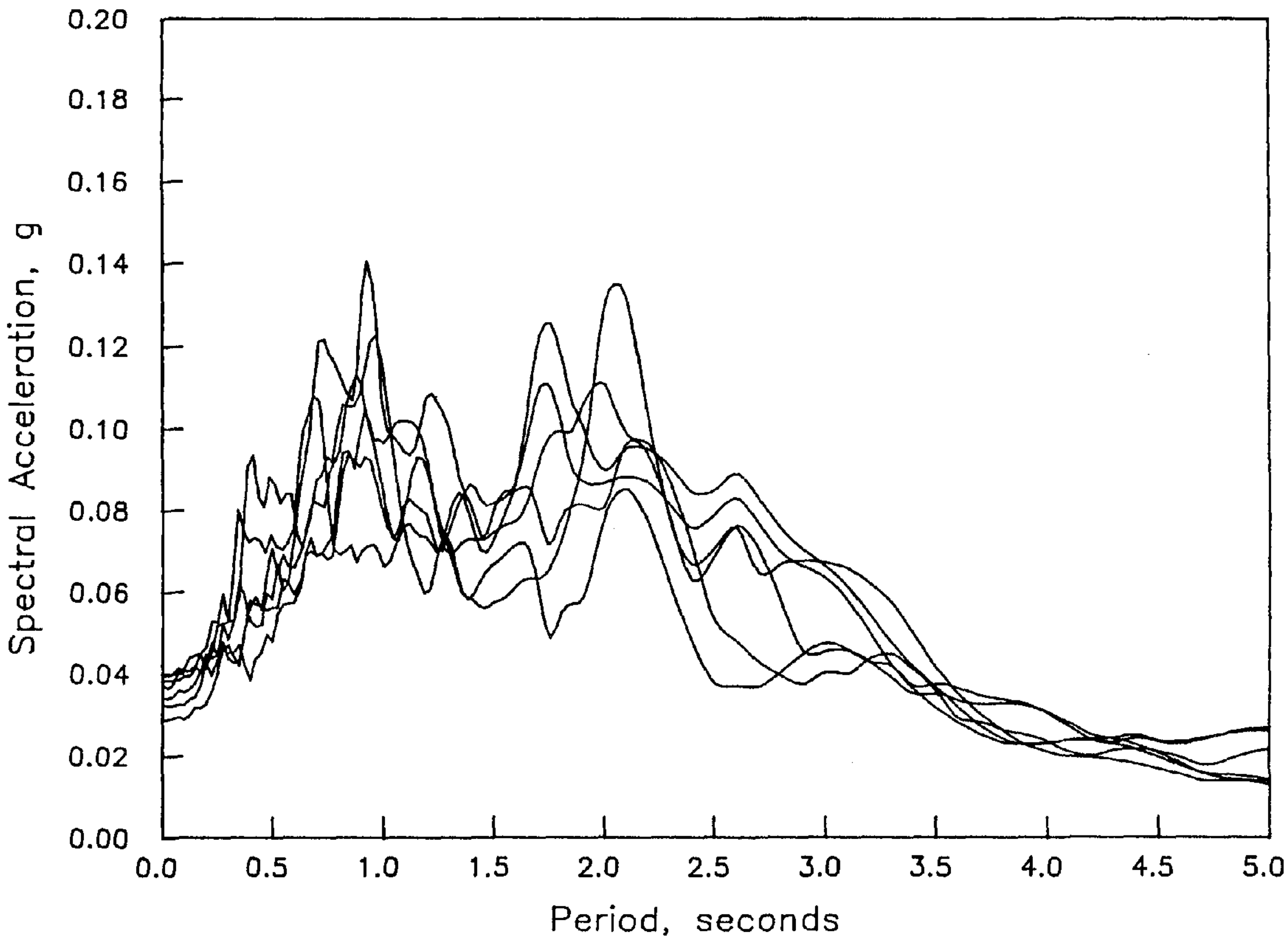


Fig. 3-2 ACCELERATION RESPONSE SPECTRA FOR GROUND MOTIONS RECORDED AT UNAM SITES

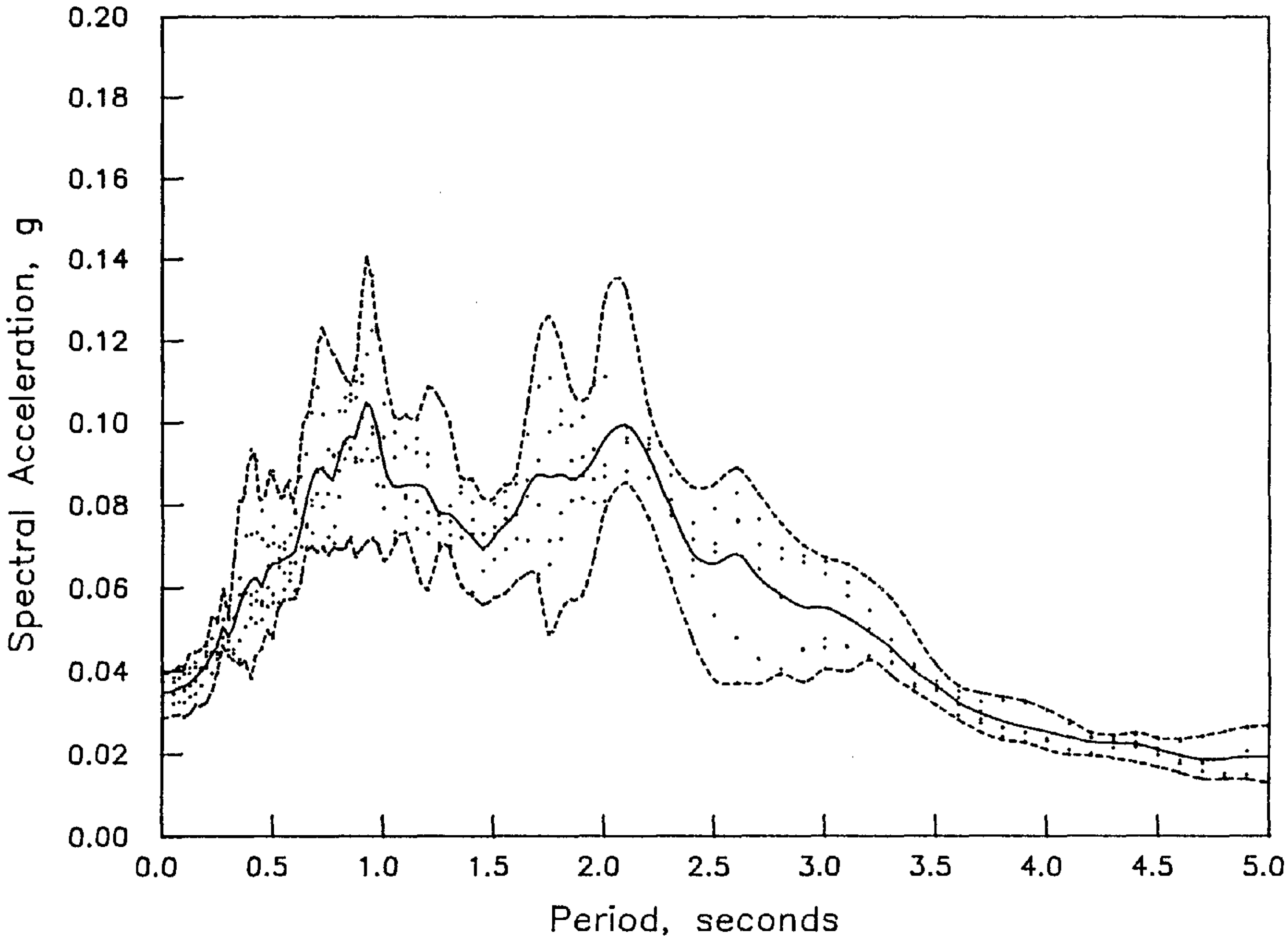


Fig. 3-3 UPPER AND LOWER BOUNDS AND AVERAGE SPECTRA FOR MOTIONS RECORDED AT UNAM SITES

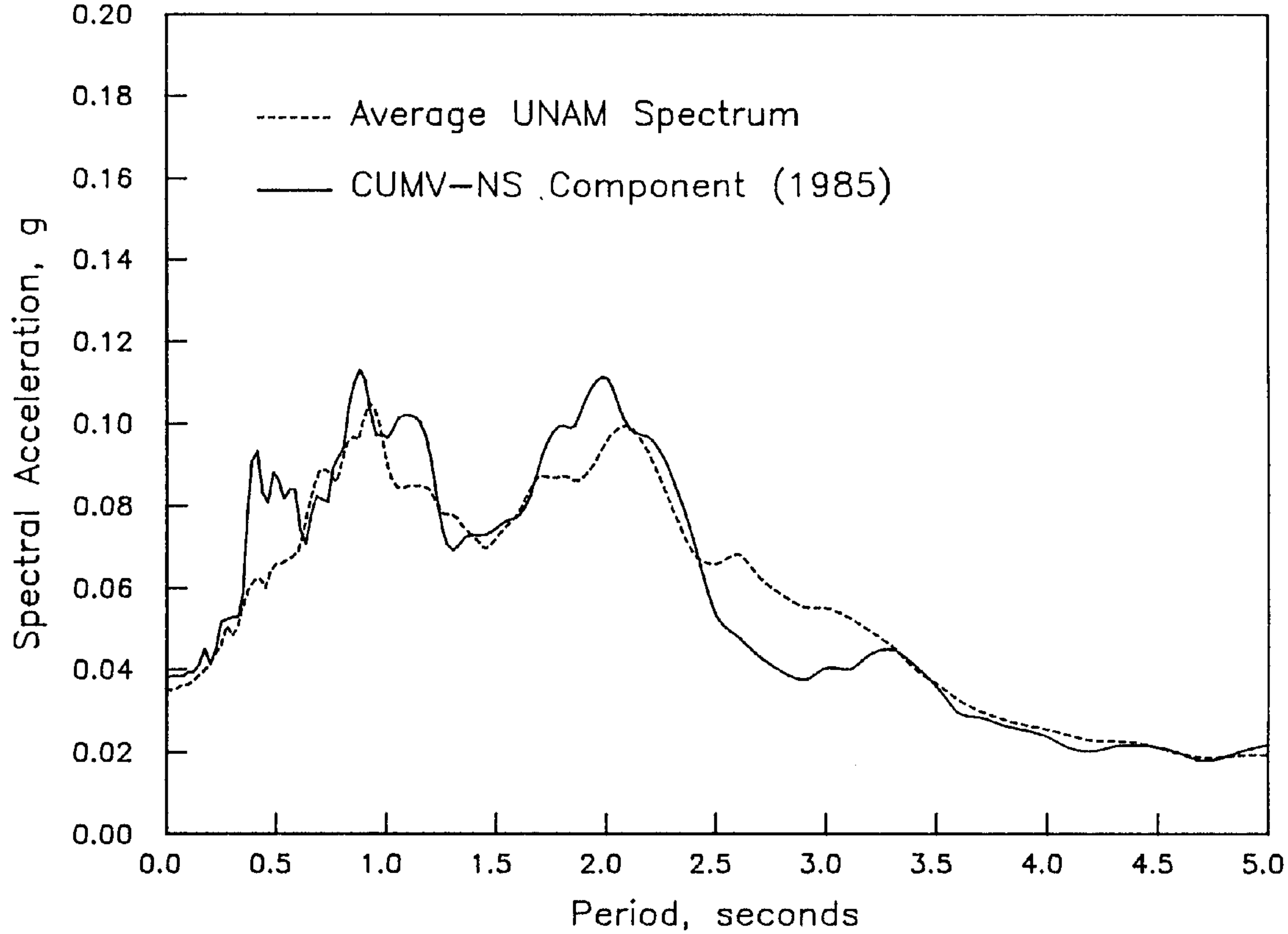


Fig. 3-4 COMPARISON OF AVERAGE SPECTRUM FOR MOTIONS RECORDED AT UNAM SITES WITH SPECTRUM FOR N-S COMPONENT OF MOTIONS RECORDED AT CUMV SITE

response spectra for the six UNAM records with the response spectrum for one of the components (N-S) of the motion recorded at the CUMV site at UNAM. It may be seen that this NS component has spectral characteristics very close to the average for all components and thus provides a reasonable representation of the average motions on the hard-rock formation in the Mexico City area.

This record has a peak ground acceleration of 0.038 g and it has spectral peaks at about 0.9 seconds and 2.1 seconds. The full acceleration and velocity time histories of the motion are shown in Fig. 3-5.

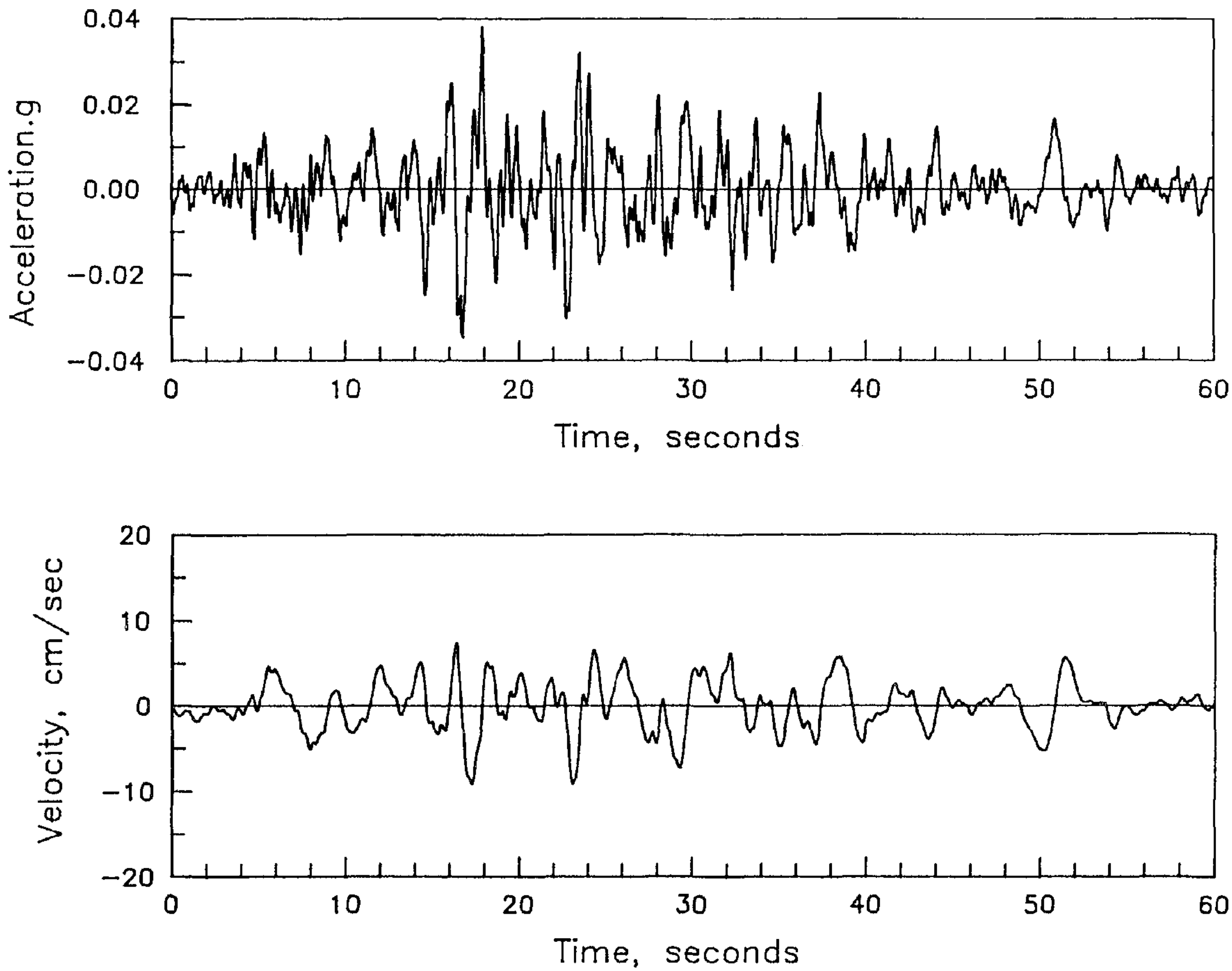


Fig. 3-5 ACCELERATION AND VELOCITY TIME HISTORIES FOR N-S COMPONENT OF MOTIONS RECORDED AT CUMV SITE

4. Detailed Studies of Soil Conditions at Recording Stations

The characteristics of the Mexico City clay and other soils at the recording stations in and around Mexico City were determined using a variety of techniques including:

1. Boring and sampling procedures.
2. Measurements of penetration resistance using CPT procedures.
3. Laboratory tests (resonant column and cyclic triaxial tests) on good quality undisturbed samples.
4. Evaluation of average shear wave velocities of the soils from the earthquake records for each station. For this purpose the clay at any given site was considered to be uniform with depth and the average stiffness was determined from the natural frequency of the site evaluated directly from the Fourier spectrum of the recorded motions. It was recognized that this procedure would not normally be available for other sites but it was considered to provide probably the best estimate of average shear wave velocities of the soils of any of the techniques available.
5. Direct measurements in boreholes of the shear wave velocity profile of the soil deposits using down-hole techniques and P-S suspension logging techniques.

These studies led to the following determinations of the soil conditions at the various sites.

(1) SCT Site

The subsoil conditions at the SCT site consist of a compact 4 m thick layer of mixed sand, silt and clay, followed by a 27 m thick clay layer with interbedded seams of silty sand, volcanic glass, fly ash, sands and

silts; the water content in the clayey materials ranges from about 100% to 450% and the undrained shear strength varies from 0.25 to 0.8 kg/cm^2. Underlying this layer there is a very compact, lightly cemented 3 m thick stratum of sandy silt, followed by a 4 m thick layer of very stiff clay overlying the so-called hard layer; the hard layer consists of deep deposits of a very hard and stiff layer (more than 100 SPT blows/ft) of cemented silty sand which is usually considered as the base of the soil profile.

Based on the natural period of the site, the average shear wave velocity of the clay layer was determined to be about 75 m/sec leading to a determination of the soil profile for the site as shown in Fig. 4-1.

The results of direct measurements of the shear wave velocities of the various soil layers are shown in Fig. 4-2, and an interpreted representative shear wave velocity profile, based on these results is shown in Fig. 4-3. It may be seen that the measured shear wave velocities in the clay are somewhat lower than the average value determined from the natural period of the site for the motions recorded in the 1985 earthquake.

(2) <u>CAO Site</u>

The subsoil conditions at the CAO site consist of a layer of silty sand 5 m deep followed by a 37 m thick layer of clay with interbedded seams of silty sand, fly ash, volcanic glass and silts; the water content in the clayey soils varies from about 150 to 500 percent, and the undrained shear strength from about 0.2 to 0.6 kg/cm^2. Underneath this clay layer are a series of intercalated strata of sandy silts and silty clays about 10 m in thickness, followed by a 4 m thick layer of stiff clay which overlies the deep hard deposits.

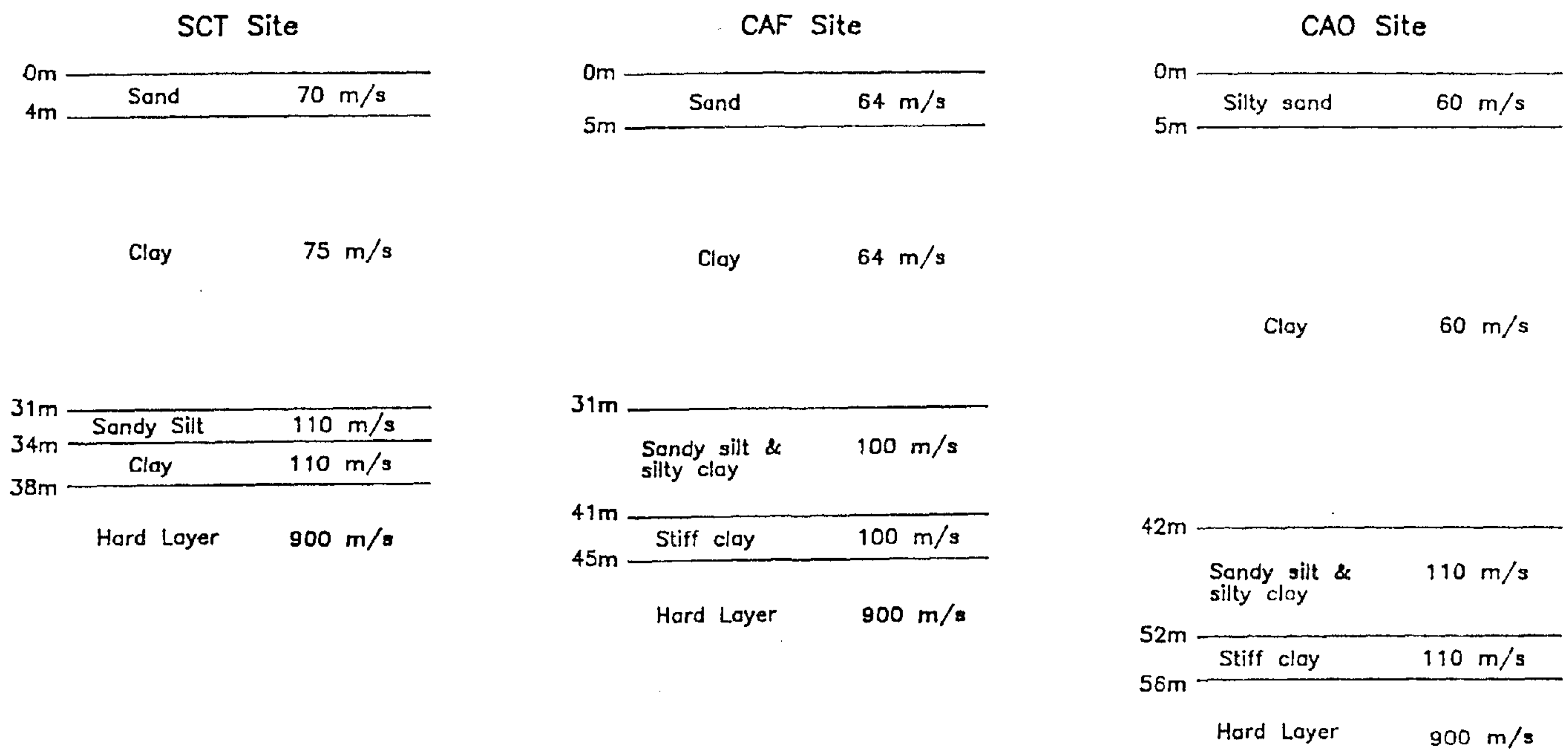


Fig. 4-1 SOIL PROFILES AT SCT, CAF AND CAO SITES BASED ON BORINGS AND FREQUENCY CHARACTERISTICS OF RECORDED GROUND MOTIONS

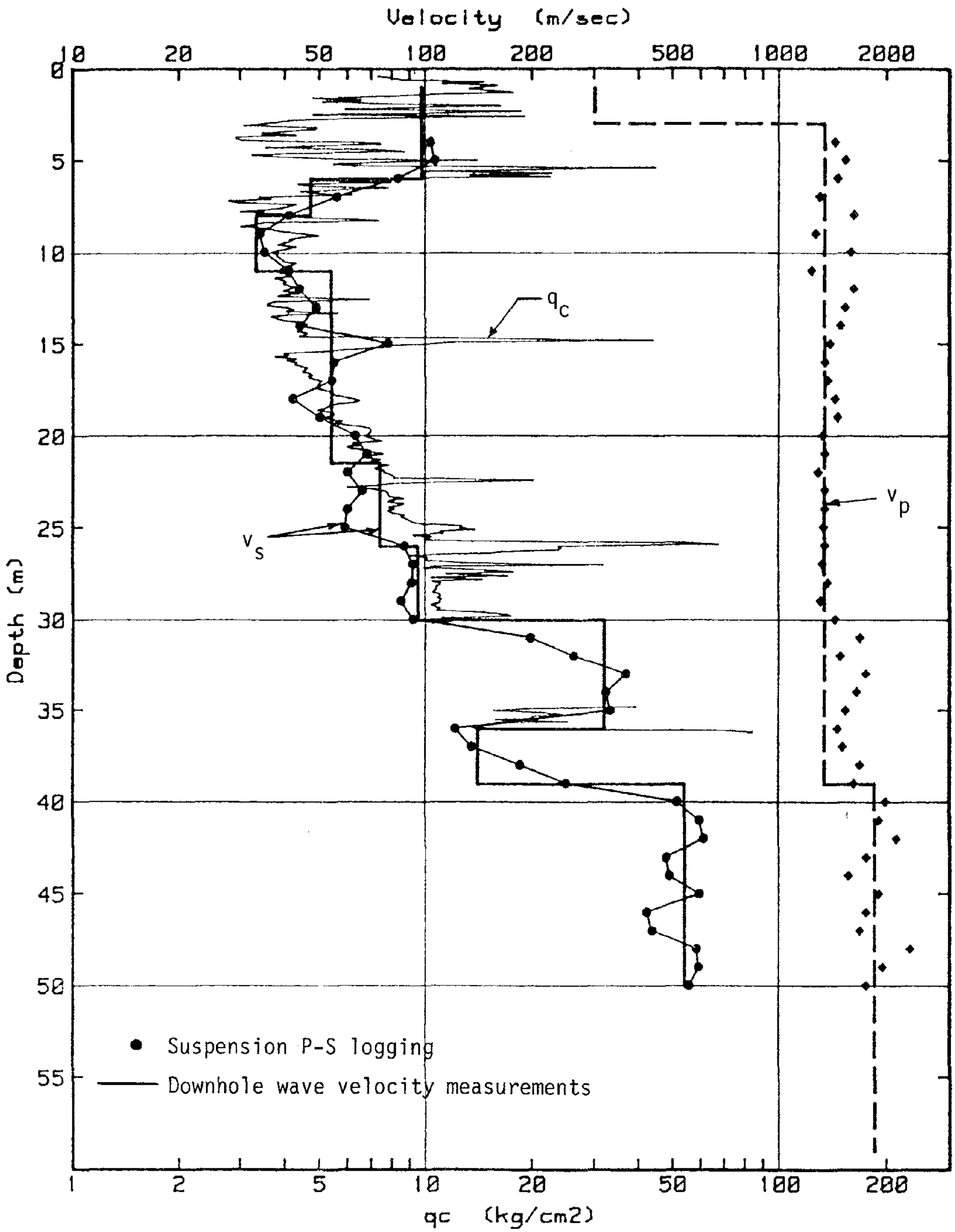


Fig. 4-2 MEASURED SHEAR WAVE VELOCITIES AT SCT SITE

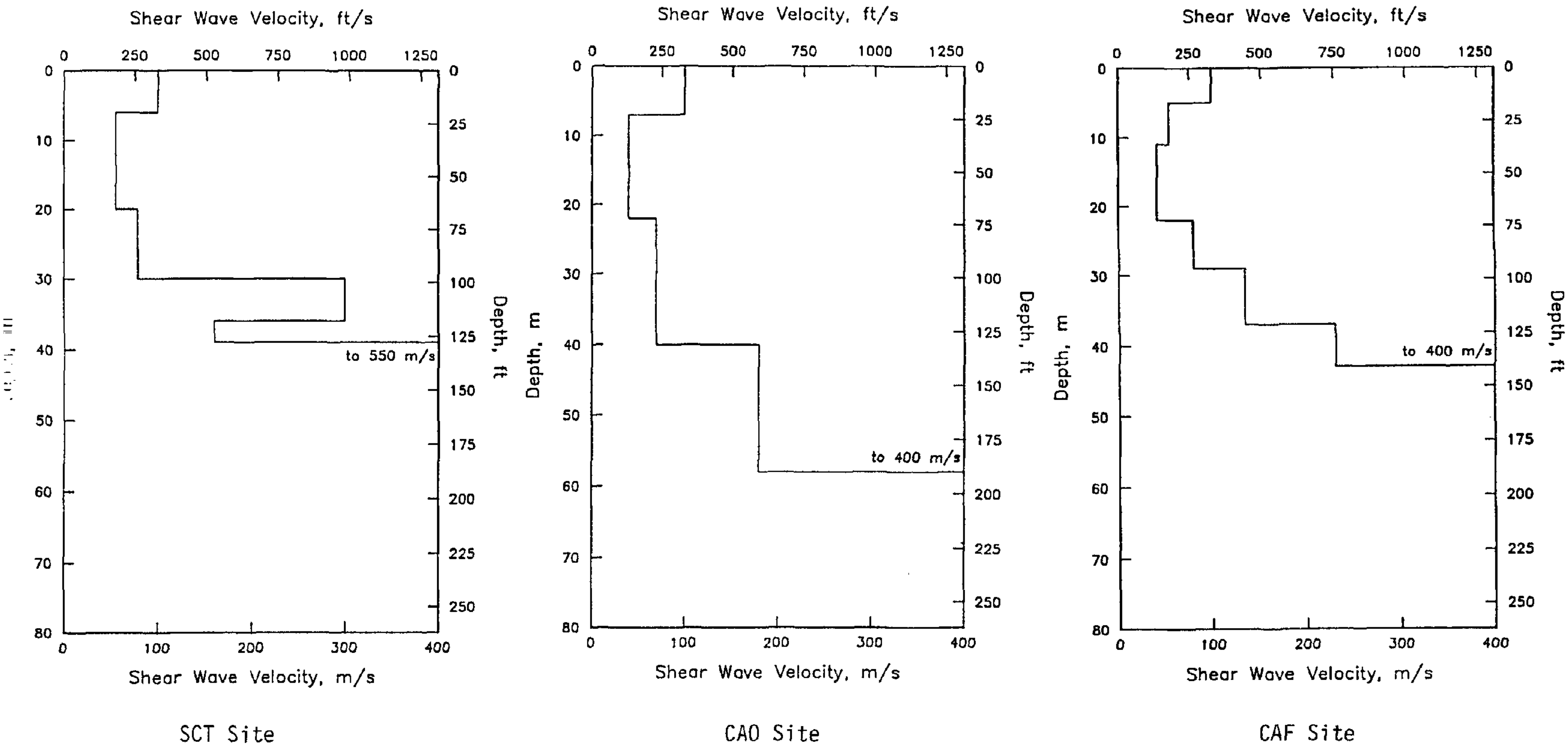


Fig. 4-3 INTERPRETED SHEAR WAVE VELOCITY PROFILES AT SCT, CAO AND CAF SITES

Based on the natural period of the site, the average shear wave velocity of the clay was estimated to be about 60 m/sec, leading to a determination of a representative soil profile as shown in Fig. 4-1.

The results of direct measurements of the shear wave velocities of the various soil layers are shown in Fig. 4-4, and an interpreted representative shear wave velocity profile, based on these results, is shown in Fig. 4-3.

(3) <u>CAF Site</u>

The CAF site is located about 0.8 km south of the CAO site. The upper 15 m of the soil profiles at the two sites are very similar but the clay layer at the CAF site seems to be slightly stiffer and about 11 m less in thickness. Thus the hard layer is encountered at a depth of about 45 m at the CAF site.

Based on the natural period of the site, the average shear wave velocity of the clay was estimated to be about 64 m/sec and the soil profile to have the general characteristics shown in Fig. 4-1.

The results of direct shear wave velocity measurements at the site using downhole techniques and P-S logging techniques are shown in Fig. 4-5, and an interpreted representative shear wave velocity profile based on these results is shown in Fig. 4-3.

(4) <u>TLB Site</u>

The soil conditions at the TLB site consist of a layer of sand fill about 5 m thick underlain by a thick layer of clay, containing seams of sand and silt, which extends to a depth of about 105 m, where the hard layer is encountered.

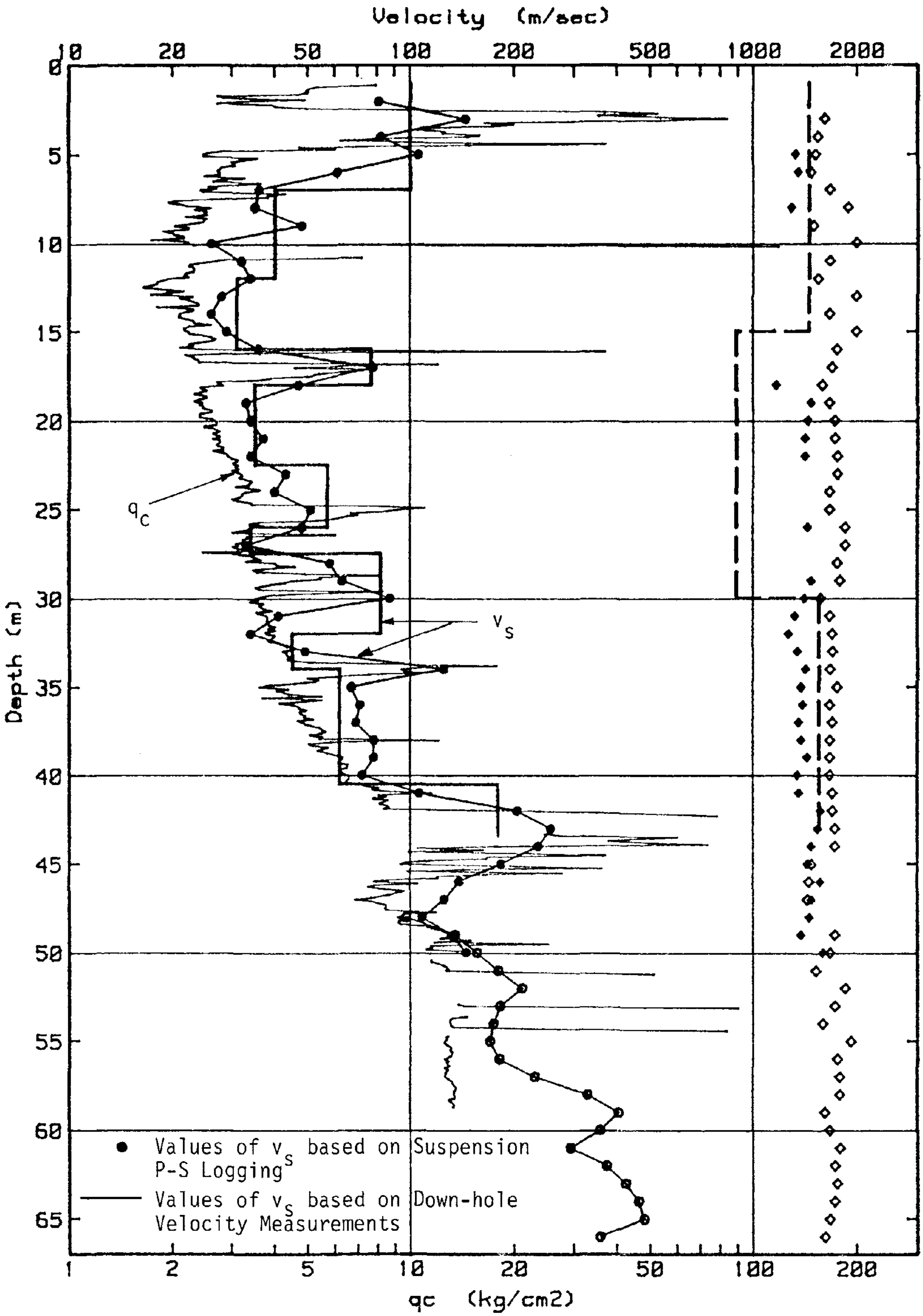


Fig. 4-4 MEASURED SHEAR WAVE VELOCITIES AT CAO SITE

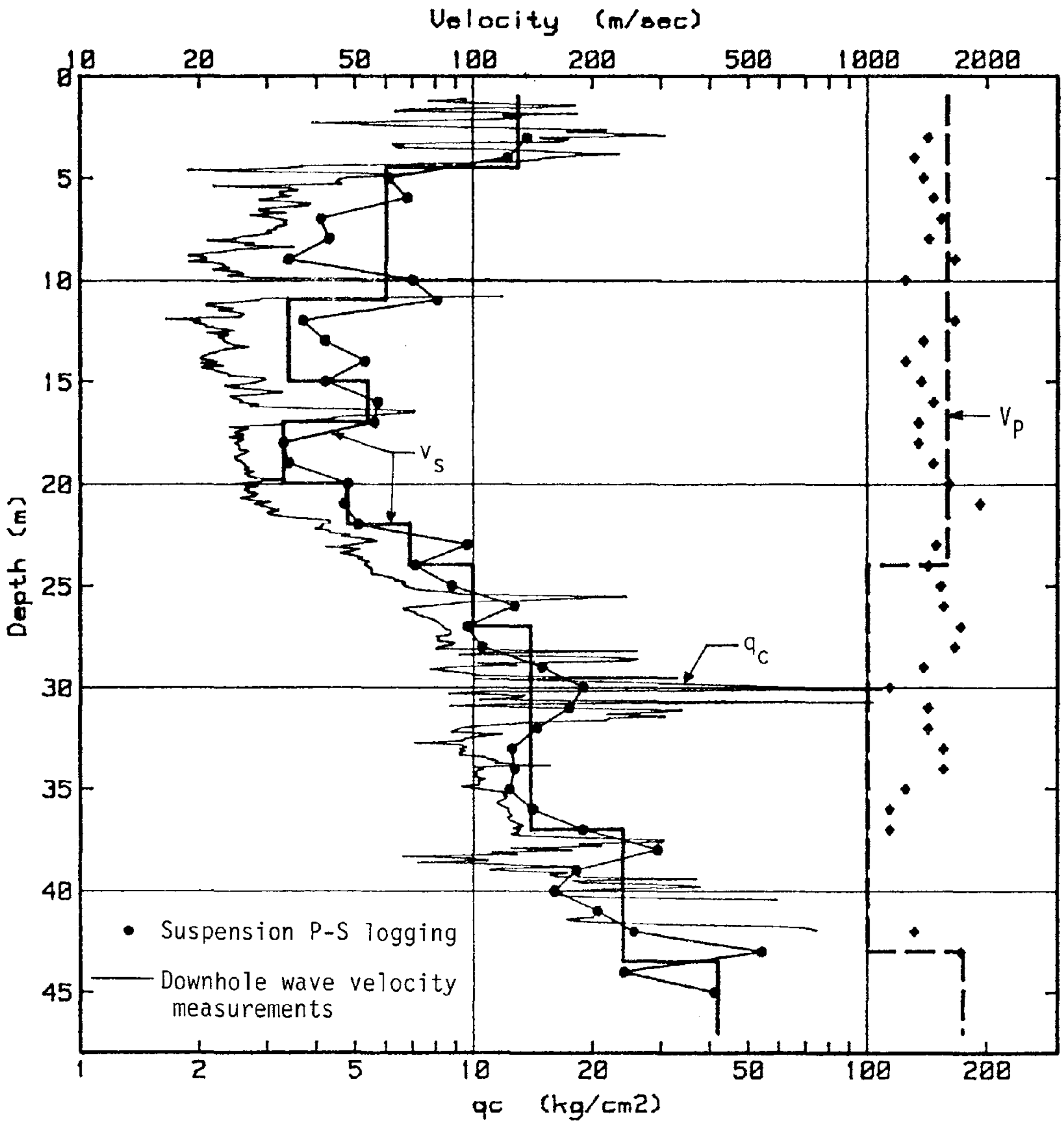


Fig. 4-5 MEASURED SHEAR WAVE VELOCITIES AT CAF SITE

The results of direct measurements of the shear wave velocities of the various soil layers using P-S logging techniques are shown in Fig. 4-6, and an interpreted representative soil profile, based on these results, is shown in Fig. 4-7.

(5) TLD Site

The soil conditions at the TLD site are generally similar to those at the TLB site but the depth of the clay layer is substantially smaller. The hard layer in this case is reached at a depth of about 65 m.

The results of direct measurements of the shear wave velocities of the soil deposits are shown in Fig. 4-8, and an interpreted representative soil profile, based on these results, is shown in Fig. 4-7.

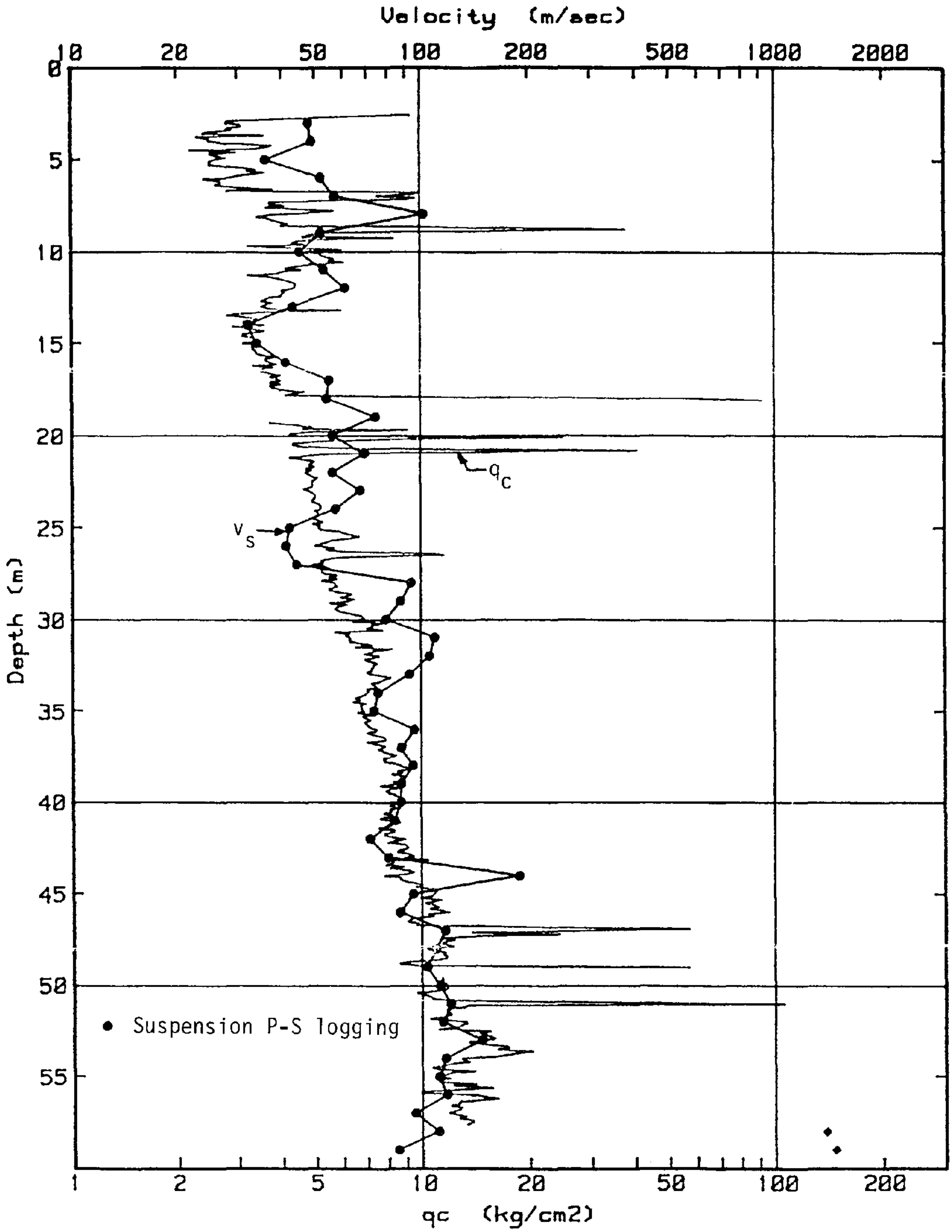
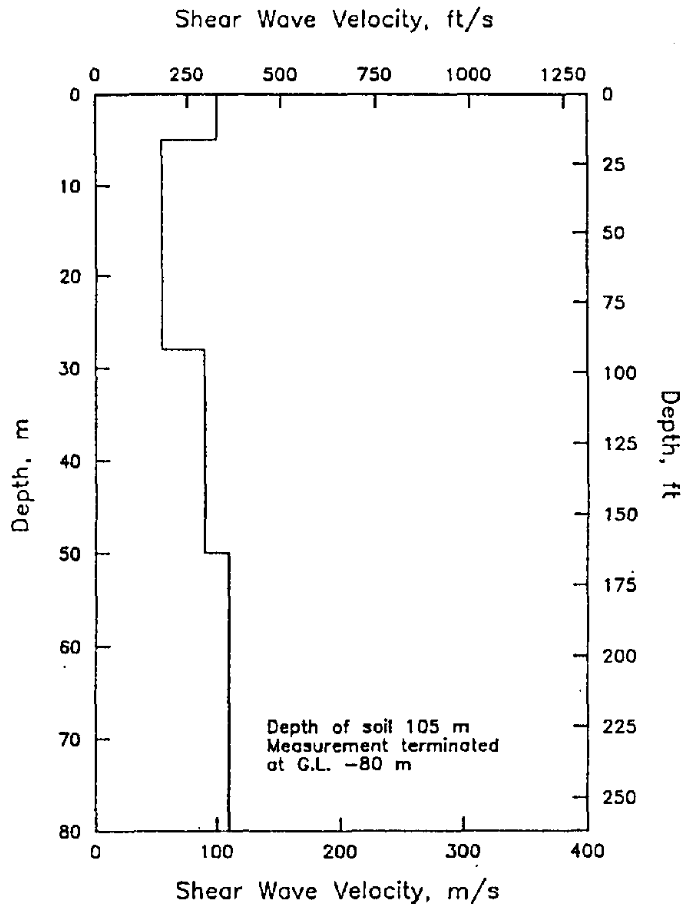
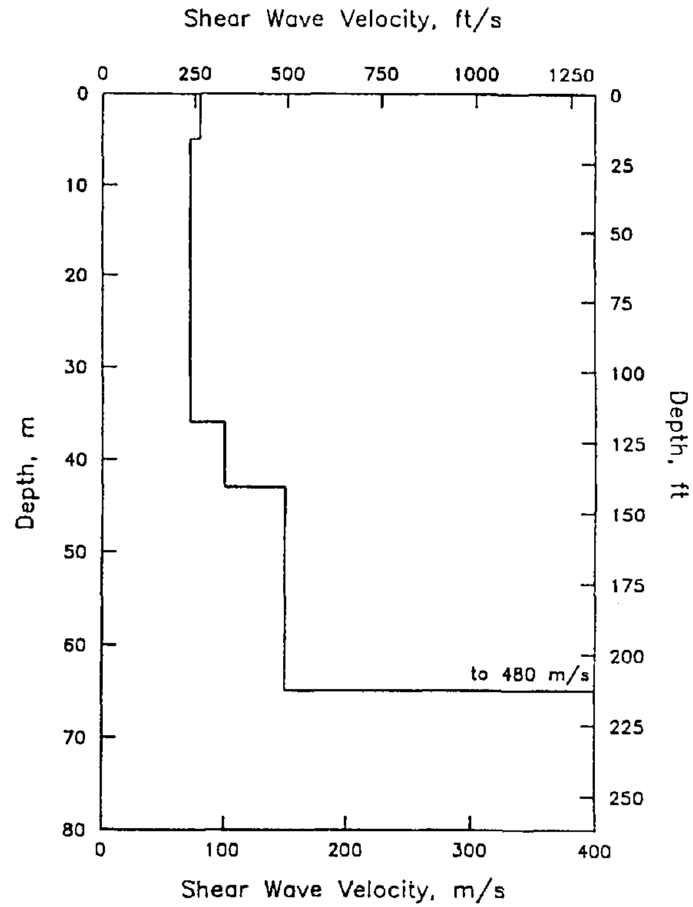


Fig. 4-6 MEASURED SHEAR WAVE VELOCITIES AT TLB SITE



TLB Site



TLD Site

Fig. 4-7 INTERPRETED SHEAR WAVE VELOCITY PROFILES AT TLB AND TLD SITES

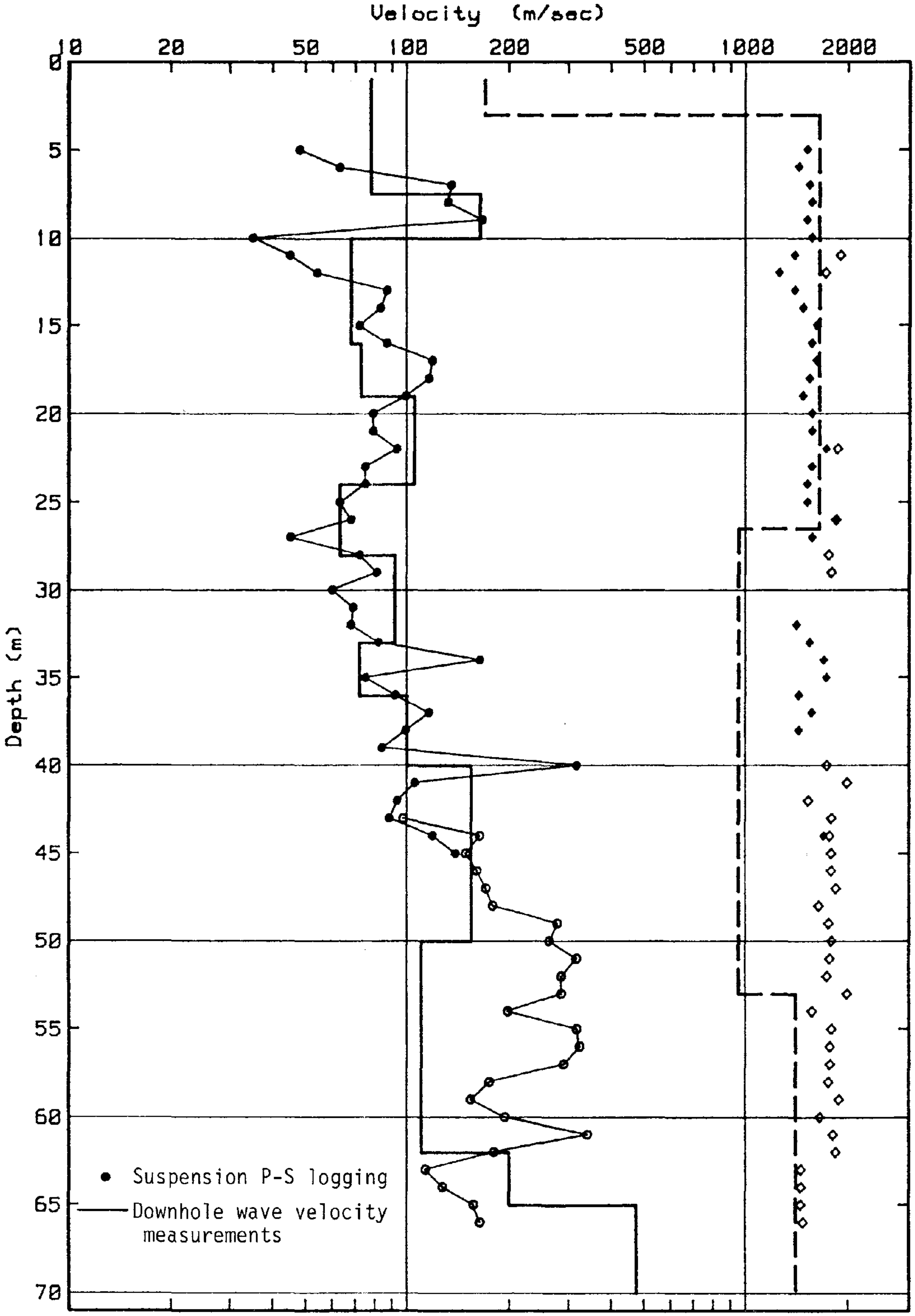


Fig. 4-8 MEASURED SHEAR WAVE VELOCITIES AT TLD SITE

5. Dynamic Properties of Mexico City Clay

The dynamic properties of Mexico City clay have been the subject of several studies, notably by Leon, Jaime and Rabago (1974) and again by Romo and Jaime as part of an on-going investigation following the earthquake of September 19, 1985.

The results of both of these studies provide generally similar results of the form shown in Fig. 5-1. Compared with other clays Mexico City clay shows only a small reduction in shear modulus over a large range of strains, the shear modulus reducing by only about 10% even at strains as high as 0.15%. At strains above this level, however, there is a marked reduction in shear modulus.

Similarly the damping ratio of Mexico City clay is relatively low at strains up to about 0.15% and shows marked increases at strain levels above this value.

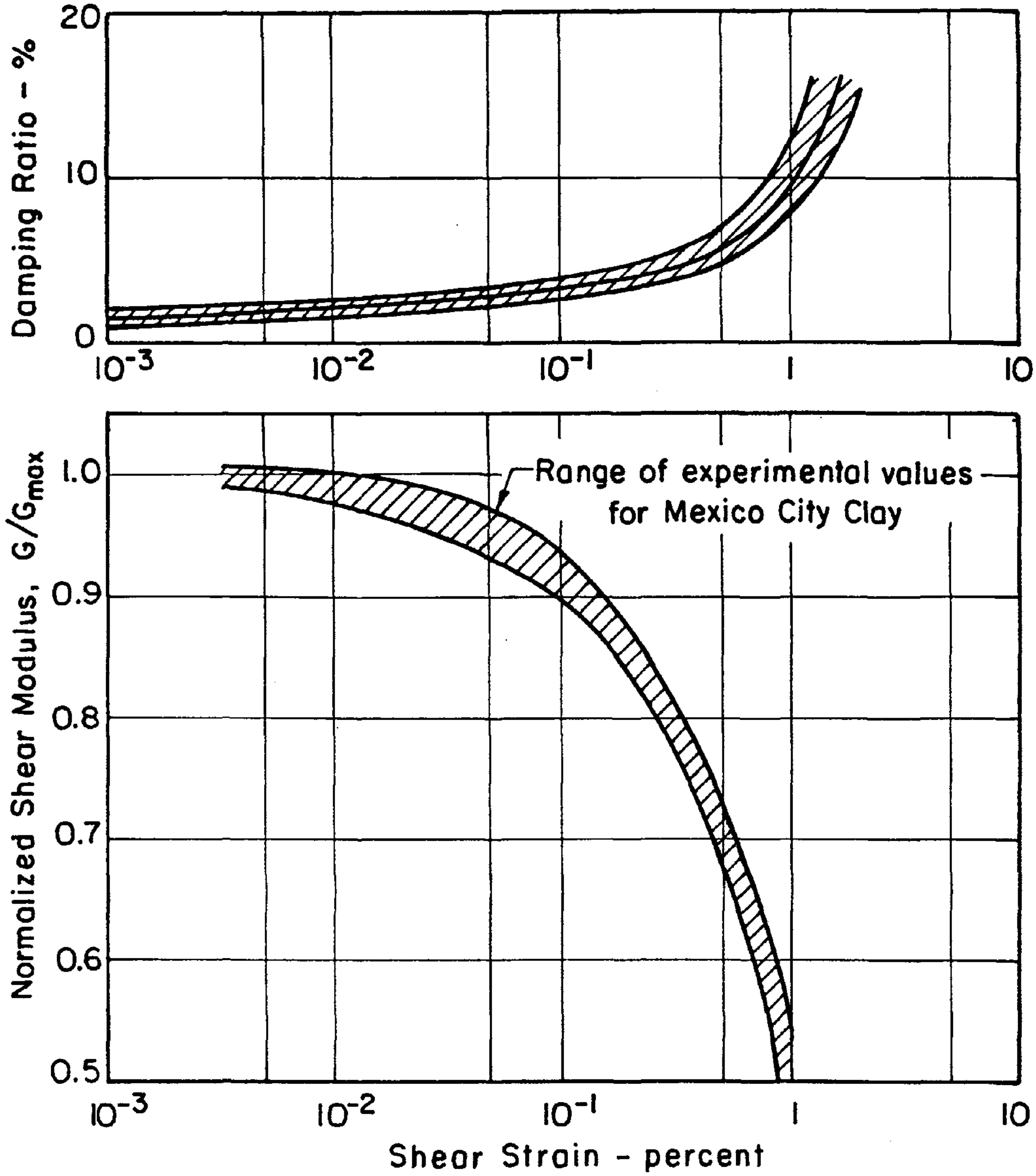


Fig. 5-1 STRAIN-DEPENDENT SHEAR MODULI AND DAMPING RATIOS FOR MEXICO CITY CLAY
(after Leon et al., 1974 and Romo and Jaime, 1986)

6. Relationship Between Soil Conditions and Ground Motion Records

The establishment of soil profiles, both in terms of soil types and shear wave velocities at six of the major recording stations in Mexico City (UNAM, SCT, CAF, CAO, TLB and TLD) makes it possible to prepare plots showing the relationship between ground motion characteristics and local soil conditions at these sites. Thus Figs. 6-1 to 6-6 present plots showing in the upper part of the figure the average response spectrum for the motions recorded at each of the six sites and in the lower part of each figure a shear wave velocity profile for the soil conditions at the site.

It is very clear that the UNAM site is very different from the other sites but for the remaining five sites it is necessary to examine the soil profiles in detail to be able to determine the changes in depth and stiffness of the soils which led to the marked variations in ground surface motions at the five sites. This is particularly well-illustrated by a comparison of the soil conditions underlying the SCT and CAF sites, which are shown together in Fig. 6-7. From an engineering point of view these sites might be considered to be very similar with regard to the depths and stiffnesses of the underlying soils, but as shown in the upper part of the figure, the minor differences in soil conditions were apparently sufficient to cause significant differences in the response spectra of the ground surface motions.

It was to permit the development of procedures for anticipating these differences that ground response analyses were performed for the five sites underlain by clay soils. The results of these analyses are described in the following sections of this report.

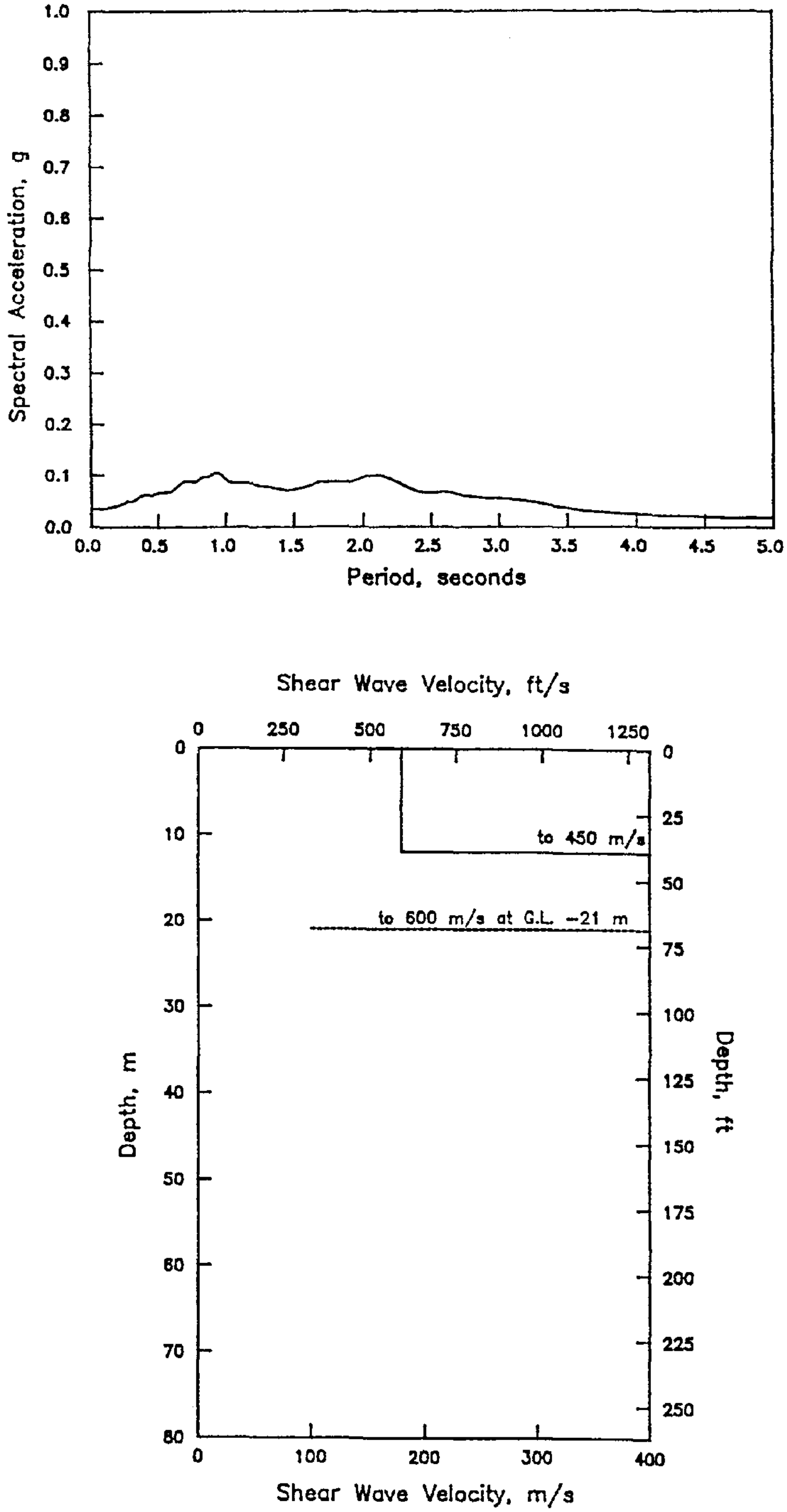
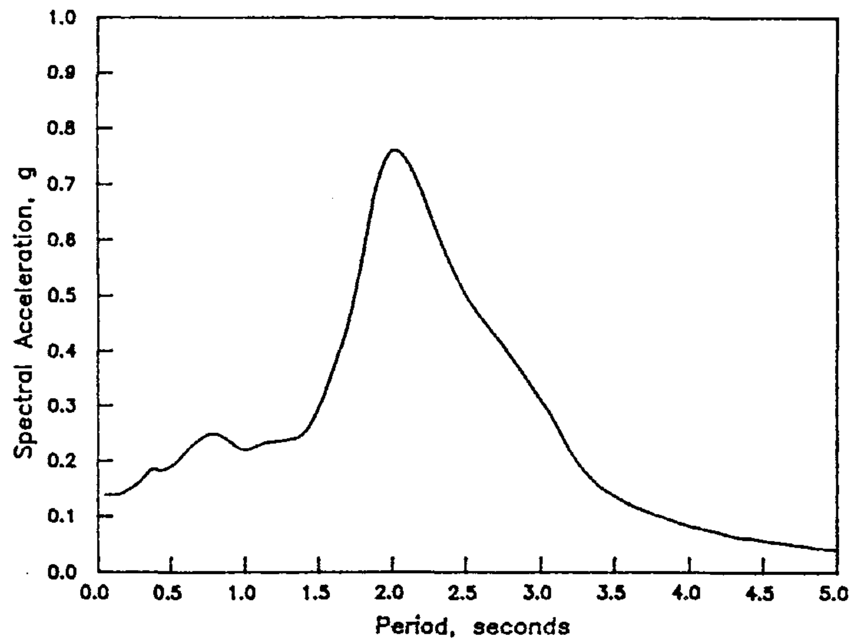


Fig. 6-1 AVERAGE ACCELERATION SPECTRUM FOR RECORDED MOTIONS AND INTERPRETED SHEAR WAVE VELOCITY PROFILE FOR UNAM SITE



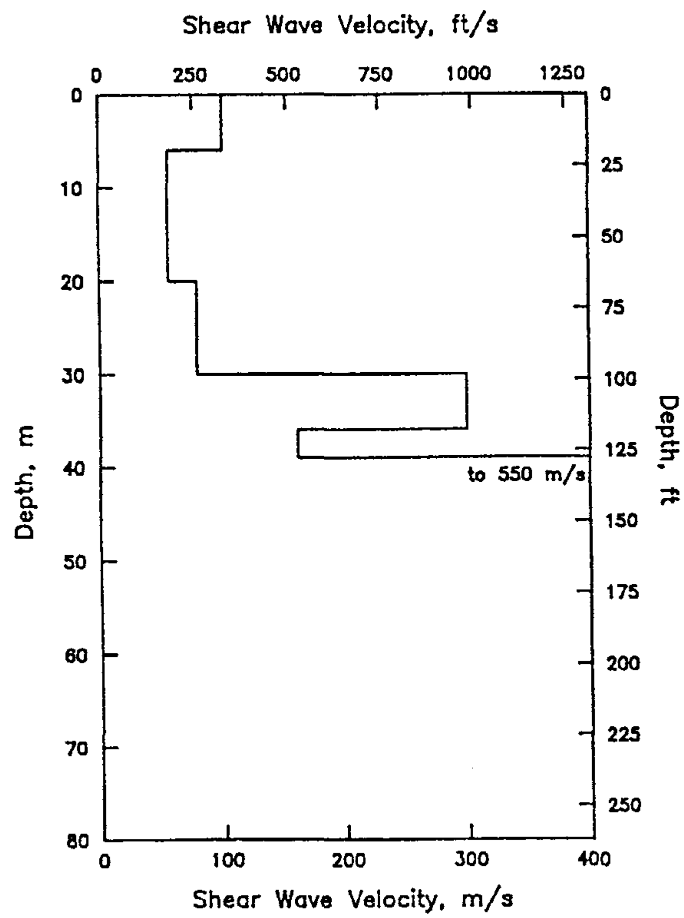
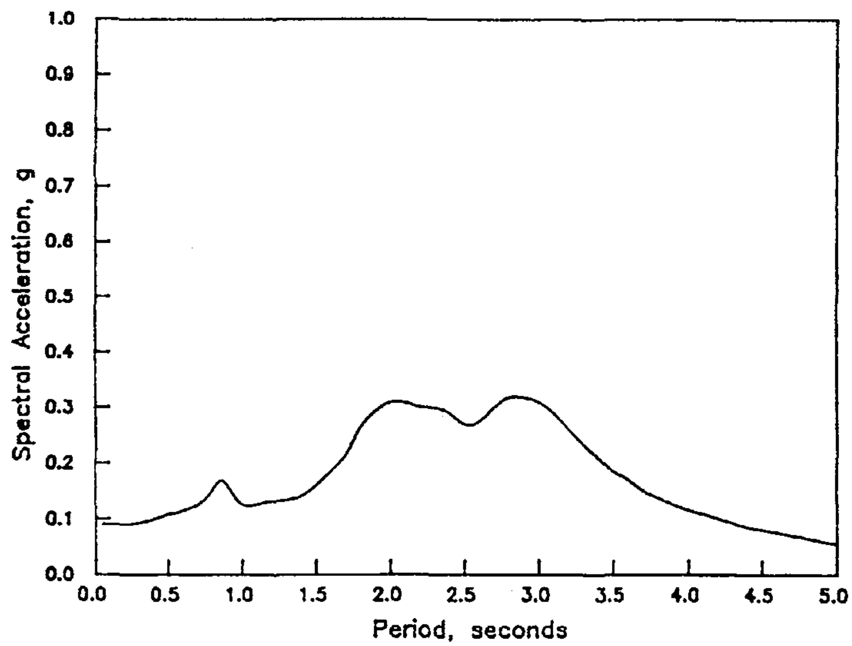


Fig. 6-2 AVERAGE ACCELERATION SPECTRUM FOR RECORDED MOTIONS AND INTERPRETED SHEAR WAVE VELOCITY PROFILE FOR SCT SITE



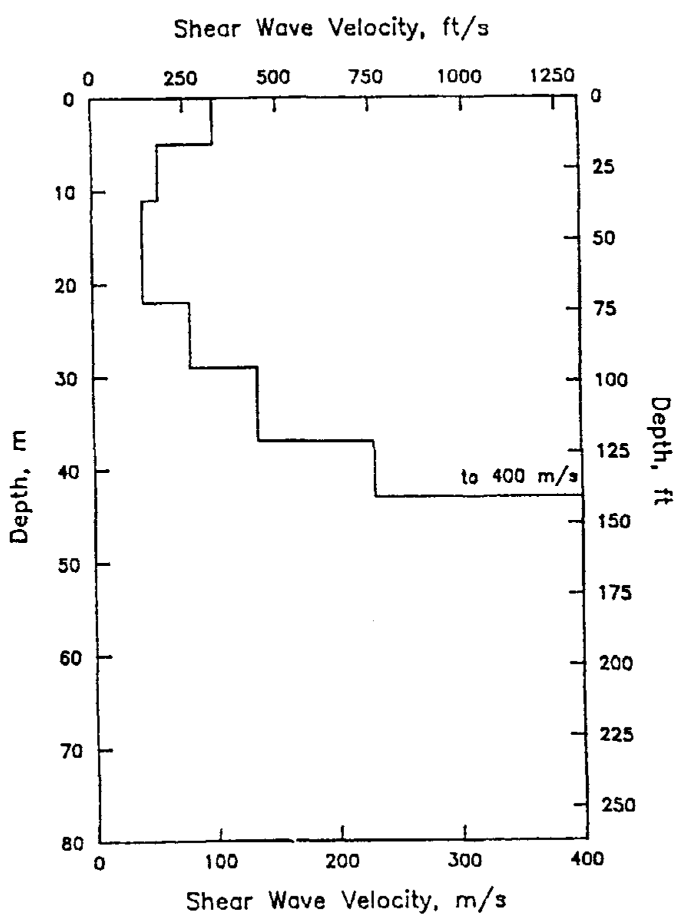
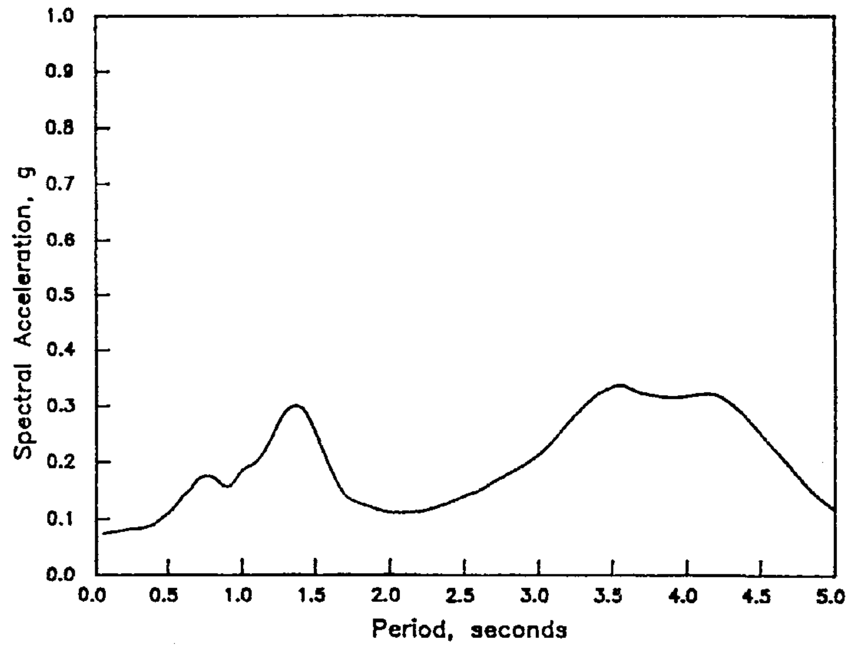


Fig. 6-3 AVERAGE ACCELERATION SPECTRUM FOR RECORDED MOTIONS AND INTERPRETED SHEAR WAVE VELOCITY PROFILE FOR CAF SITE



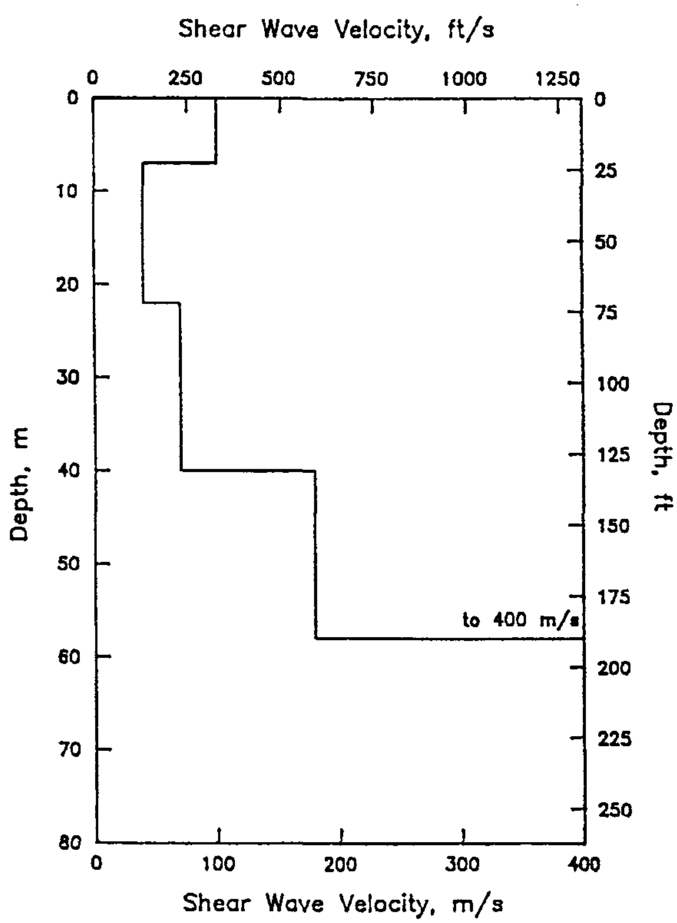
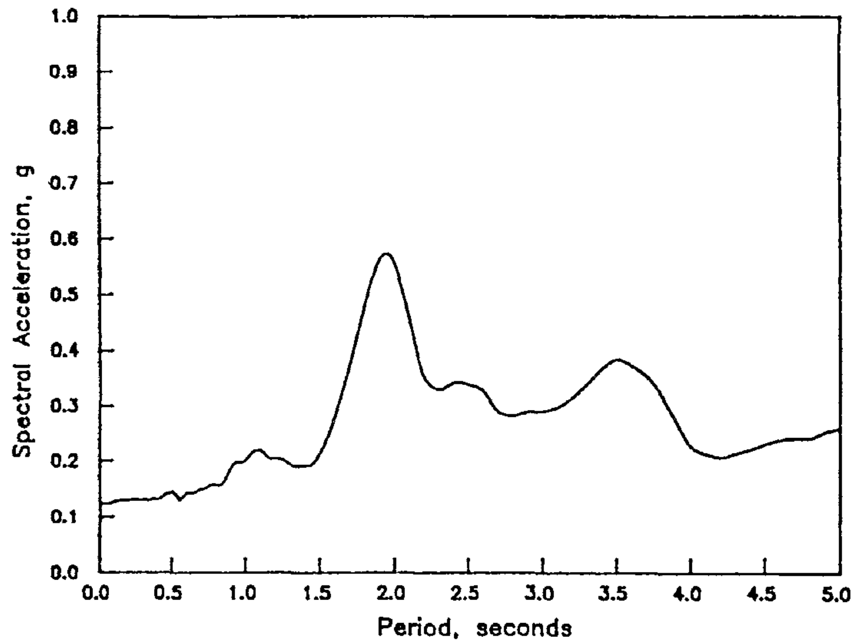


Fig. 6-4 AVERAGE ACCELERATION SPECTRUM FOR RECORDED MOTIONS AND INTERPRETED SHEAR WAVE VELOCITY PROFILE FOR CAO SITE



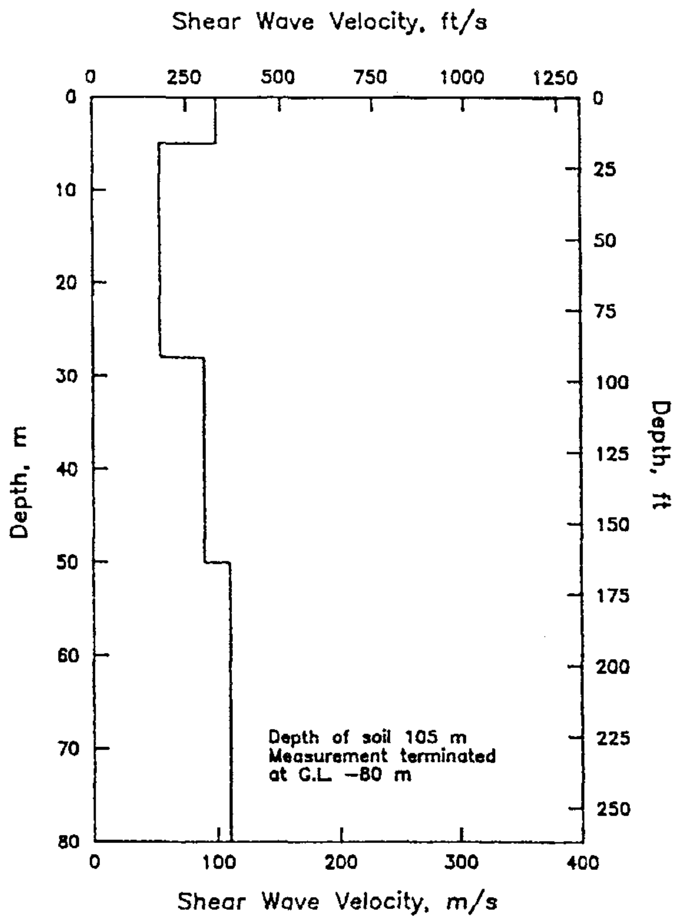
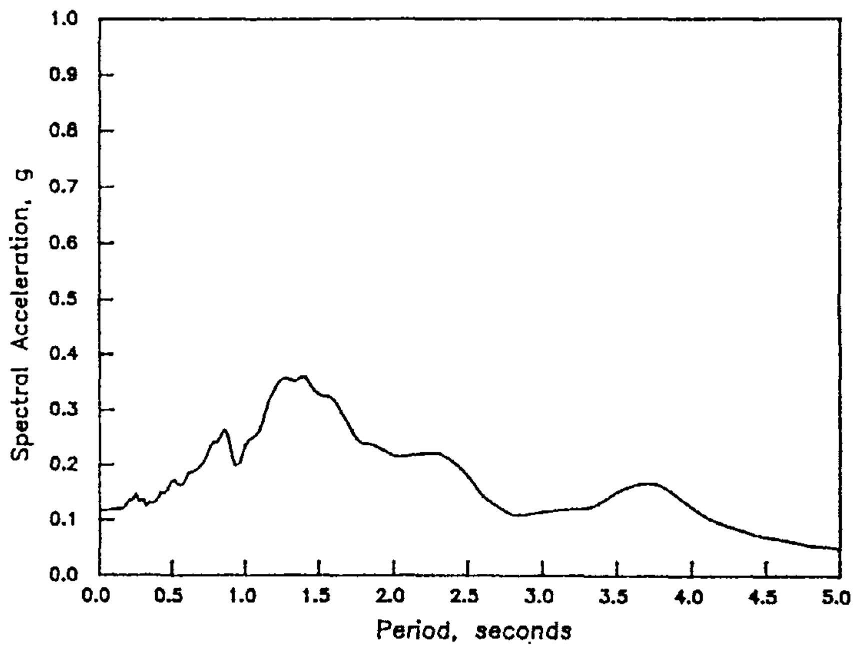


Fig. 6-5 AVERAGE ACCELERATION SPECTRUM FOR RECORDED MOTIONS AND INTERPRETED SHEAR WAVE VELOCITY PROFILE FOR TLB SITE



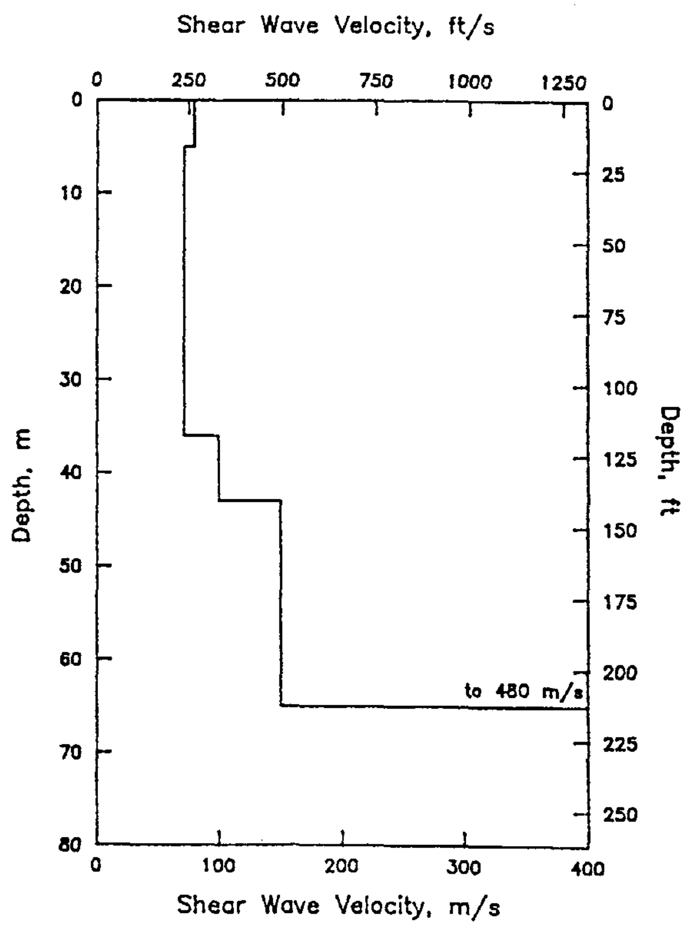


Fig. 6-6 AVERAGE ACCELERATION SPECTRUM FOR RECORDED MOTIONS AND INTERPRETED SHEAR WAVE VELOCITY PROFILE FOR TLD SITE

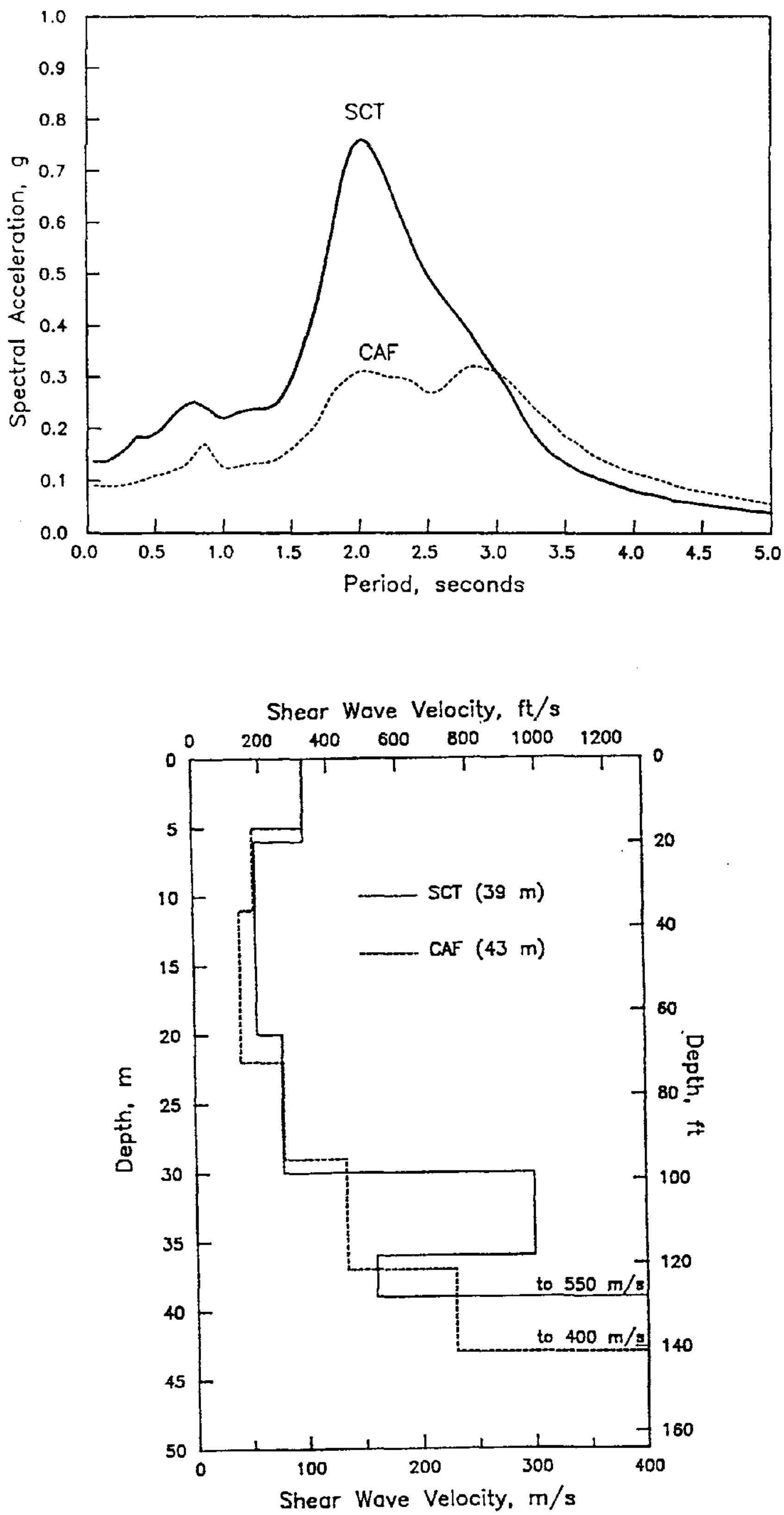


Fig. 6-7 COMPARISON OF AVERAGE ACCELERATION SPECTRA FOR RECORDED MOTIONS AND INTERPRETED SHEAR WAVE VELOCITY PROFILES FOR SCT AND CAF SITES

7. Analytical Studies of Ground Motions in Mexico City Based on Soil Properties Determined from Earthquake Records

Because of the fact that the heavy damage zone in Mexico City is located in the area of the lake-bed deposits mainly to the north of the SCT Building site, it is desirable to develop procedures for evaluating the characteristics of the earthquake ground motions in those parts of the city where no records were obtained but which are never-the-less of major interest for damage evaluation purposes. To this end it is first necessary to demonstrate that any analysis procedure which may be used for this purpose is capable of predicting the main characteristics of the motions at those sites where recordings were made. Analyses of ground response using wave propagation procedures seem to provide the most logical choice of a suitable method for these purposes.

Such analyses for the sites in Mexico City are made possible by:

1. The existence of information such as that presented in the preceding pages which provides detailed information concerning the soil conditions above the hard layer at the recording stations.
2. The availability of information, such as that shown in Fig. 5-1, concerning the dynamic properties of the clay and other generally applicable information for the sandy formations in the soil deposits.
3. The fact that the clay deposits in Mexico City are very thin compared with their lateral extent so that in most cases, the dynamic response of the deposit at any given site can be evaluated using one-dimensional wave propagation theory.

4. The fact that previous studies (Herrera and Rosenblueth, 1965; Seed and Idriss, 1969) have shown that one-dimensional ground response analyses using vertical wave propagation, as illustrated in Fig.7-1, can provide values of ground surface motions in good agreement with values recorded in previous earthquakes, and that most of the amplification of motions takes place in the soil deposits overlying the hard layer.
5. The availability of the records at UNAM to provide good general information on the characteristics of the motions developed on the hard layer in the 1985 earthquakes.

Thus, assuming that the motions developed on the hard formations are reasonably represented by the N-S component of the record obtained at the CUMV station at UNAM (see Fig. 3-4) and that for preliminary analysis purposes the soil properties at the recording stations are reasonably well-represented by the wave velocities deduced from the observed natural frequencies of the various sites (see Fig. 4-1), it is possible to make analyses of the ground motions likely to develop at the ground surface in areas underlain by clay deposits using one-dimensional wave propagation theory, as incorporated in computer programs such as SHAKE (Schnabel et al., 1972). Because of the low intensity of the motions developed in the hard layer in the 1985 earthquake, the response does not involve any large non-linear effects and thus equivalent linear methods are likely to be sufficiently accurate for the conditions involved.

On this basis, analyses were made for the following conditions:

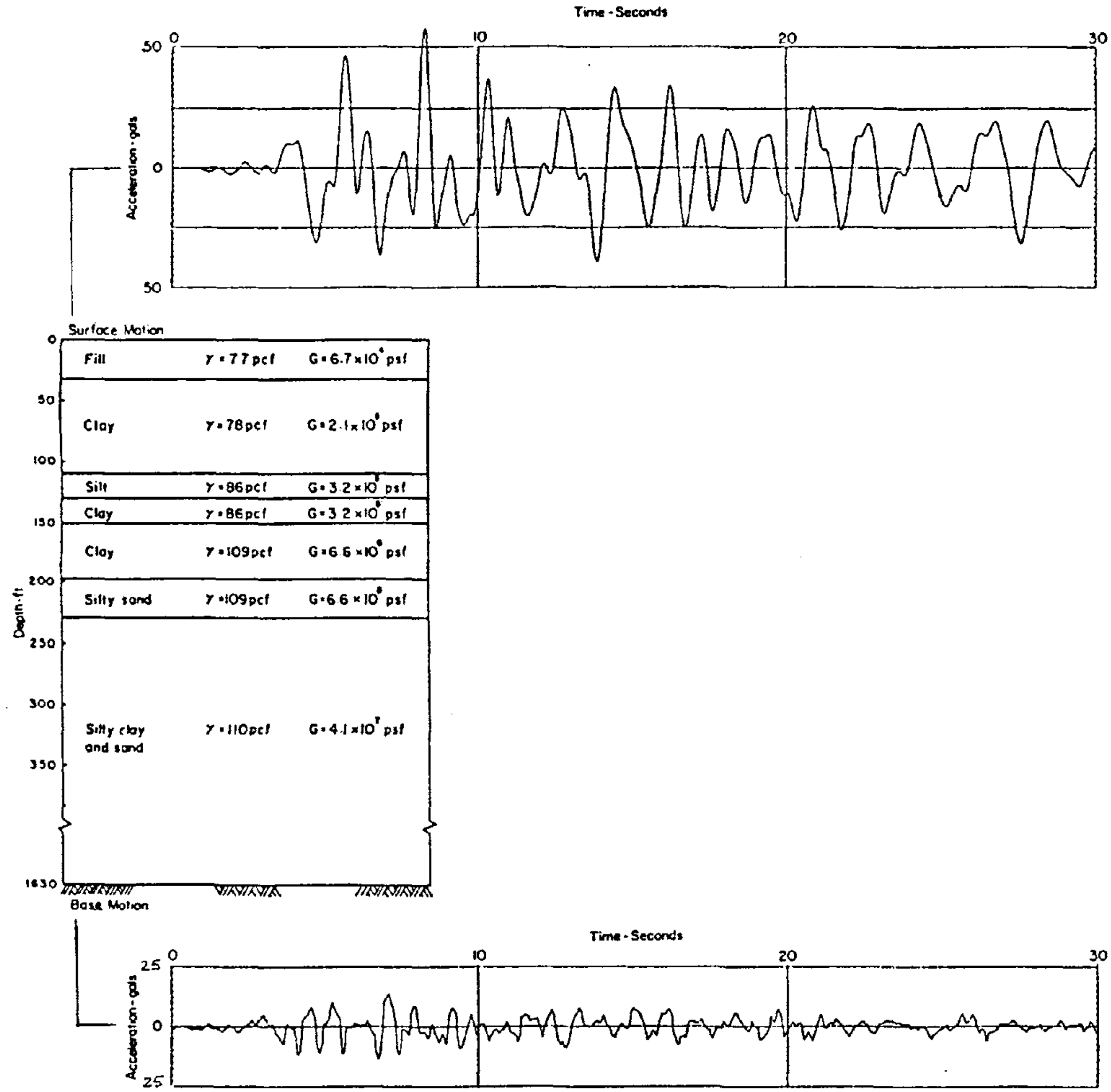
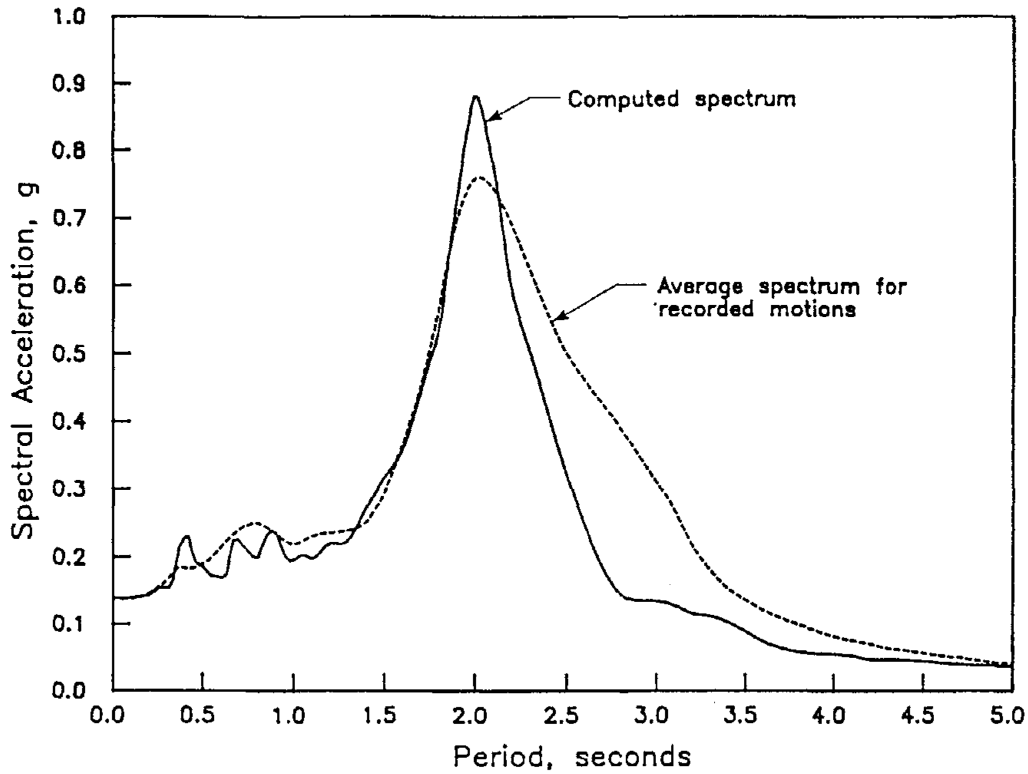


Fig. 7-1 ANALYSIS OF SOIL RESPONSE AT SITE IN ALAMEDA PARK, MEXICO CITY (after Seed and Idriss, 1969)

Site	Depth	Shear Wave Velocity of Clay	Soil Profile	Unit Weight of Soil
SCT	38 m	75 m/sec	As shown in Fig. 4-1	1.2 t/m^3
CAF	45 m	64 m/sec	As shown in Fig. 4-1	1.2 t/m^3
CAO	56 m	60 m/sec	As shown in Fig. 4-1	1.2 t/m^3

Using these characteristics, in conjunction with the strain-dependent values of soil properties shown in Fig. 5-1, and an iterative procedure to determine strain compatible properties for use in equivalent linear analyses, computations of the ground surface motions were made for the SCT, CAF and CAO sites.

The results of these studies are shown in Figs. 7-2, 7-3, and 7-4, where the acceleration response spectra for the computed motions are compared with the average spectra for the recorded motions. It may be seen that there is a very good degree of agreement between the spectra for the computed and recorded motions, indicating that the analytical procedures and the soil characteristics determined from earthquake records provide a good basis for predicting motions for the Mexico City environment (Romo and Seed, 1986).



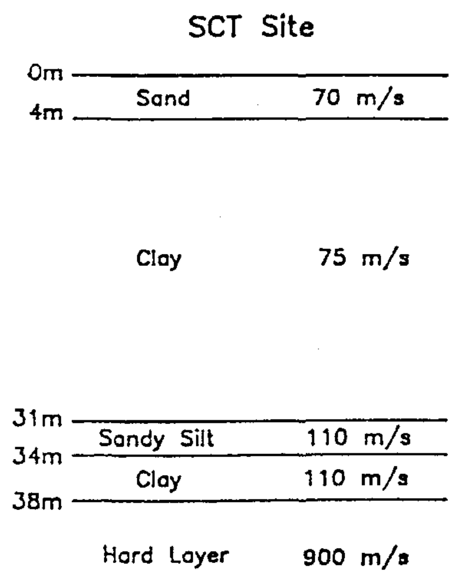


Fig. 7-2 ANALYSIS OF GROUND RESPONSE AT SCT SITE BASED ON SOIL PROFILE DETERMINED BY BORINGS AND FREQUENCY CHARACTERISTICS OF RECORDED MOTIONS

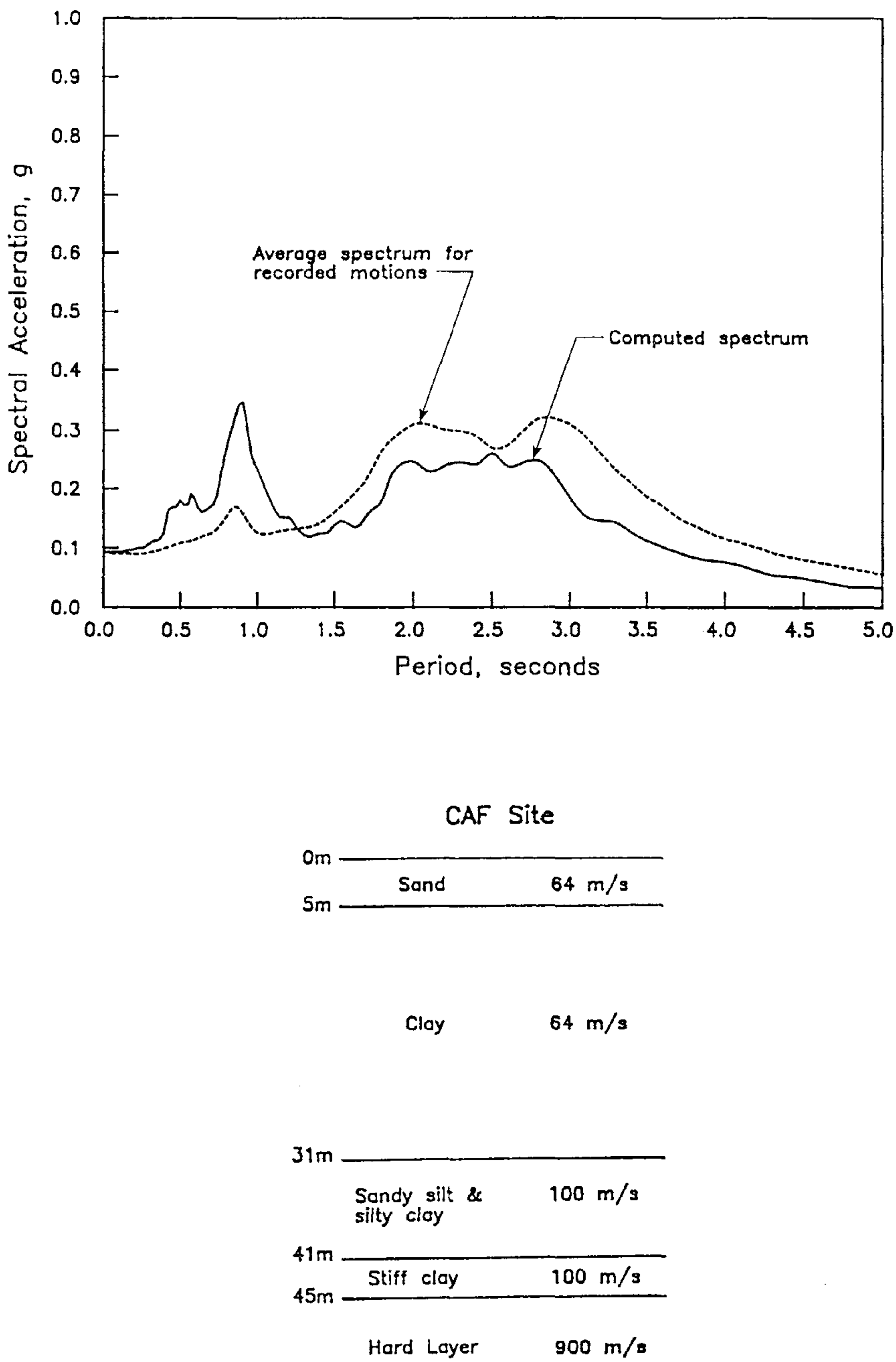


Fig. 7-3 ANALYSIS OF GROUND RESPONSE AT CAF SITE BASED ON SOIL PROFILE DETERMINED BY BORINGS AND FREQUENCY CHARACTERISTICS OF RECORDED MOTIONS

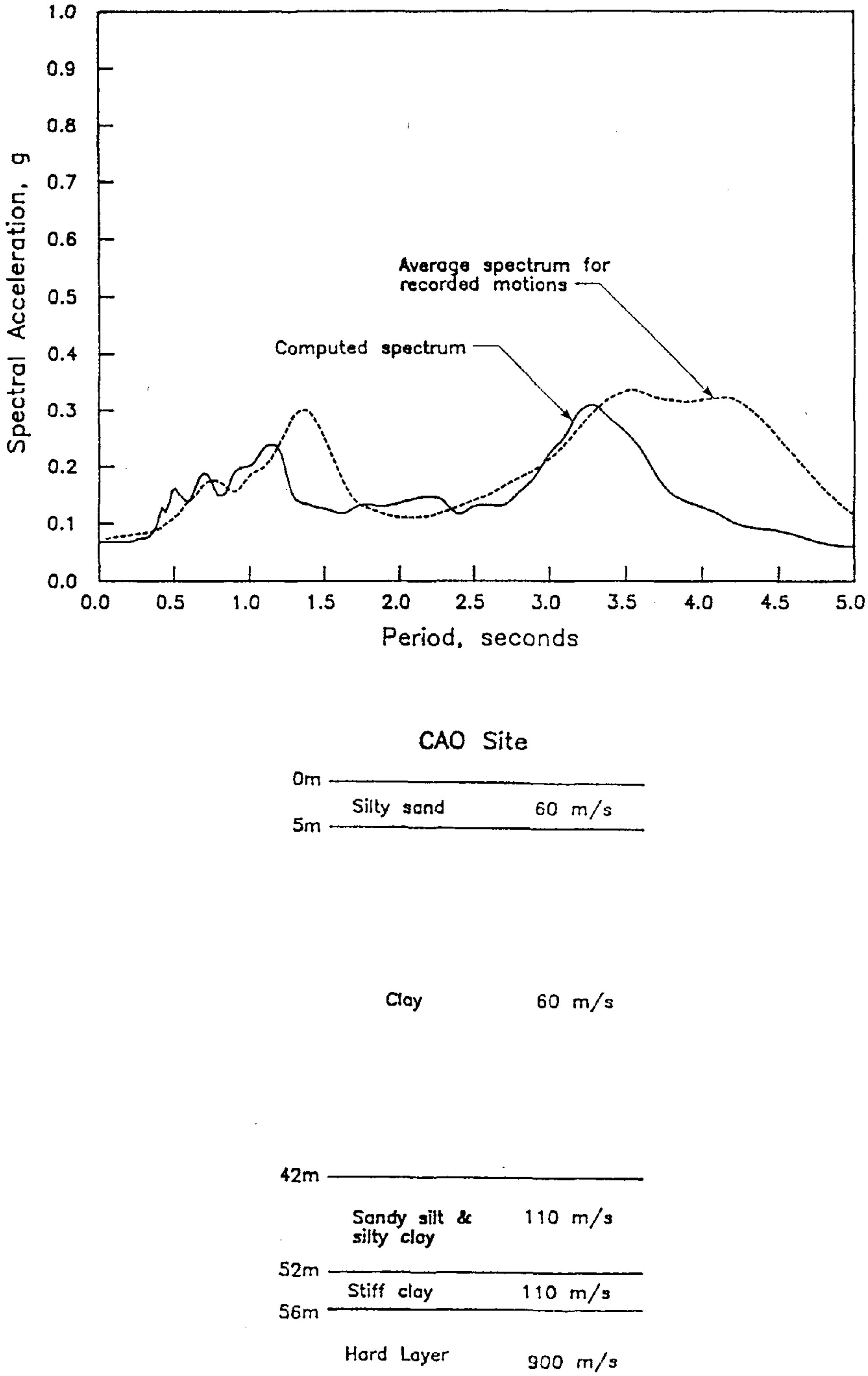


Fig. 7-4 ANALYSIS OF GROUND RESPONSE AT CAO SITE BASED ON SOIL PROFILE DETERMINED BY BORINGS AND FREQUENCY CHARACTERISTICS OF RECORDED MOTIONS

8. Analytical Studies of Ground Motions in Mexico City Based on Measured Values of Shear Wave Velocity of Soils

In the preceding section of this report, analyses of ground motions in Mexico City were based on values of shear wave velocity for the clay deposits estimated from the frequency characteristics of the earthquake ground motion records. Thus there is good reason to expect that such values, incorporated in a reasonable method of analyses, would provide good evaluations of ground response effects at the various sites of interest.

In other conditions, such records of ground motions from which soil properties can be determined may not be available and it is therefore necessary to determine the shear wave velocities of different soil layers by direct measurement. There are a number of in-situ techniques available for accomplishing this including cross-hole measurements, downhole measurements, up-hole measurements, P-S suspension logging, etc. and in some cases representative values of shear wave velocity can be determined by laboratory tests on good-quality undisturbed samples.

It is generally recognized, however, that in-situ tests provide the most reliable results because they are not significantly influenced by sample disturbance and, in the present study, direct measurements of shear wave velocities were made at four sites (SCT, CAF, CAO, and TLD) using downhole shear wave velocity measurements and P-S suspension logging methods (Ohya et al., 1986). At a fifth site (TLB) shear wave velocities were determined by P-S wave logging only. The results of these tests have already been presented in Section 4 of this report.

It will be noted that there are some differences between the values measured at each site by the two measurement techniques used in this study

and that the direct measurements indicate somewhat lower values for shear wave velocities in Mexico City clay than the average values determined from the ground motion records. There are a number of technical reasons why some small errors may exist in the direct measurement of shear wave velocities:

1. For the P-S suspension logging method, the sides of the bore holes were not cased and irregularities in the sides of the holes would tend to lower the measured values below the time values.
2. Although casing was used in the downhole velocity measurements the sensing device may not have been tight against the walls of the hole, thus leading to a lowering of apparent wave velocity values.
3. In some cases the values of shear wave velocity measured in the field tests were lower than the values determined by resonant column tests on undisturbed samples. Since even extremely small levels of sample disturbance can cause major reductions in shear moduli and shear wave velocities for clay soils, this result is difficult to understand unless the field values were too low for some reason.

Because of these possible errors in the measured values of shear wave velocity it was considered desirable to allow for these uncertainties by allowing some variations in the soil property data used in the analytical studies of ground response. At the same time it was recognized that errors might also result from the use of a single ground motion record to represent the hard-layer motions in Mexico City. It is apparent from the data shown in Fig. 3-3 for motions recorded at the three UNAM sites that some deviations may occur from the average spectrum, no matter how closely a single earthquake record may represent this motion.

Accordingly in making the ground response analyses for the five clay sites in Mexico City it was considered desirable to consider the probability of errors both in the input motions and in the soil properties used in the analyses by adopting the following probabilistic procedure:

1. Using the best representative hard-layer record (i.e. the N-S component of the motions recorded at the CUMV site at UNAM) as the mean value for ground motion characteristics and then considering other motions which might deviate from this mean value by differences in amplitude of ±20% or by differences in predominant period of ±10%.

2. Using the interpreted shear wave velocity profiles shown in Figs. 4-3 and 4-7 as mean values and then considering that actual shear wave velocities might deviate from these values by ±10%. This is a rather small allowance for possible errors. It could well be argued that since any errors in field shear wave velocity measurements are likely to lead to values which are too low, it would be more appropriate to vary the soil properties by amounts ranging from 0 to +20% or more, but the value adopted was ±10% never-the-less.

Allowing for these variations from the mean values of intensity and predominant period in the hard-layer motions and from the representative mean values of shear wave velocity in the soil profiles requires the conduct of 27 separate analyses using the ground response analysis program SHAKE. Although the time required is not excessive, it may be desirable in the future to write a probabilistic version of the SHAKE program or use some other similar program such as PLUSH (Romo et al., 1980) which can consider such variations in analysis parameters more expeditiously.

The results of probabilistic analyses of the ground surface motions at the five recording stations located on clay deposits in Mexico City (SCT, CAF, CAO, TLB and TLD) are presented in Figures 8-1 to 8-20. For each site plots are presented to show:

1. The soil profile used for the analyses of ground response together with the upper and lower bounds of the spectra for the computed motions and the average spectrum for all the computed motions at the site.
2. A comparison of the upper and lower bounds of the spectra for the computed motions for the site and the average spectrum for the motions recorded at that site.
3. A comparison for each site of the average spectrum for the computed motions and the average spectrum for the motions recorded at that site.
4. A comparison of the 75-percentile response spectrum for the computed motions at each site and the average spectrum for the motions recorded at that site.

Thus such results are shown:

(a) For the SCT site in Figures 8-1 to 8-4.

(b) For the CAF site in Figures 8-5 to 8-8.

(c) For the CAO site in Figures 8-9 to 8-12.

(d) For the TLD site in Figures 8-13 to 8-16.

(e) For the TLB site in Figures 8-17 to 8-20.

It may be seen that the spectral characteristics of the ground motions determined by the analytical studies are in reasonably good agreement with the average spectra for the recorded motions at most of the recording stations. To evaluate the degree of agreement, assessments were made of

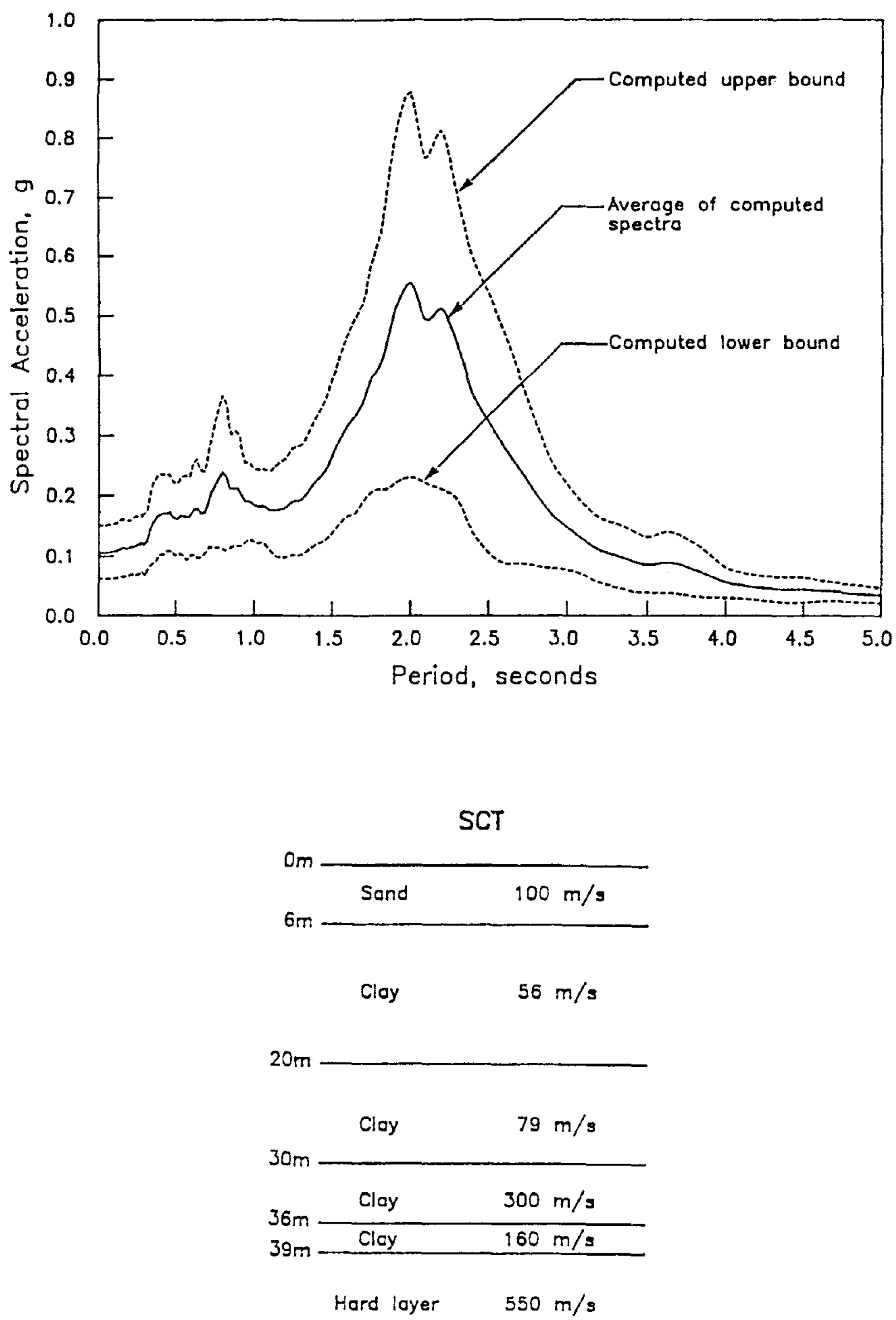


Fig. 8-1 RESULTS OF GROUND RESPONSE ANALYSES FOR SCT SITE BASED ON SHEAR WAVE VELOCITIES INTERPRETED FROM FIELD MEASUREMENTS --ACCELERATION RESPONSE SPECTRA FOR COMPUTED MOTIONS

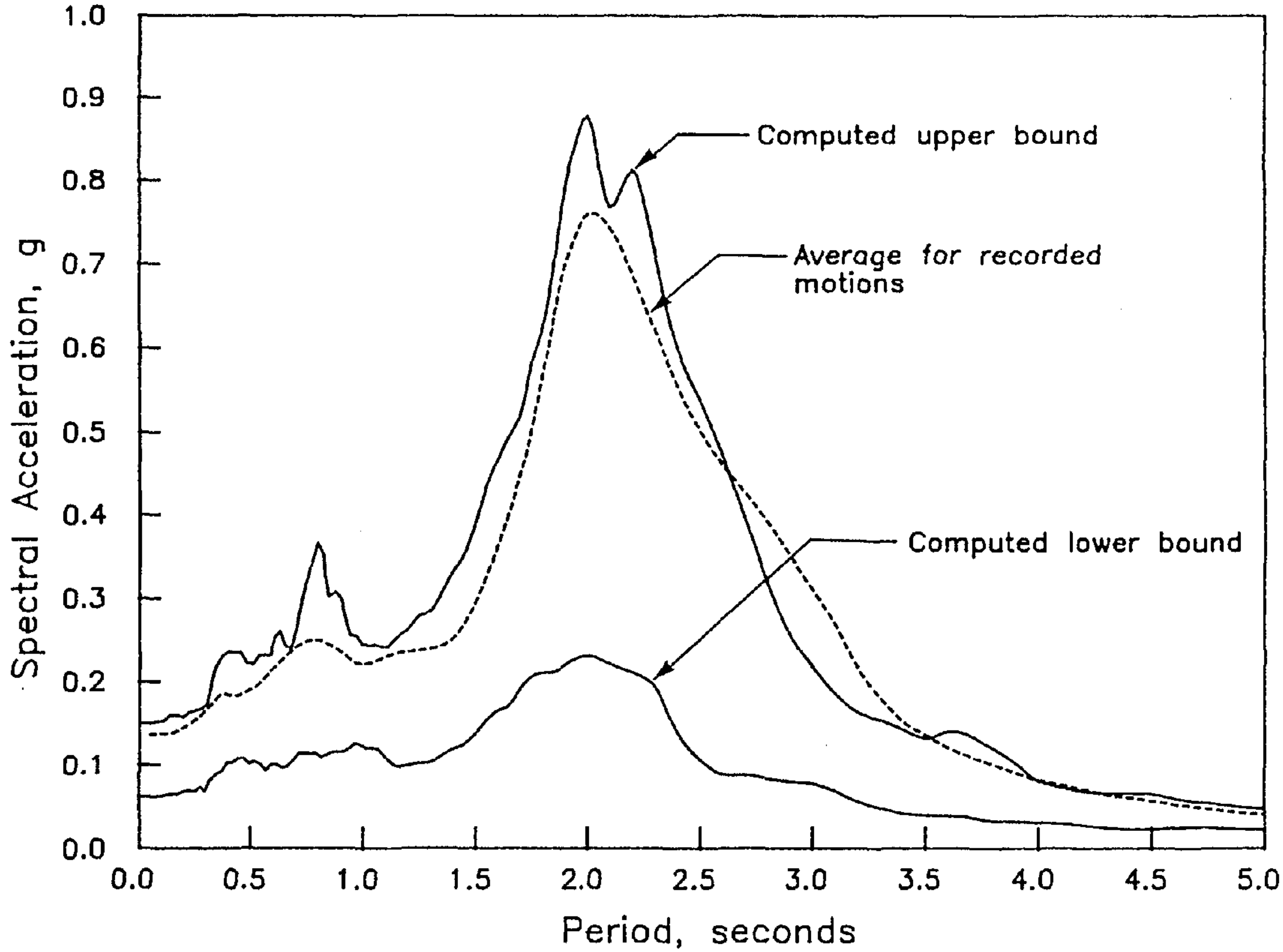


Fig. 8-2 COMPARISON OF RESPONSE SPECTRA DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT SCT SITE

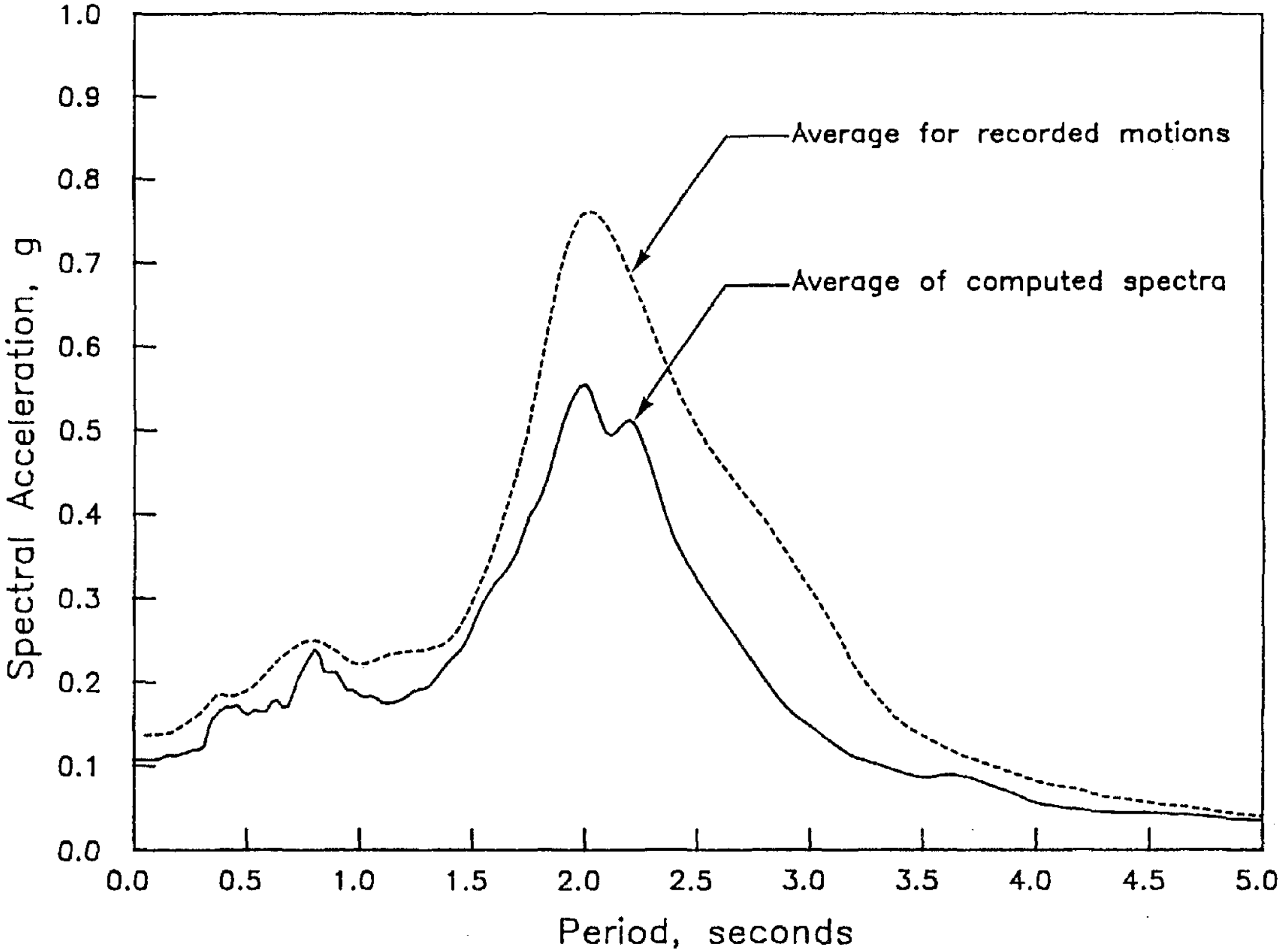


Fig. 8-3 COMPARISON OF AVERAGE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT SCT SITE

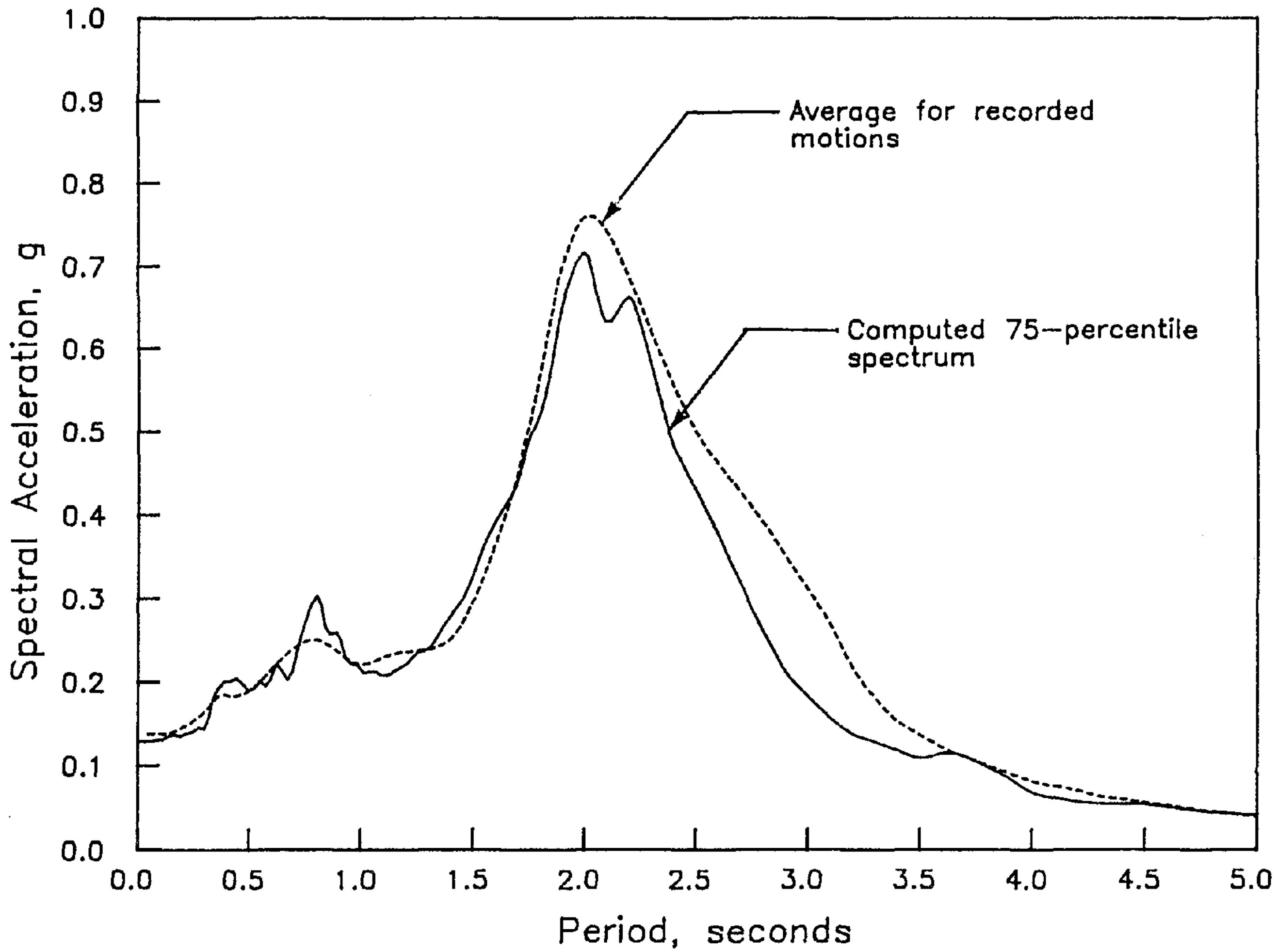
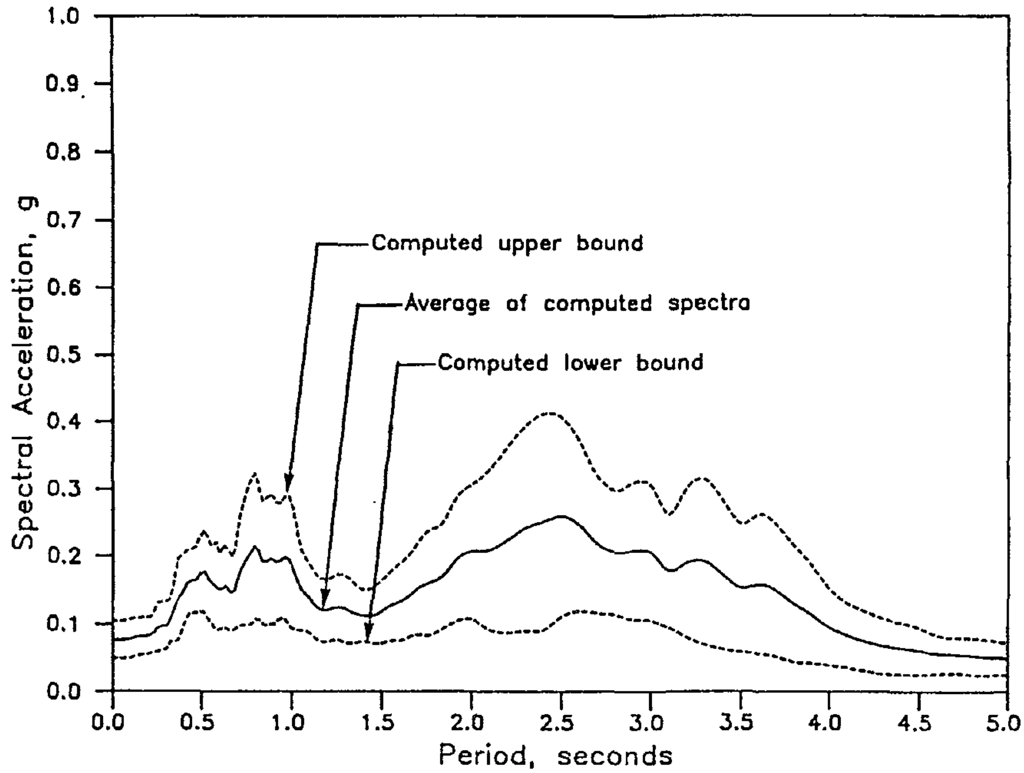


Fig. 8-4 COMPARISON OF 75-PERCENTILE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMETNS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT SCT SITE



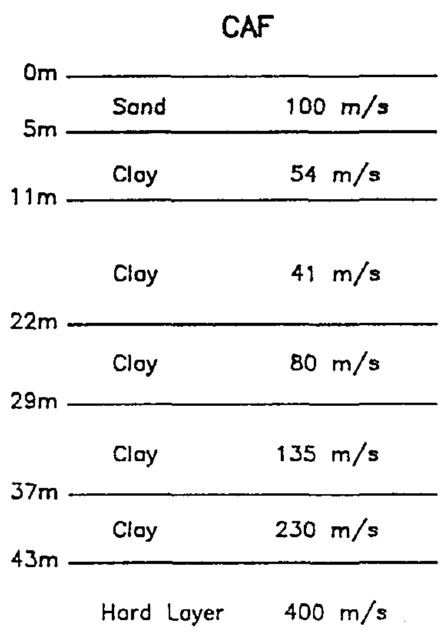


Fig. 8-5 RESULTS OF GROUND RESPONSE ANALYSES FOR CAF SITE BASED ON SHEAR WAVE VELOCITIES INTERPRETED FROM FIELD MEASUREMENTS--ACCELERATION RESPONSE SPECTRA FOR COMPUTED MOTIONS

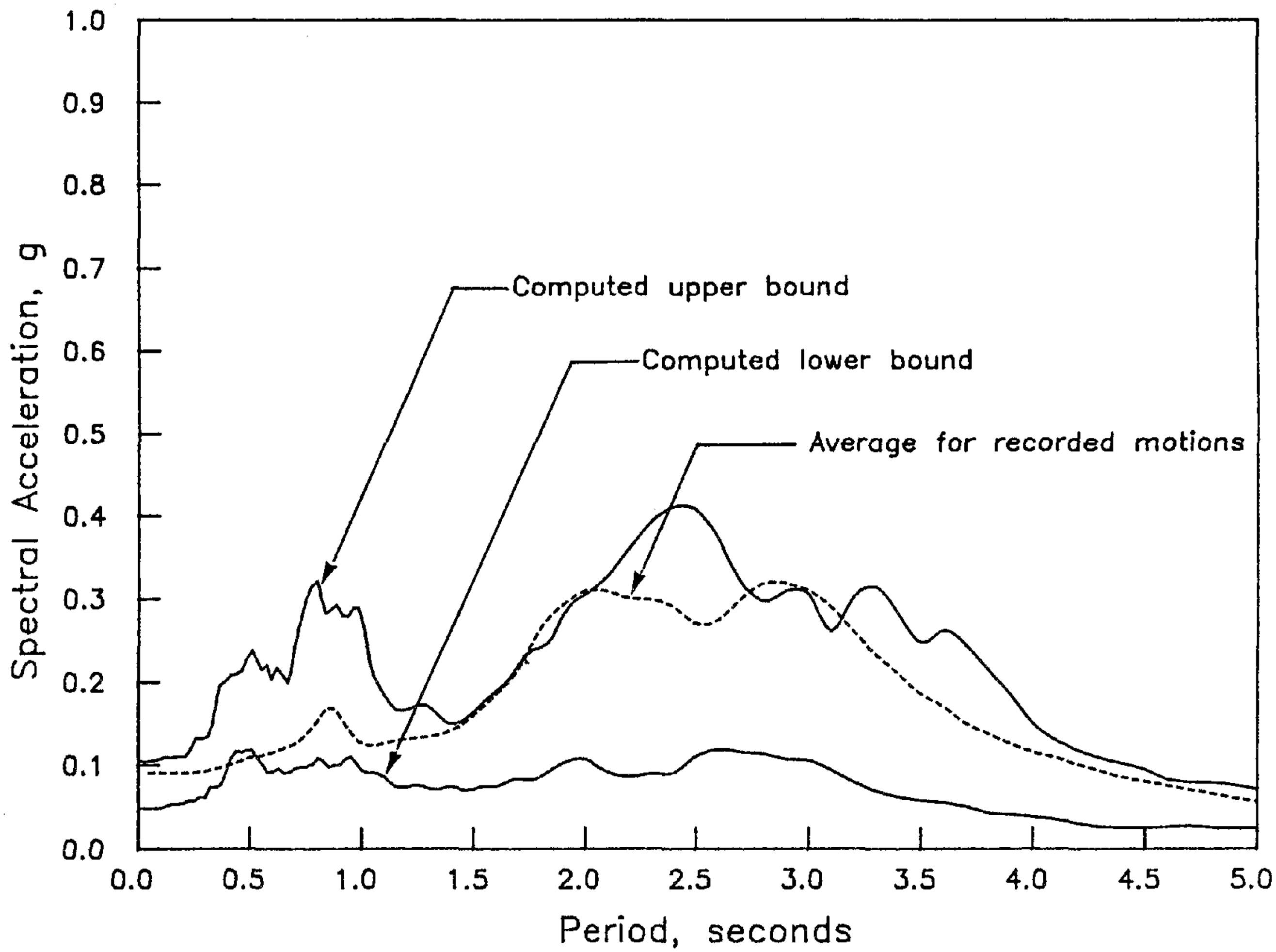


Fig. 8-6 COMPARISON OF RESPONSE SPECTRA DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT CAF SITE

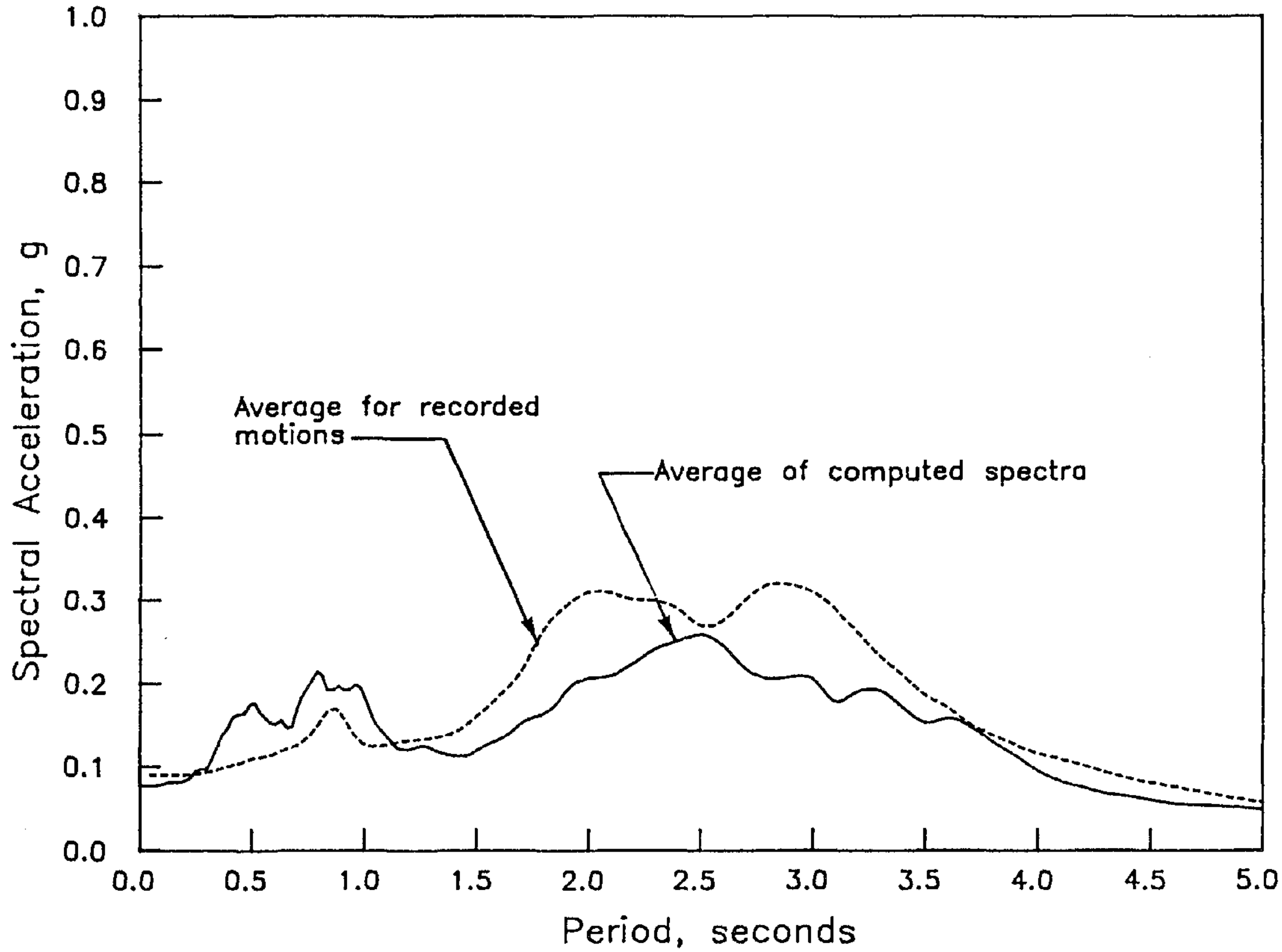


Fig. 8-7 COMPARISON OF AVERAGE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT CAF SITE

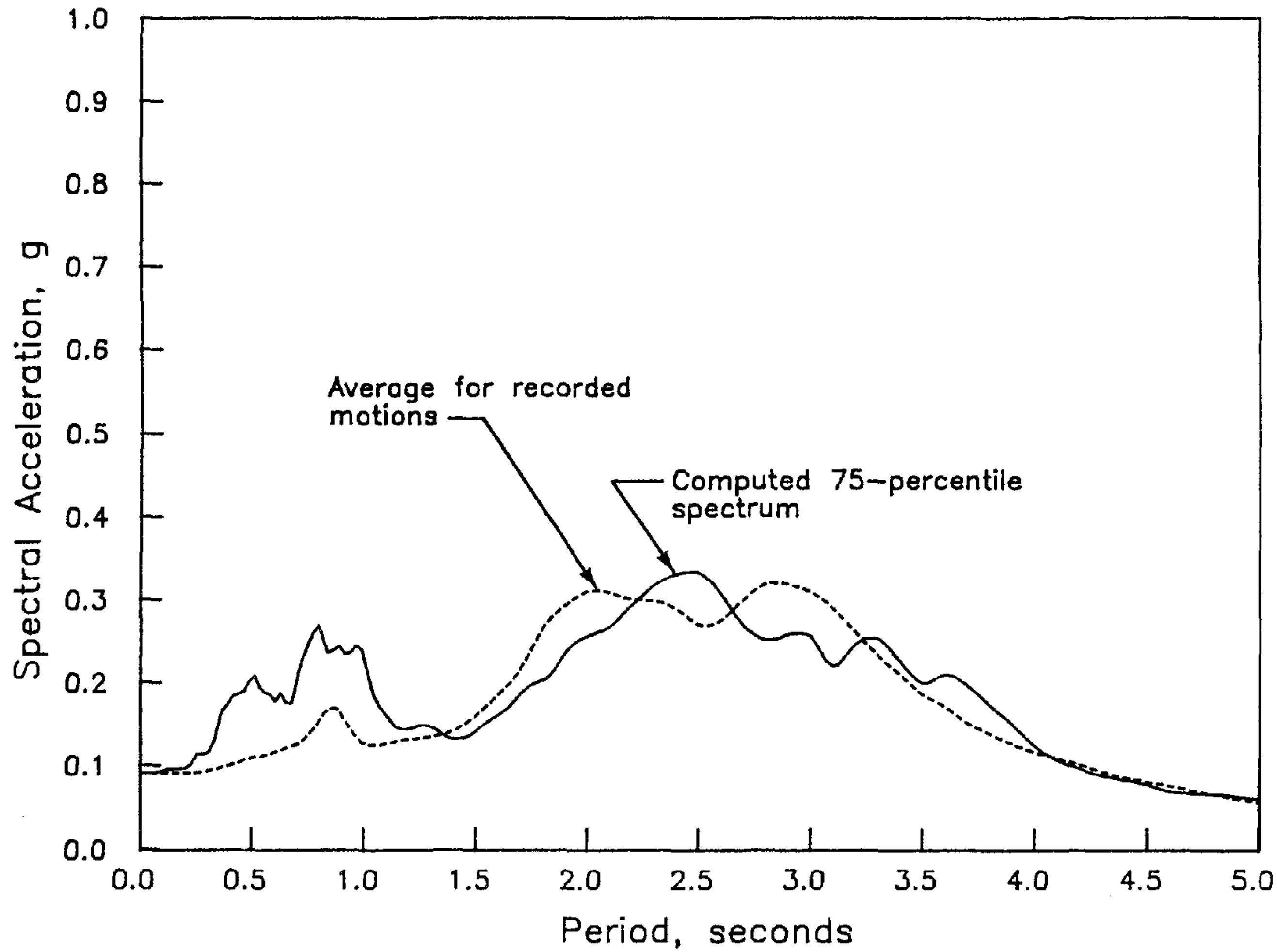
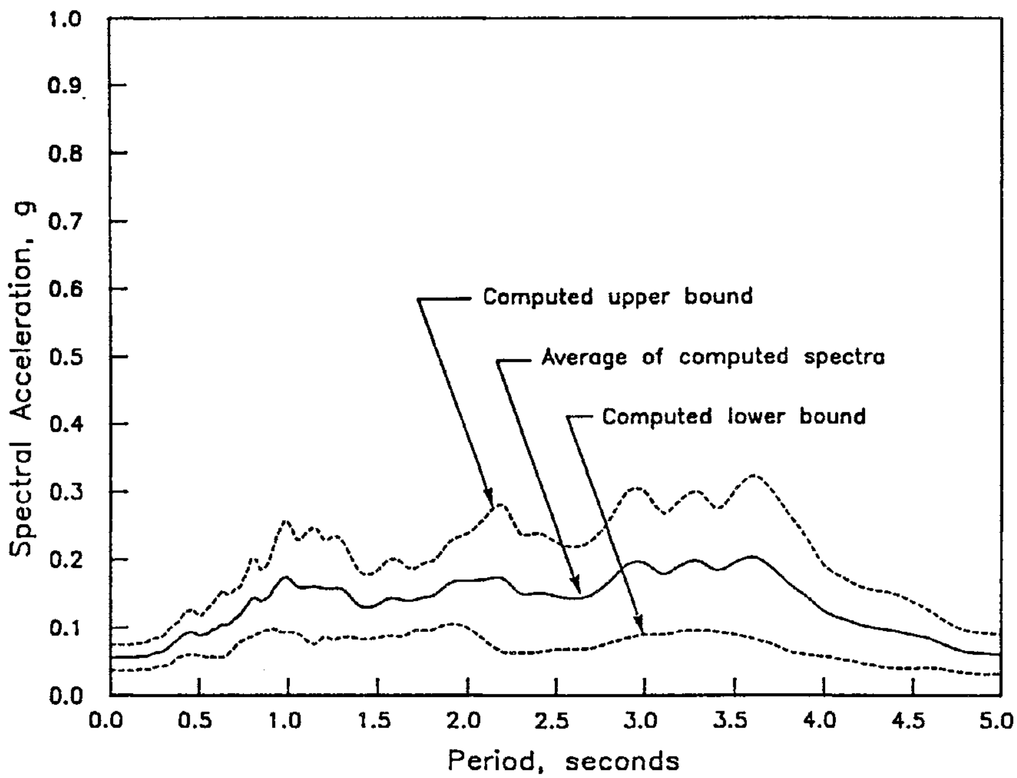


Fig. 8-8 COMPARISON OF 75-PERCENTILE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT CAF SITE



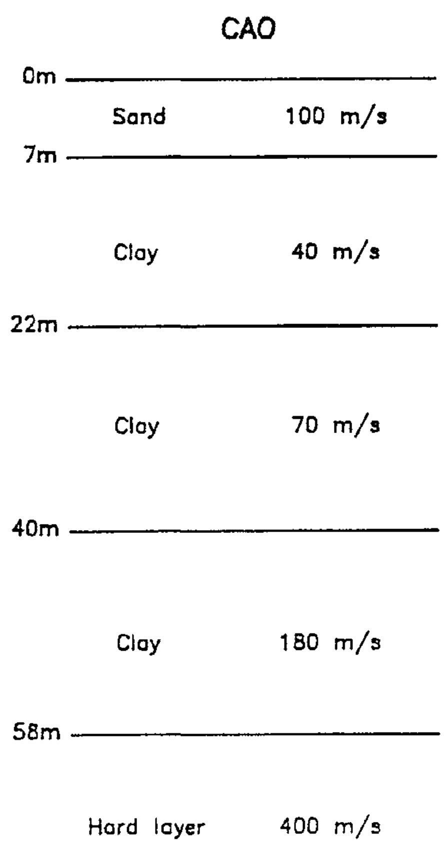


Fig. 8-9 RESULTS OF GROUND RESPONSE ANALYSES FOR CAO SITE BASED ON SHEAR WAVE VELOCITIES INTERPRETED FROM FIELD MEASUREMENTS--ACCELERATION RESPONSE SPECTRA FOR COMPUTED MOTIONS

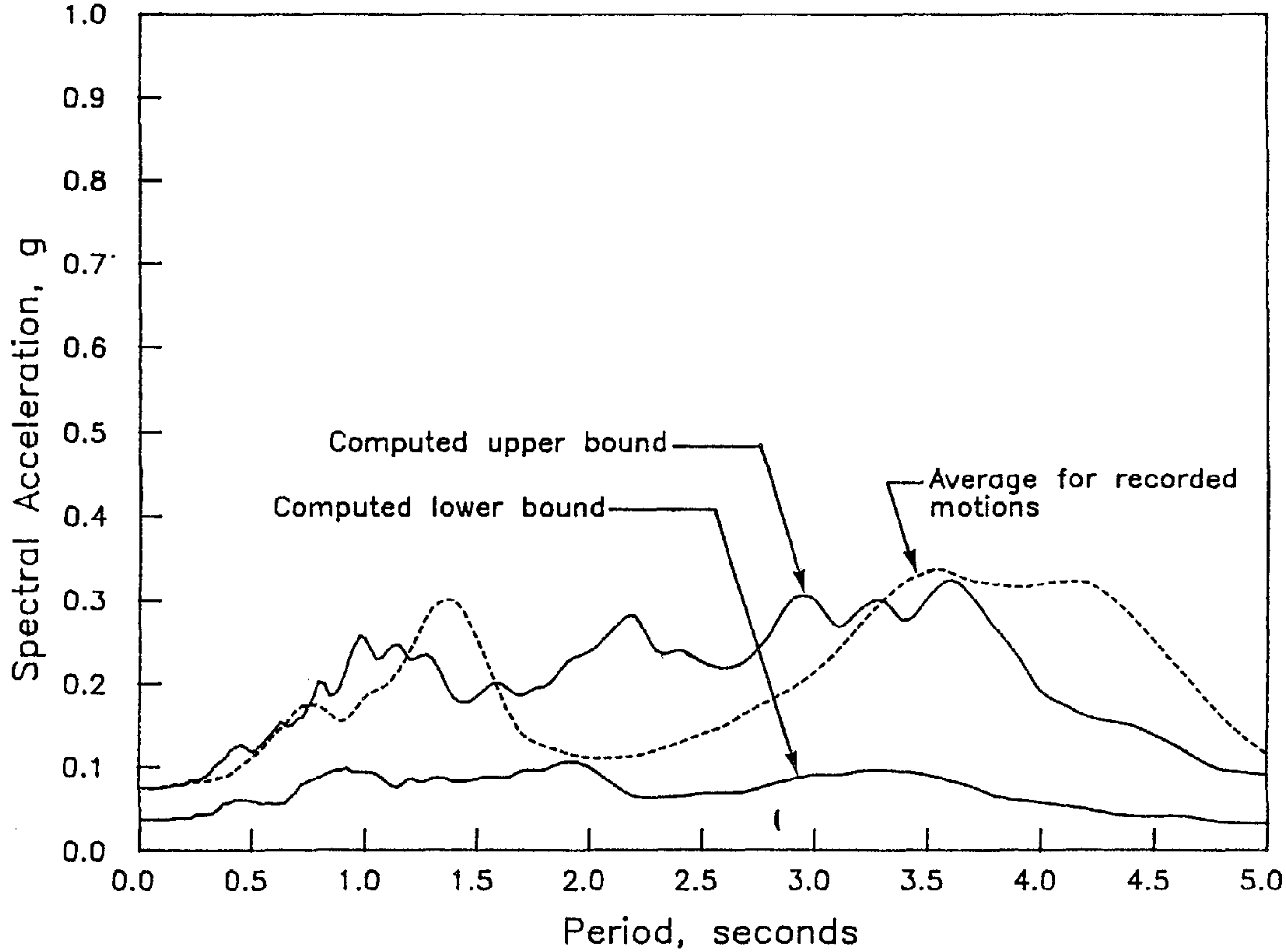


Fig. 8-10 COMPARISON OF RESPONSE SPECTRA DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT CAO SITE

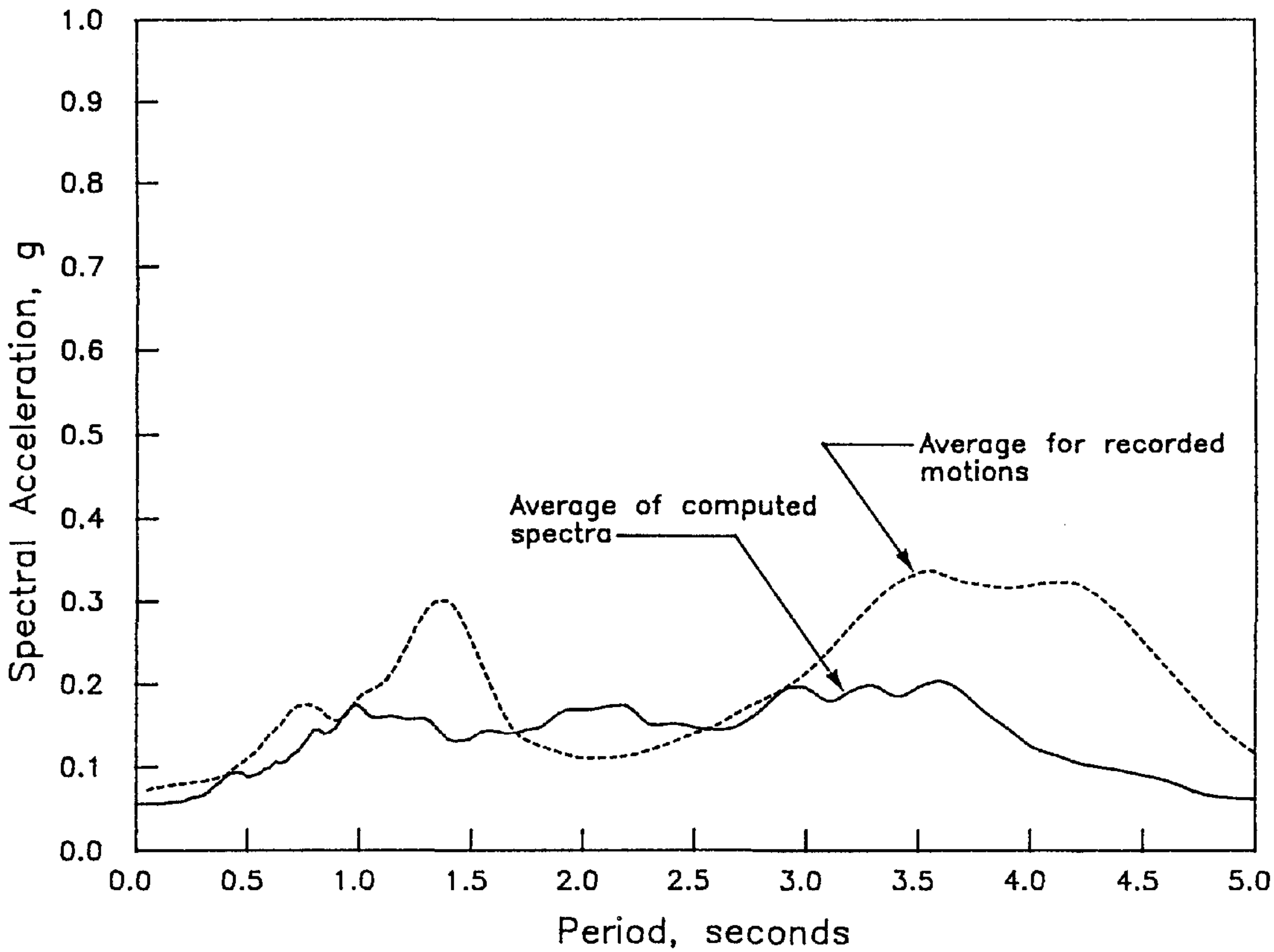


Fig. 8-11 COMPARISON OF AVERAGE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT CAO SITE

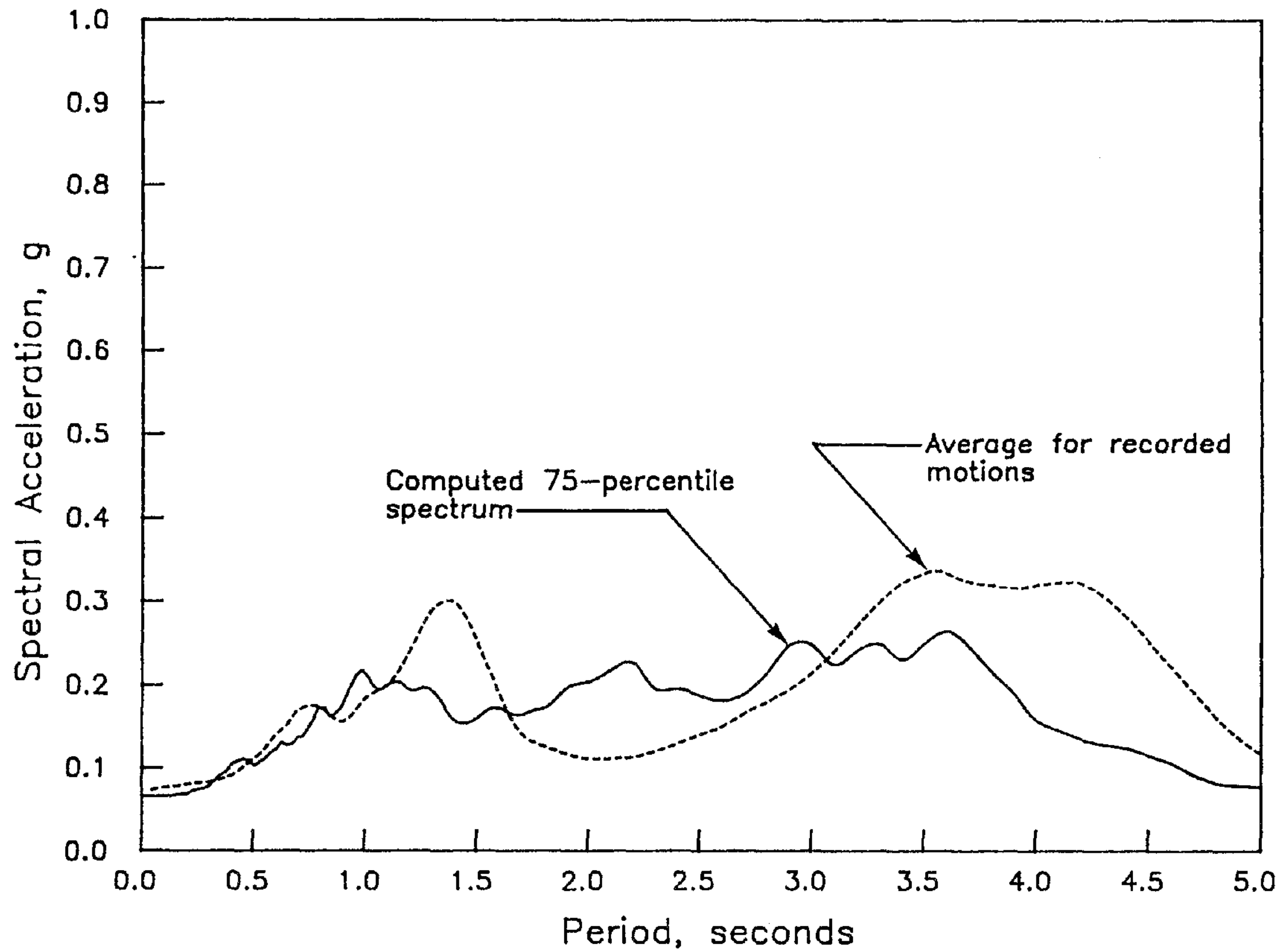
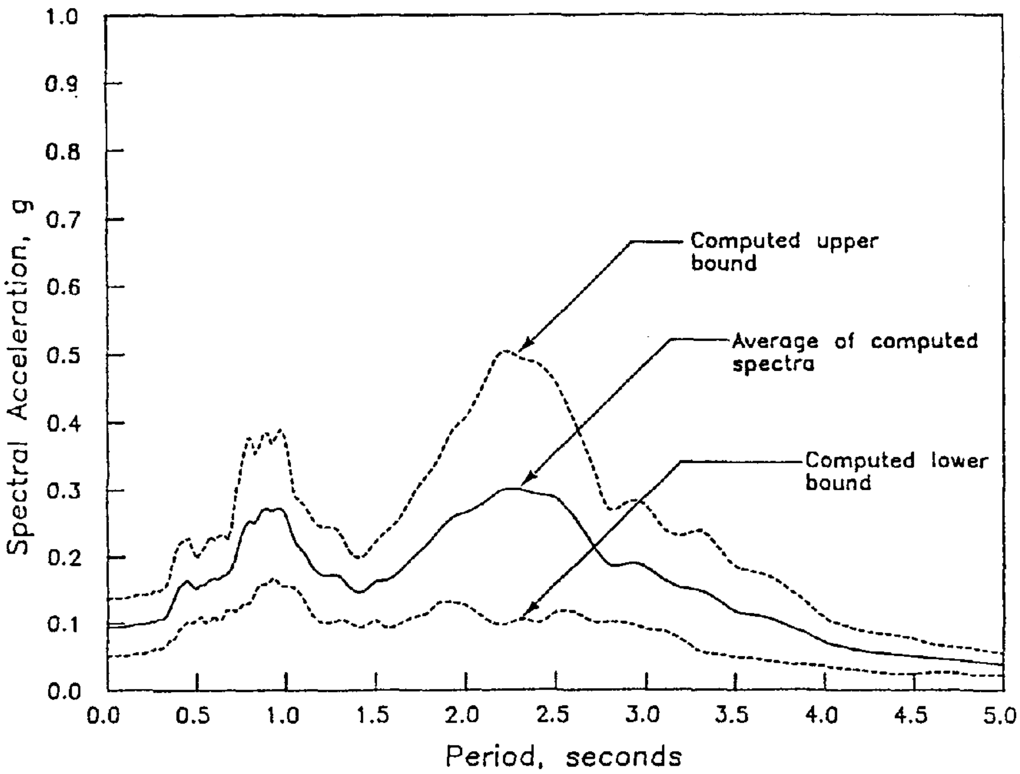


Fig. 8-12 COMPARISON OF 75-PERCENTILE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE RESPONSE SPECTRUM FOR RECORDED MOTIONS AT CAO SITE



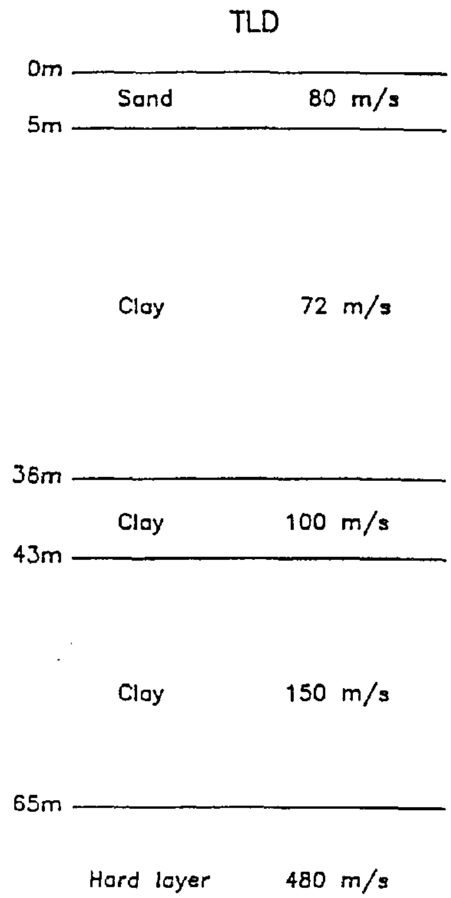


Fig. 8-13 RESULTS OF GROUND RESPONSE ANALYSES FOR TLD SITE BASED ON SHEAR WAVE VELOCITIES INTERPRETED FROM FIELD MEASUREMENTS--ACCELERATION RESPONSE SPECTRA FOR COMPUTED MOTIONS

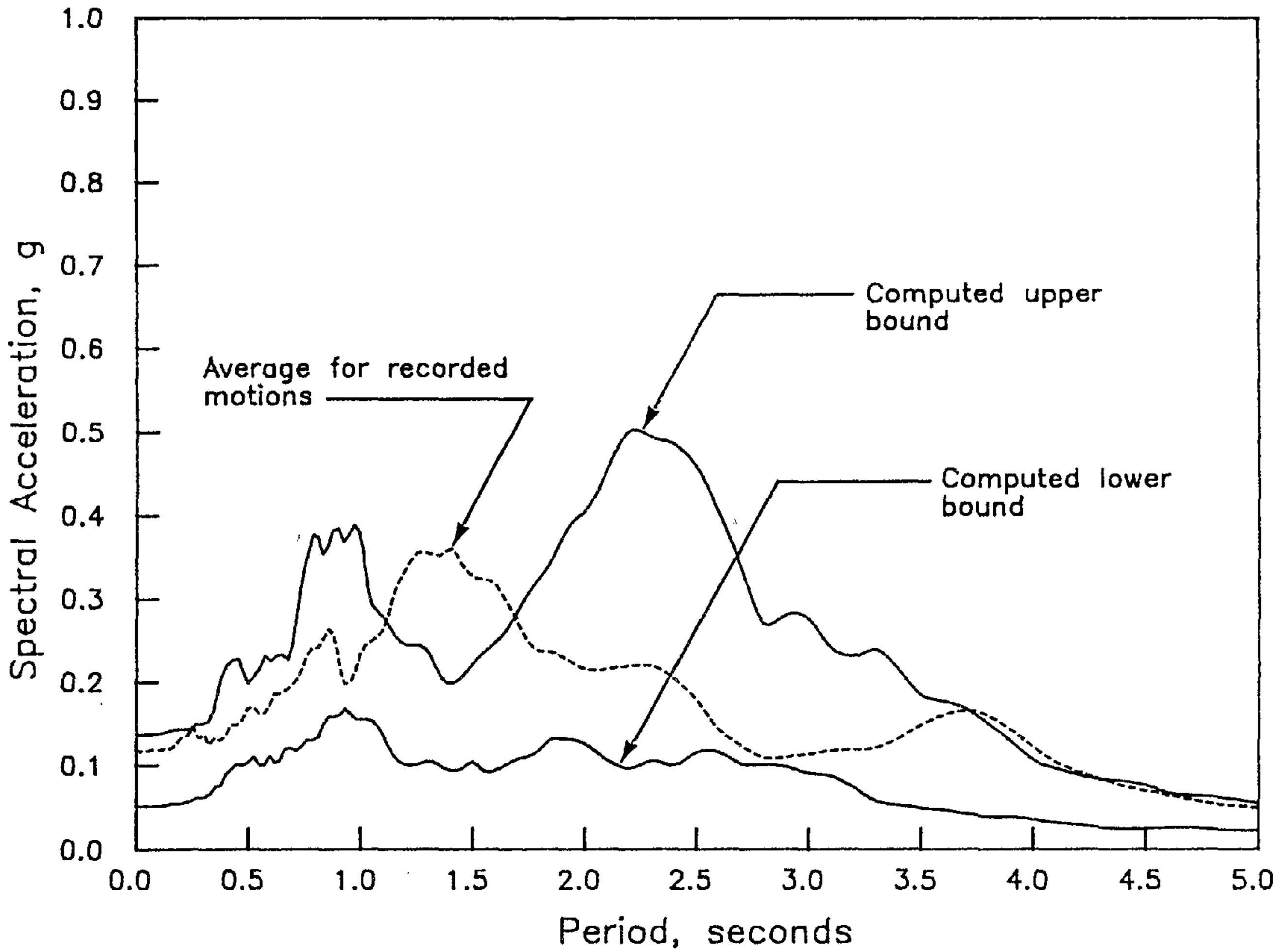


Fig. 8-14 COMPARISON OF RESPONSE SPECTRA DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT TLD SITE

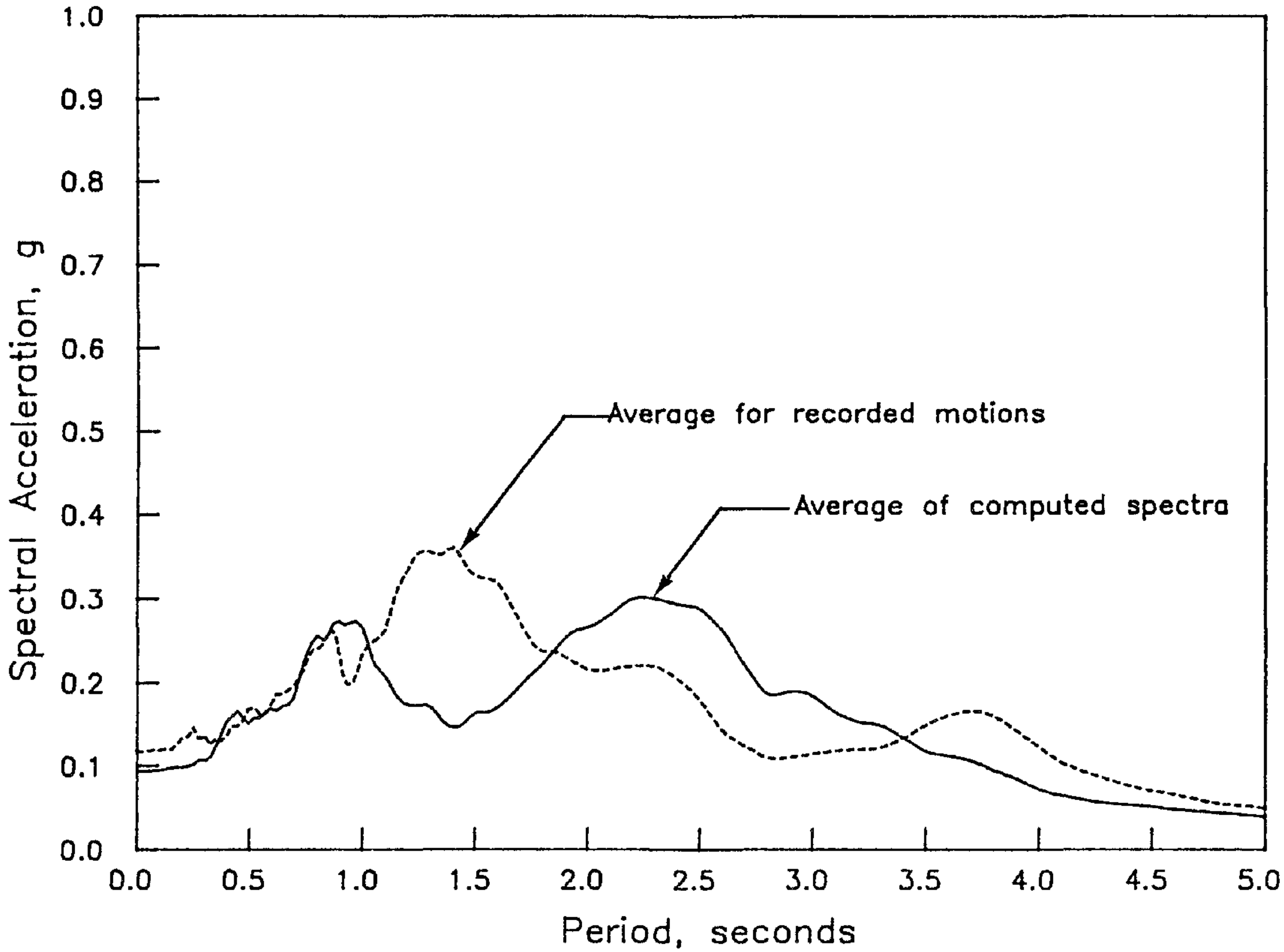


Fig. 8-15 COMPARISON OF AVERAGE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT TLD SITE

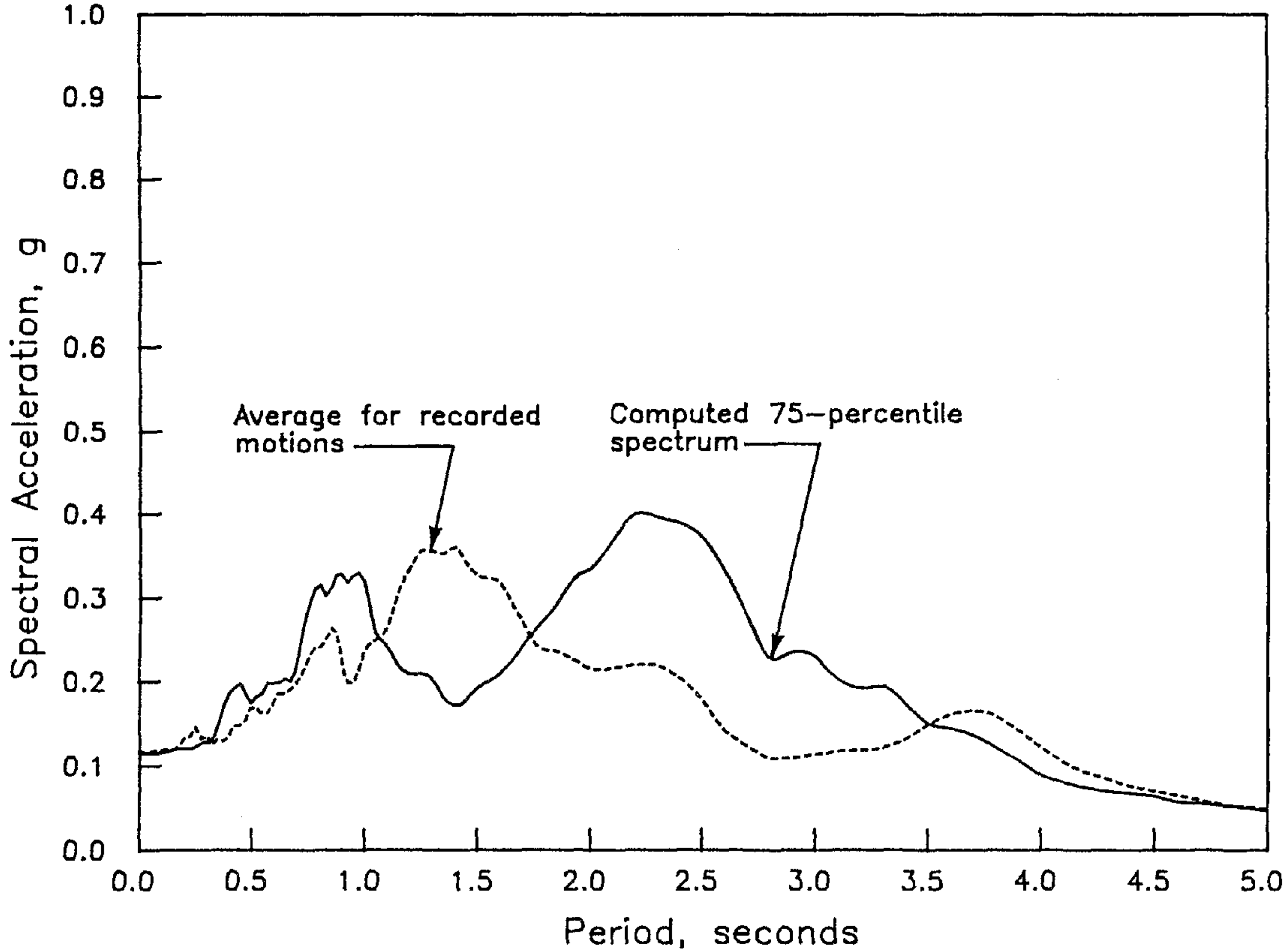


Fig. 8-16 COMPARISON OF 75-PERCENTILE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT TLD SITE

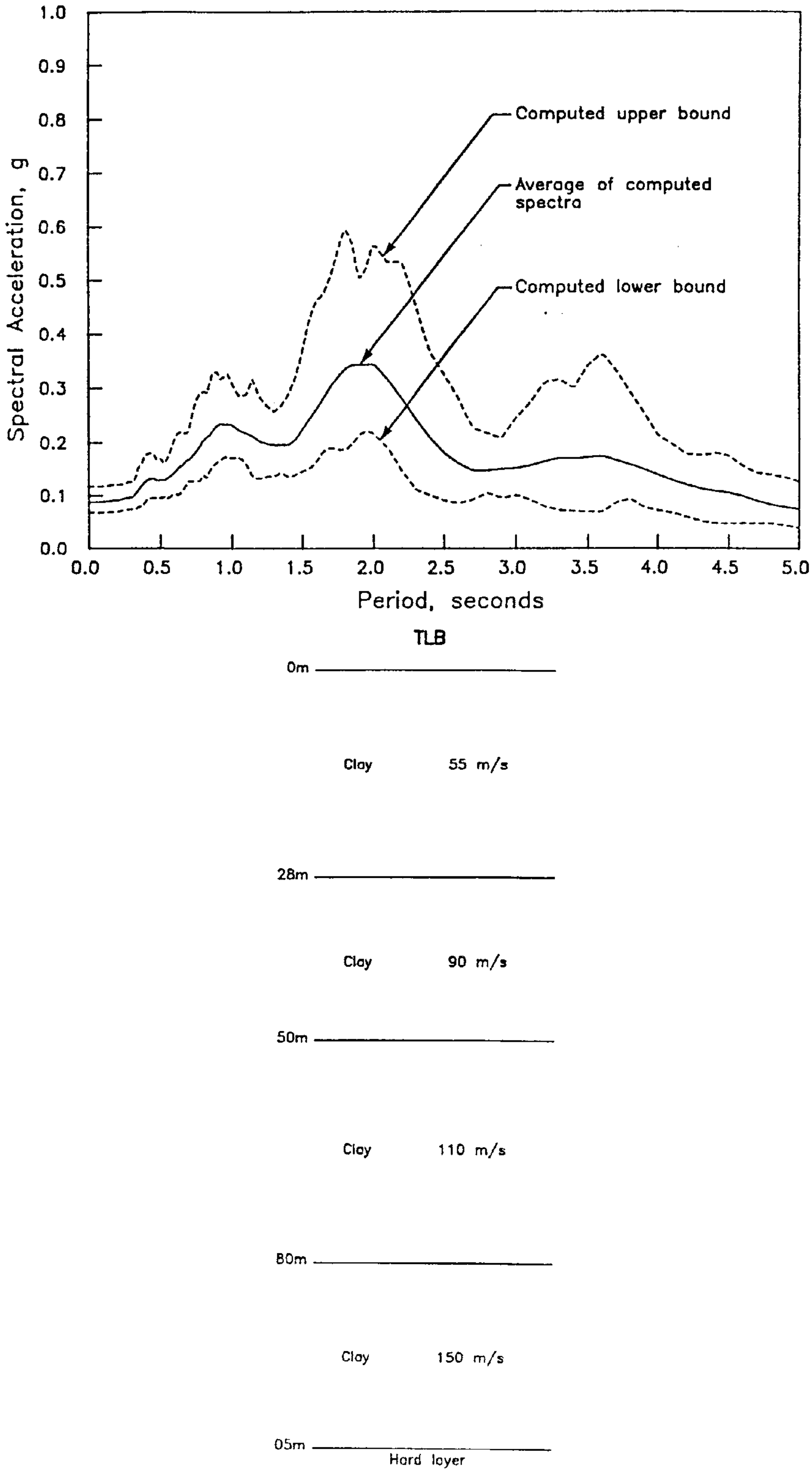


Fig. 8-17 RESULTS OF GROUND RESPONSE ANALYSES FOR TLB SITE BASED ON SHEAR WAVE VELOCITIES INTERPRETED FROM FIELD MEASUREMENTS--ACCELERATION RESPONSE SPECTRA FOR COMPUTED MOTIONS

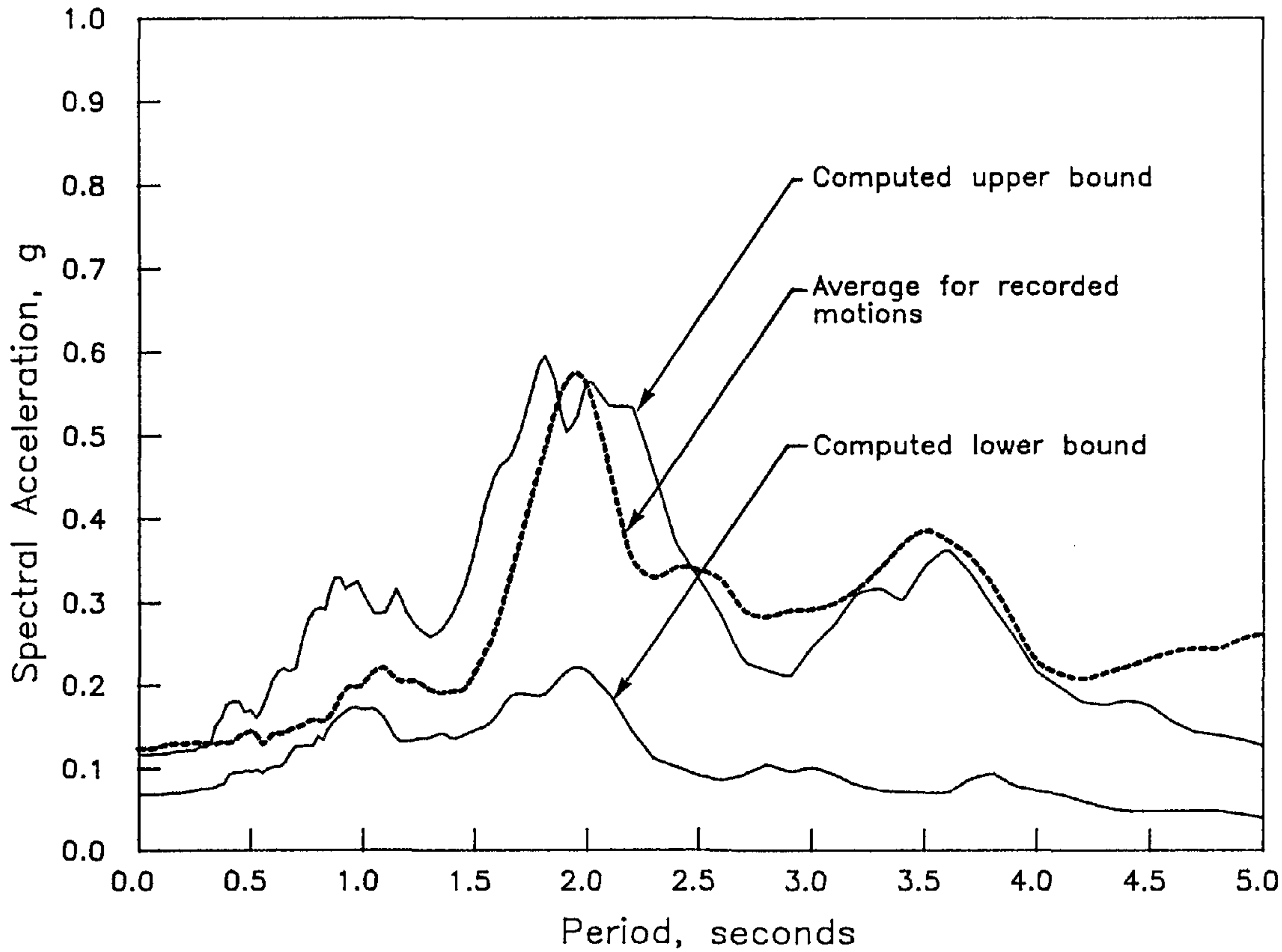


Fig. 8-18 COMPARISON OF RESPONSE SPECTRA DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT TLB SITE

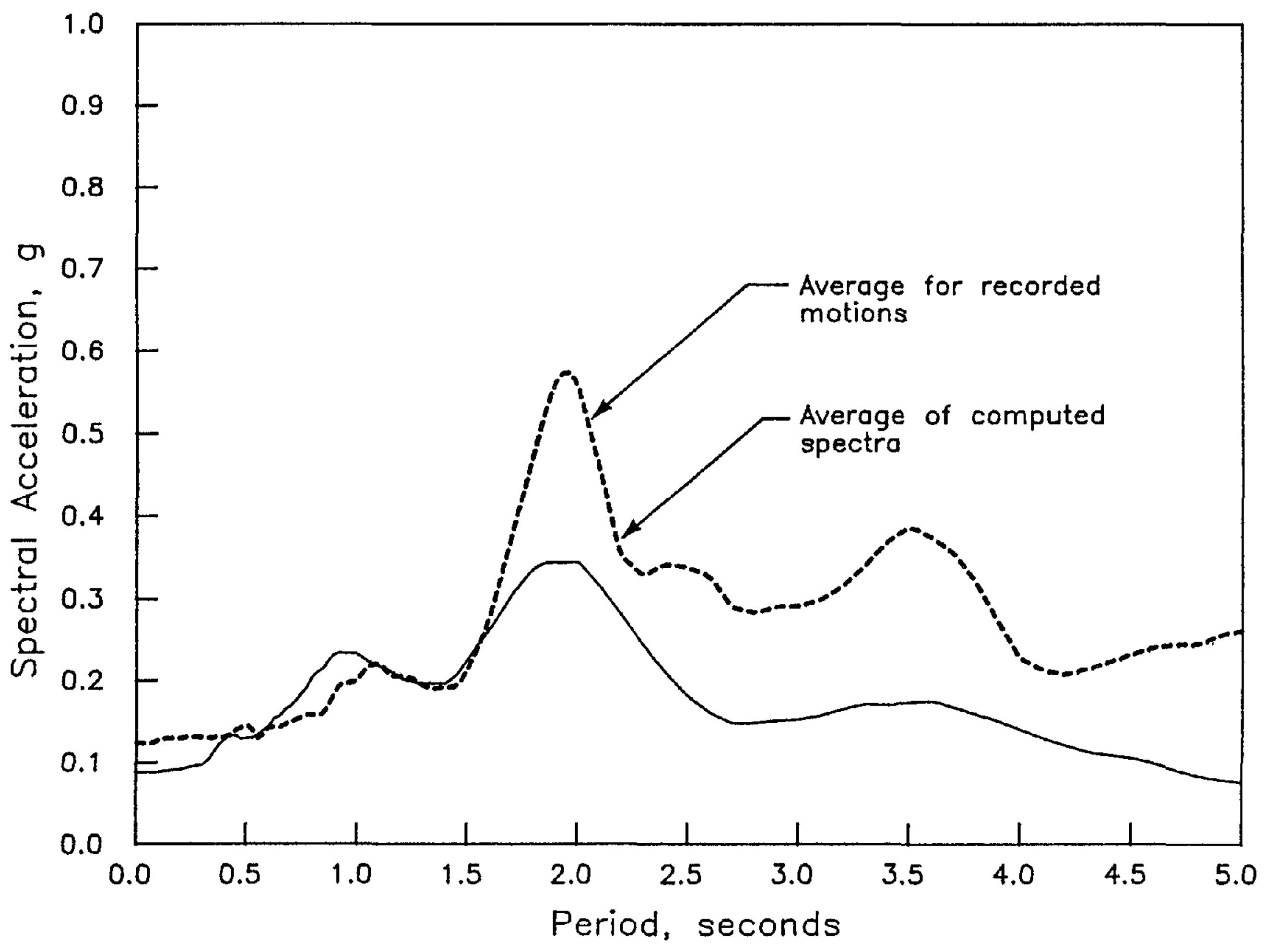


Fig. 8-19 COMPARISON OF AVERAGE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT TLB SITE

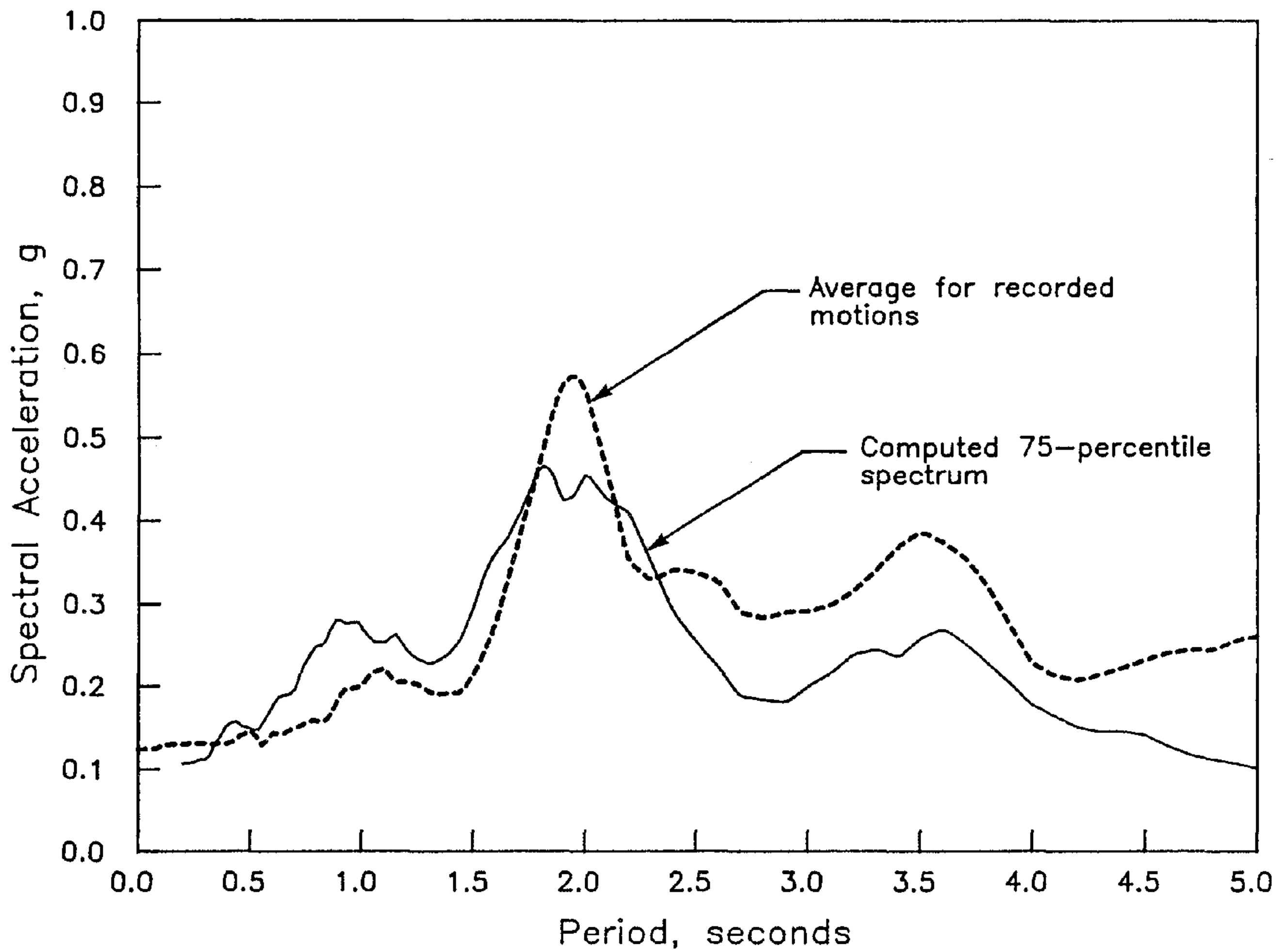


Fig. 8-20 COMPARISON OF 75-PERCENTILE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES BASED ON SHEAR WAVE VELOCITY MEASUREMENTS WITH AVERAGE RESPONSE SPECTRUM FOR RECORDED MOTIONS AT TLB SITE

1. Whether the average spectrum for the recorded motions falls within the upper and lower bounds of those for the computed motions (bearing in mind that the ranges of parameters incorporated in the analyses were quite small, e.g. $V_s = \pm 10\%$, etc.).
2. The degree of agreement between the average spectra for the recorded and computed motions.

and 3. The degree of agreement between the average spectrum for the recorded motions and the 75 percentile spectrum for the computed motions. This comparison was made in recognition of the fact that the measured values of shear wave velocities are probably lower than the true values and the use of these values tends to lead to unreasonably low values of computed motions for the Mexico City sites. Allowance for this bias in the data could be made either by making the analyses using values of shear wave velocity which vary by -0 and +20% from the measured values or alternatively, allowing variations of ±10% from the measured values and then adopting a higher than 50 percentile value of the computed motion spectrum for predictive purposes. The latter option was used in this case and the spectral level selected was the 75 percentile value for each site.

The comparative results for each of the five sites included in the study are summarized in Table 8-1. On balance it may be concluded that in most cases the average spectra for the recorded motions lie within the bounds of those corresponding to the computed motions and that the agreement between the average spectra for the recorded motions and the 75 percentile spectra for the computed motions ranges from Fair to Very Good, with the overall assessment being rated as Good.

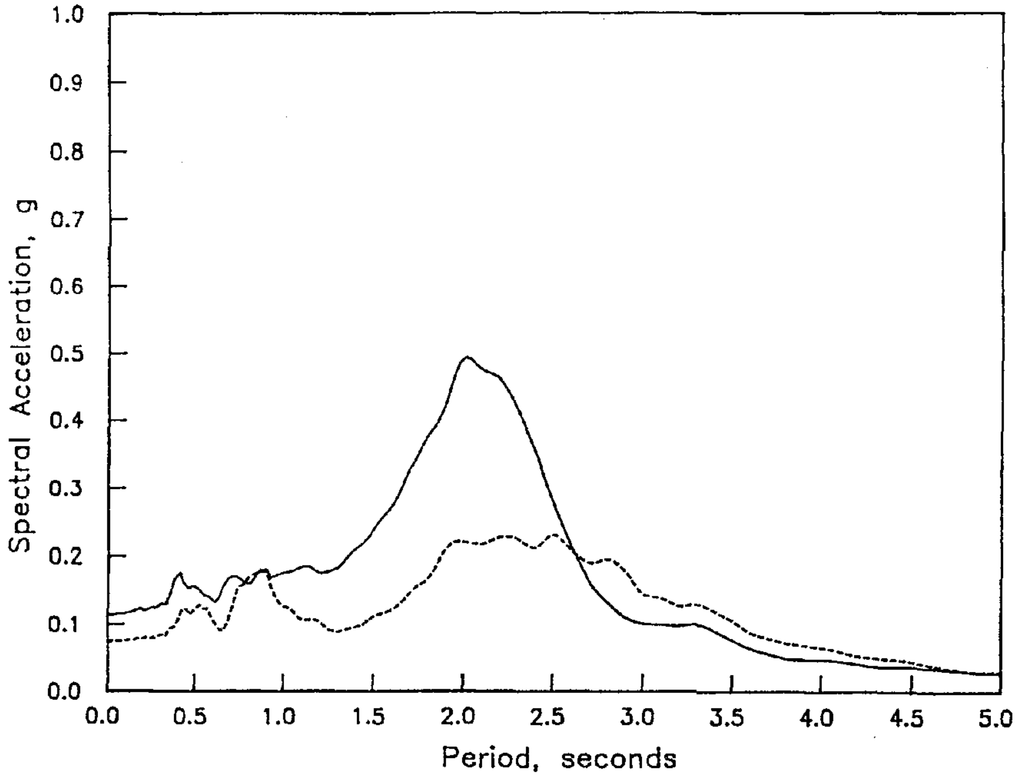
Table 8-1

Site	SCT	CAF	CAO	TLD	TLB
Average recorded spectrum within upper and lower bounds of computed spectra	Yes	Yes	Mainly up to T = 3.5 sec	Mainly	Mainly
Degree of agreement between average recorded and average computed spectra	Fairly Good	Fairly Good	Fair	Fair	Fair
Degree of agreement between average recorded spectrum and 75-percentile computed spectrum	Very Good	Very Good	Fairly Good	Fair	Good

It would appear from these results that if allowance is made for possible deviations from the best average deterministic study results and ground response problems are considered on a probabilistic basis, they can provide very useful data for assessing the influence of local soil conditions on the general form of the earthquake motions likely to develop at sites underlain by clays, similar to the conditions existing in the old lake-bed area of Mexico City.

This need to consider possible deviations from measured properties is especially important in view of the sensitivity of the analytical results of ground response analyses to small changes in soil conditions, either in depth of soil or in stiffness of soil, under conditions such as those existing in Mexico City. This has already been illustrated in Section 6, where the small differences in soil conditions between the SCT and the CAF sites were shown to be associated with a very significant change in the response spectra of the motions recorded at these sites. It is also apparent from the very large differences in upper and lower bounds for the spectra for the computed motions, shown in Figs. 8-1, 8-5, 8-9, 8-13, and 8-17, resulting from comparatively small variations in either soil properties or the level of base excitation used in the analyses.

It can be further illustrated by the analytical results determined for the SCT site. Fig. 8-21 shows the soil profile interpreted from the results of the shear wave velocity measurements at the SCT site, together with a modified profile in which the shear wave velocity of the clay, in the depth range from 10 to 20 m below the ground surface, was considered to be reduced by 15 m/sec below the original interpreted values. This change in velocity profile is well within the accuracy of interpretation of the shear wave velocity data. The upper part of Fig. 8-21 shows the response



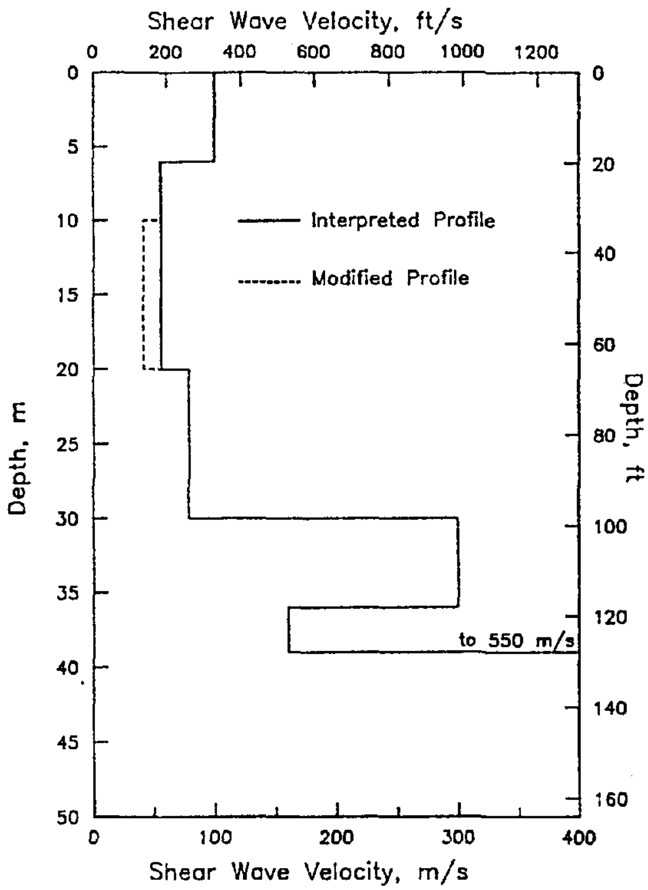


Fig. 8-21 EFFECT OF MINOR CHANGE IN SHEAR WAVE VELOCITY PROFILE AT SCT SITE ON ACCELERATION RESPONSE SPECTRUM FOR COMPUTED MOTIONS

spectra for the computed motions at the ground surface for the two profiles, using the same excitation in the hard layer for both analyses. It may be seen that this very small change in shear wave velocity over a very limited depth leads to a very significant change in the spectra for the computed motions at the ground surface.

Thus both observationally and analytically, small changes in soil characteristics, at least in Mexico City, can have a major effect on the characteristics of the ground surface motions, making it very difficult to anticipate the precise character of the motions likely to develop at any given site and emphasizing (a) that even "good" agreement between observed and computed motion characteristics is a significant achievement in ground motion prediction in the Mexico City environment; and (b) the importance of considering the possible effects of errors or variations in soil properties or base motion characteristics, through the use of probabilistic studies, in any attempt to study site effects in areas of such high sensitivity.

Despite these difficulties, however, ground response analyses can help significantly to anticipate the effects of local soil conditions on ground surface motions. This is well-illustrated by a comparison of the response spectra shown in Figs. 8-22 and 8-23. Fig. 8-22 shows the average response spectra for the motions recorded at four very different sites: UNAM, SCT, CAF and CAO. Fig. 8-23 shows the 75-percentile spectra for the computed motions at the same sites, based on the measured shear wave velocities of the soils and assuming that the UNAM motion was developed at an outcropping of the hard layer. There is considerable similarity in these two sets of results indicating the potential usefulness of ground response analyses in anticipating the nature of earthquake motions. For further comparison Fig. 8-24 shows the spectra for the same four sites based on ground response

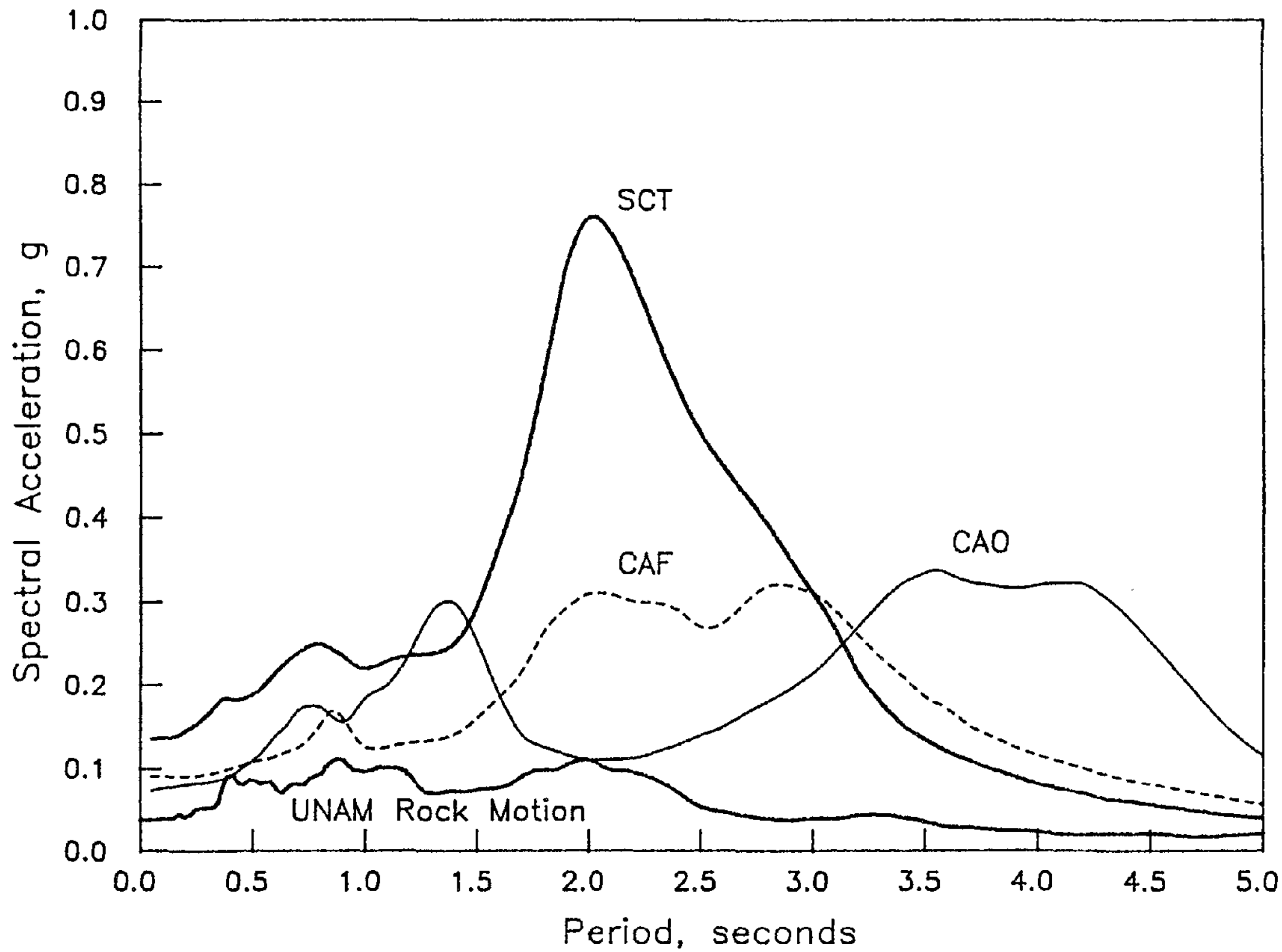


FIG. 8-22 COMPARISON OF AVERAGE SPECTRA FOR RECORDED MOTIONS AT UNAM, SCT, CAF AND CAO SITES

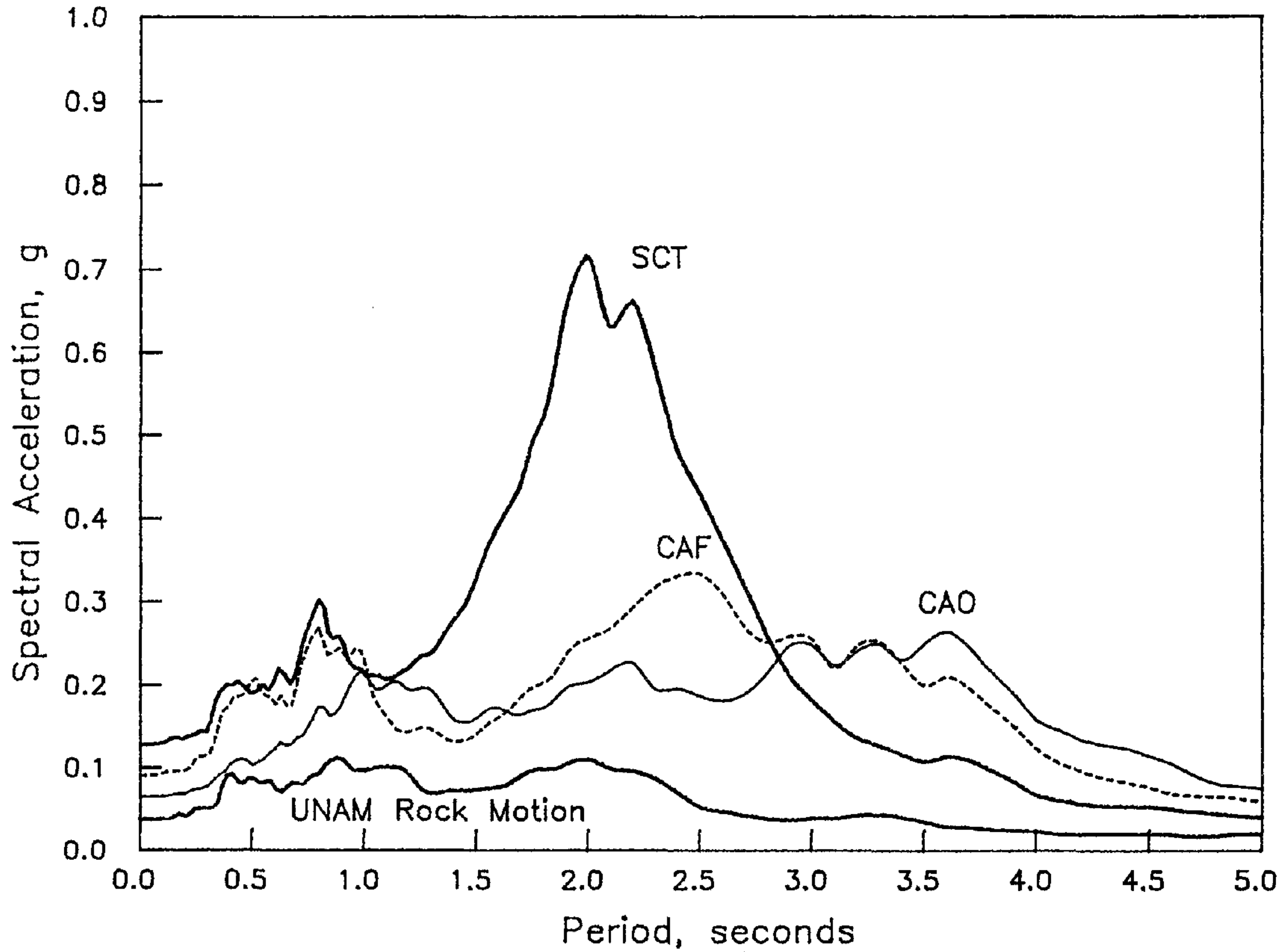


Fig. 8-23 COMPARISON OF 75-PERCENTILE SPECTRA FOR COMPUTED MOTIONS AT UNAM, SCT, CAF AND CAO SITES--ANALYSES BASED ON MEASURED SHEAR WAVE VELOCITIES

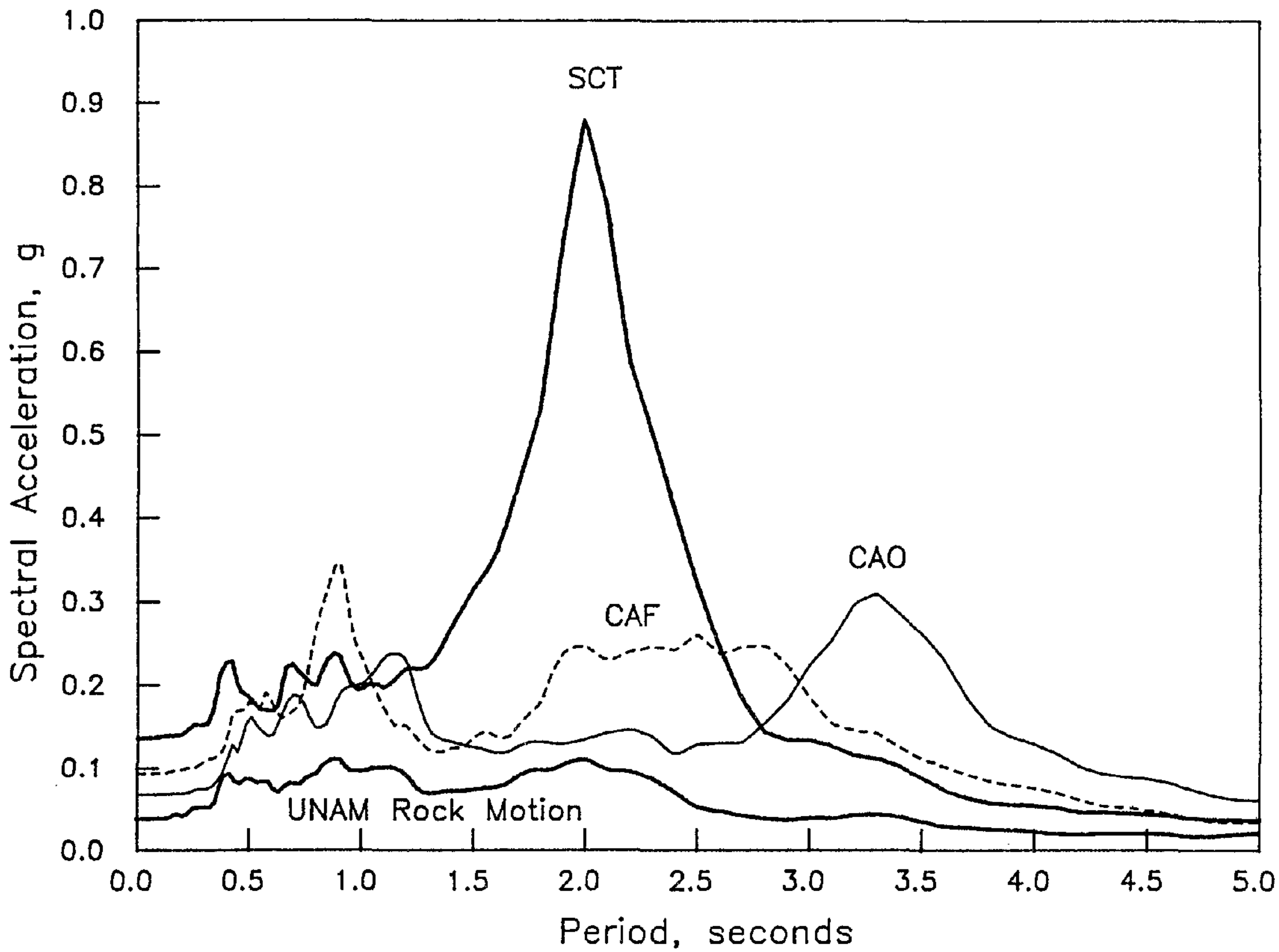


Fig. 8-24 COMPARISON OF SPECTRA FOR COMPUTED MOTIONS AT UNAM, SCT, CAF AND CAO SITES--ANALYSES BASED ON SHEAR WAVE VELOCITIES INFERRED FROM FREQUENCY CHARACTERISTICS OF RECORDED MOTIONS

analyses incorporating soil properties determined from earthquake records (Figs. 7-2 to 7-4). These analytical results are in even better accord with the spectra for the recorded motions indicating that whereever possible, it is desirable to refine direct measurements of shear wave velocities with data that may be obtained from actual earthquake records.

9. Use of Scaled Records of Outcrop Motions in Analyses of Ground Response

In the analyses of ground response in Mexico City described in previous sections of this report, motions at the SCT, CAF, CAO, TLD and TLB sites were computed on the basis of the known motions in the hard layer at the UNAM sites. In many cases where estimates of site effects are required, however, the specific details of the hard layer or rock outcrop motions will not be known and the motion can be described only in general terms, say by specific values of such parameters as peak ground acceleration, peak ground velocity, predominant period of motions, general form of response spectrum and duration of shaking. However in order to make a deterministic analysis of ground response a complete time-history of hard layer or rock outcrop motions is required.

In such cases the only means available to obtain the required time history of hard layer or rock motions are

1. To generate a totally artificial earthquake motion having the general characteristics required;

or 2. To take some existing record of earthquake motions and modify it, by appropriate scaling of either or both the acceleration and time scales to make it conform to the prescribed characteristics.

Both procedures are used, but perhaps the scaling procedure is used more frequently since it is easier to accomplish and the results will necessarily have the irregularities associated with a real earthquake record, since they are derived from a real earthquake record.

In order to investigate how the use of this procedure might affect the results of ground motion studies for a city such as Mexico City, analyses

were made to determine the ground motions which might be expected at the SCT site using a scaled accelerogram from the available set or records from past events. Desirably such a record would be generated by a magnitude 8 earthquake, would be recorded on rock or hard soil at a distance of about 300 kms from the source, would have predominant periods of about 0.9 and 2.0 seconds and would have a peak ground acceleration of about 0.038 g. Not surprisingly, such a record does not exist and it is necessary to select some record which comes reasonably close to the desired requirements and then scale the record to meet the requirements more closely.

In the United States, the largest magnitude earthquake for which records are available is the 1952 Kern County (California) earthquake which has a magnitude of 7.6. Several records are available, but one of the more distant is that obtained at a Pasadena station where the record has the following characteristics:

Peak acceleration: 0.057 g

Predominant periods: 0.65 and 0.82 seconds

By multiplying the acceleration scale of this earthquake motion by 0.52 and the time scale by a factor of 2.5, the characteristics are changed to:

Peak acceleration: 0.030 g

Predominant periods: 1.6 and 2.0 seconds

which meets the desired characteristics quite well. After scaling in this way, the time-history of accelerations has the form shown in Fig. 9-1 and the acceleration response spectrum shown in Fig. 9-2. It may be seen from Fig. 9-2 that the acceleration response spectrum of the scaled record is in reasonably close agreement with the average of the motions recorded at the UNAM sites.

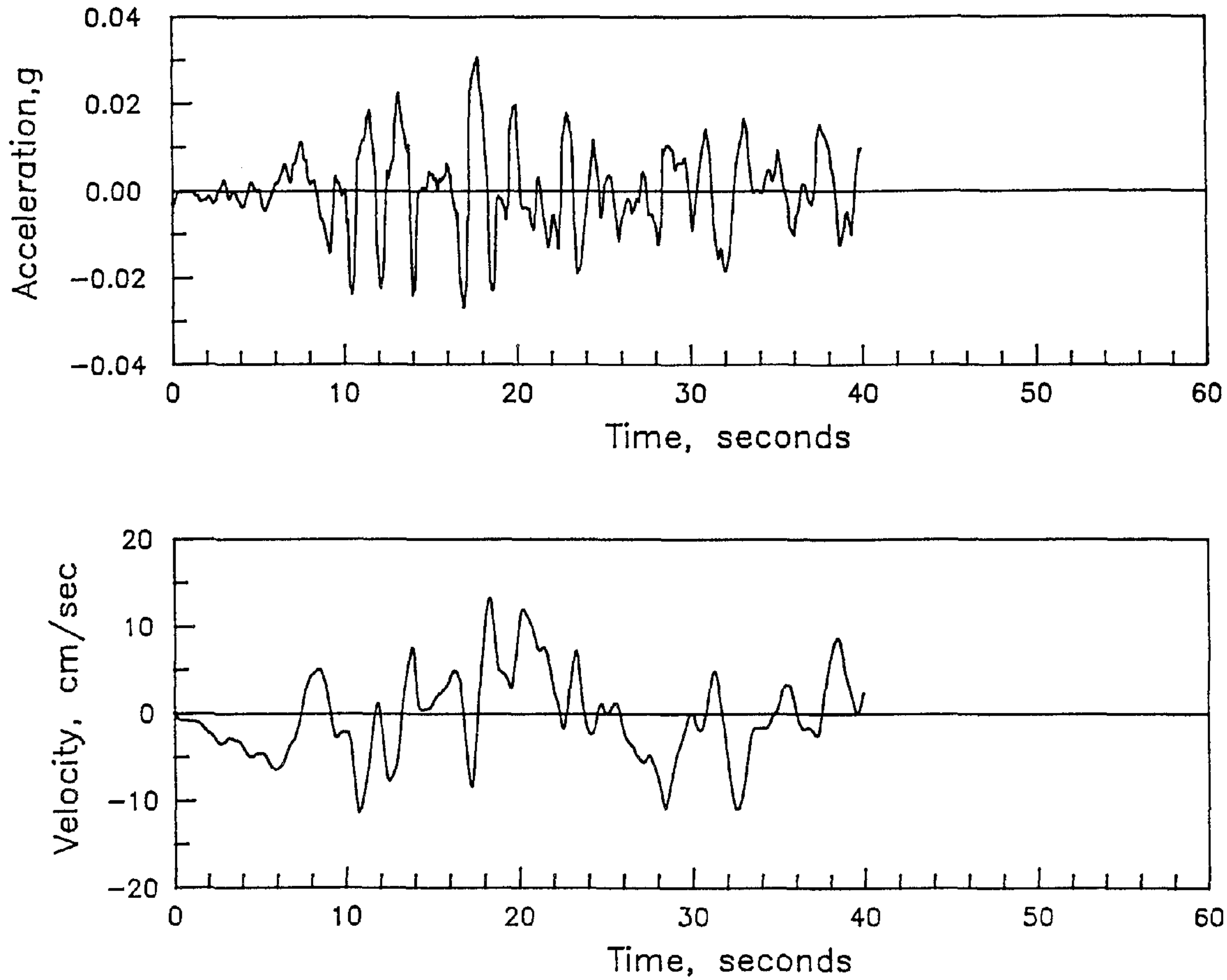


Fig. 9-1 TIME HISTORIES OF ACCELERATION AND VELOCITY FOR SCALED ACCELEROGRAM OF PASADENA RECORD OF KERN COUNTY (CALIFORNIA) EARTHQUAKE OF 1952

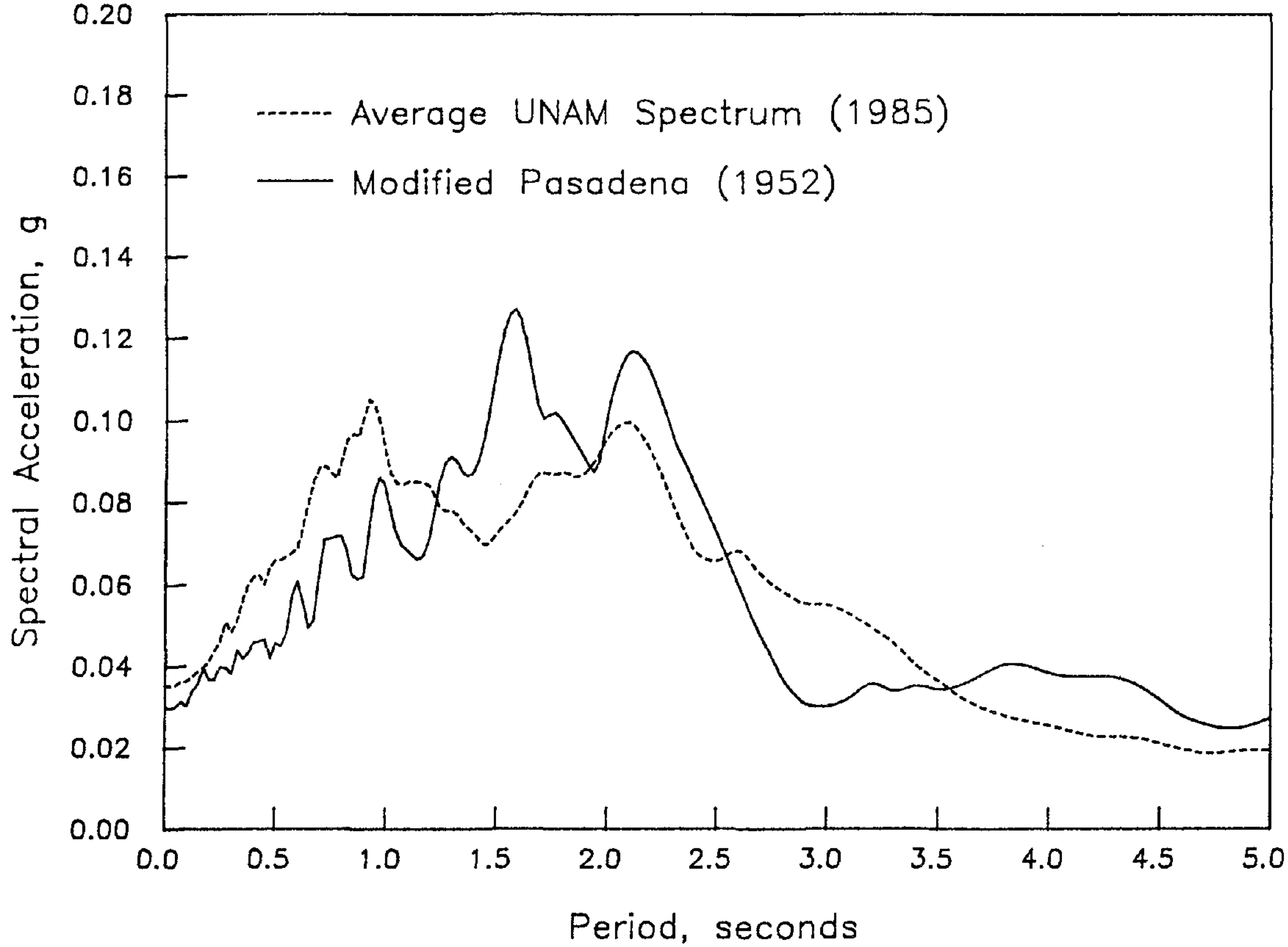


Fig. 9-2 COMPARISON OF ACCELERATION RESPONSE SPECTRUM FOR SCALED PASADENA RECORD AND AVERAGE SPECTRUM FOR UNAM RECORDS (1985)

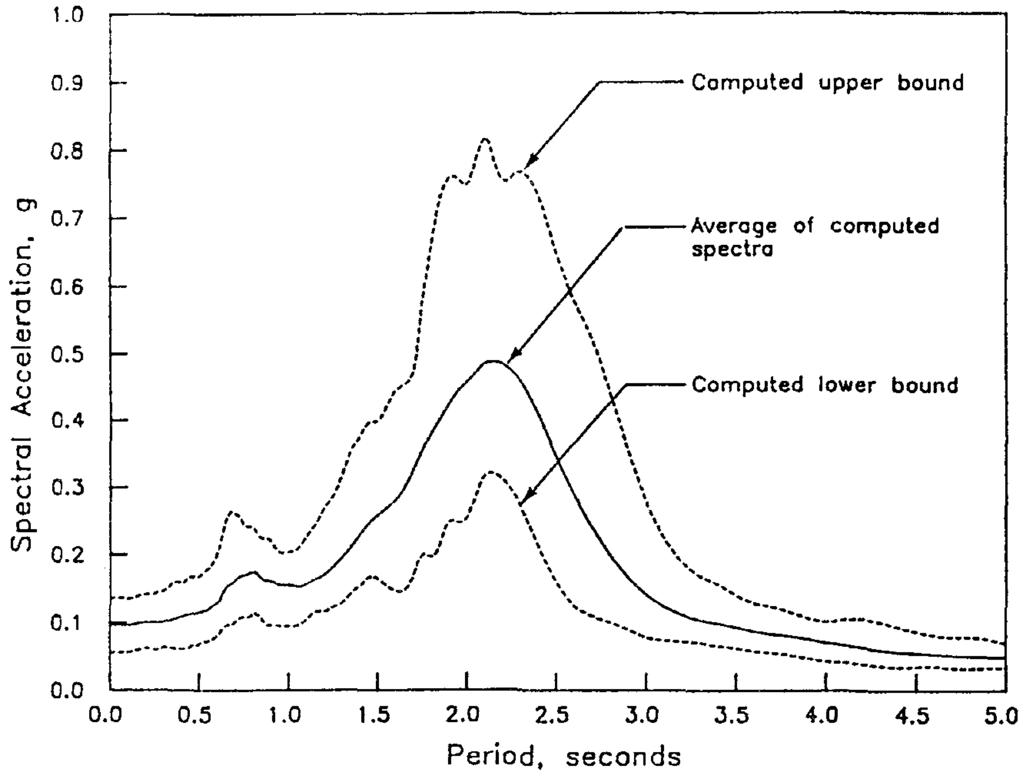
Thus the scaled record of the Pasadena recording of the Kern County earthquake was used to compute the ground surface motions at the SCT site, using the soil profile determined by the shear wave velocity measurements and shown in Fig. 9-3. As in the previous studies, soil properties and hard layer outcrop motions were allowed to vary as follows

Shear wave velocities:	$\pm 10\%$
Hard layer accelerations:	$\pm 20\%$
Predominant period of outcrop motion:	$\pm 10\%$

The results of the analyses are presented in Figs. 9-3 to 9-6. Fig. 9-3 shows the soil profile used in the analyses and the upper and lower bounds of the spectra for the computed motions. The average spectrum from the 27 analyses performed is also shown in this Figure. Figure 9-4 shows the upper and lower bound spectra for the computed motions, together with the average spectrum for the recorded motions. In general the average spectrum for the recorded motions falls within the range of the spectra for the computed motions, albeit near the upper bound of the range.

Fig. 9-5 compares the average spectrum for the recorded motions with the average spectrum for the computed motions at the SCT site and Fig. 9-6 compares the average spectrum for the recorded motions with the 75-percentile spectrum for the computed motions. As in the case of the preceding analyses described in Section 8, the 75-percentile spectrum for the computed motions is in good agreement with the average spectrum for the recorded motions.

Finally, Fig. 9-7 compares the 75-percentile spectra of the motions computed for the SCT site using both the CUMV-NS component of the motions recorded at UNAM in the 1985 earthquake and the modified Pasadena record of the Taft earthquake as hard-layer outcrop motions. It may be seen that



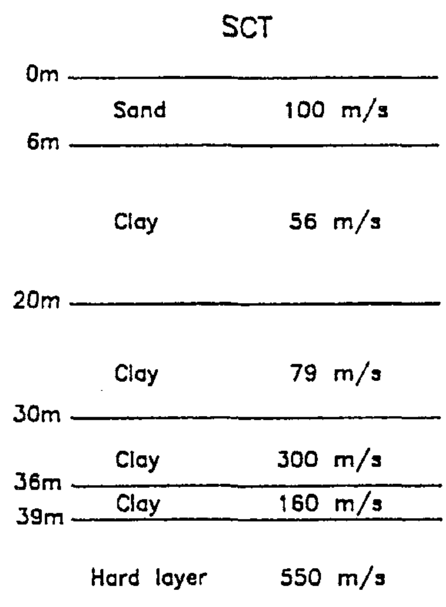


Fig. 9-3 RESULTS OF GROUND RESPONSE ANALYSES FOR SCT SITE USING SCALED PASADENA RECORD AS HARD LAYER OUTCROP MOTION

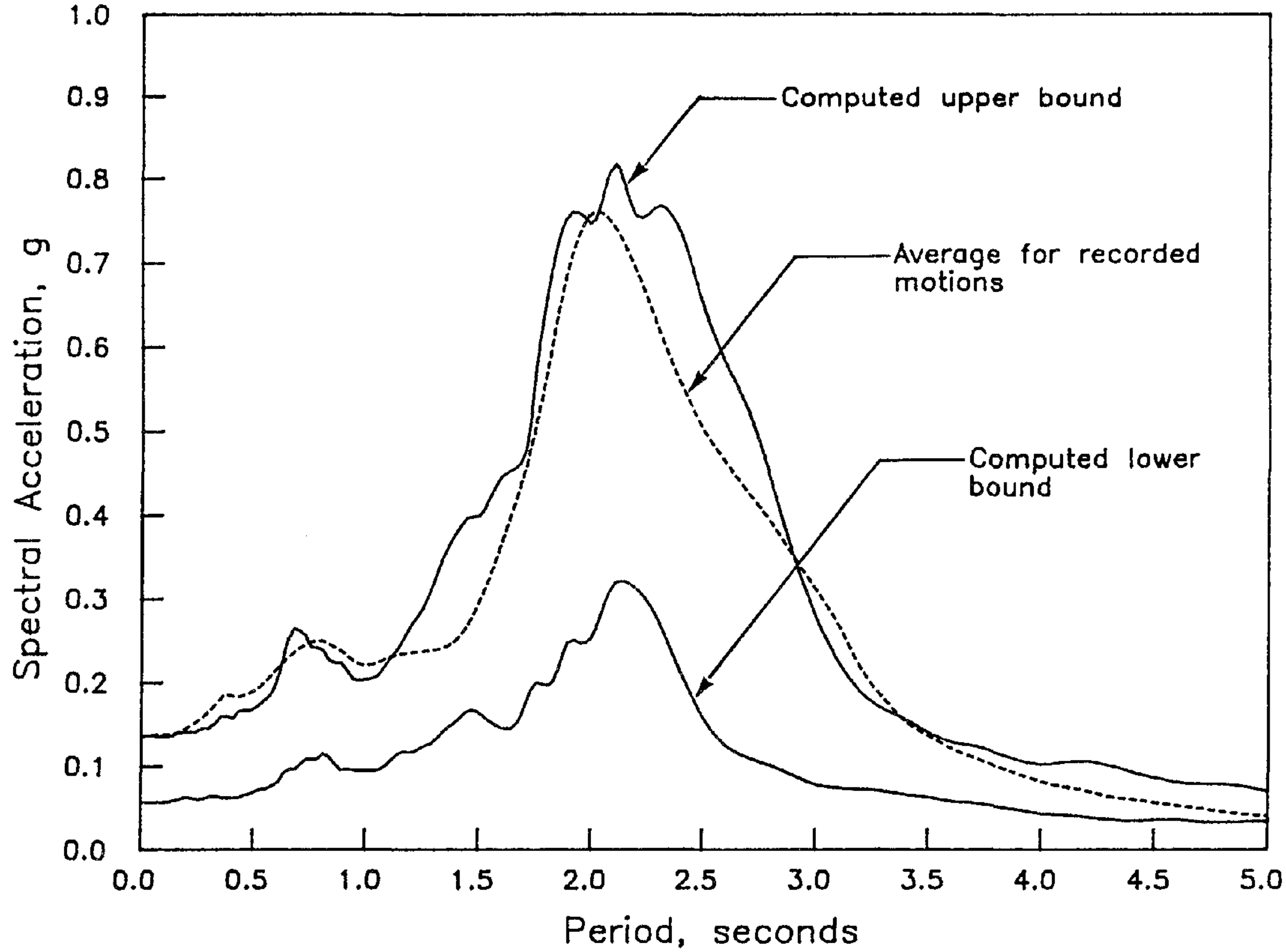


Fig. 9-4 COMPARISON OF RESPONSE SPECTRA DETERMINED BY GROUND RESPONSE ANALYSES USING SCALED PASADENA RECORD AS HARD LAYER OUTCROP MOTION WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT SCT SITE

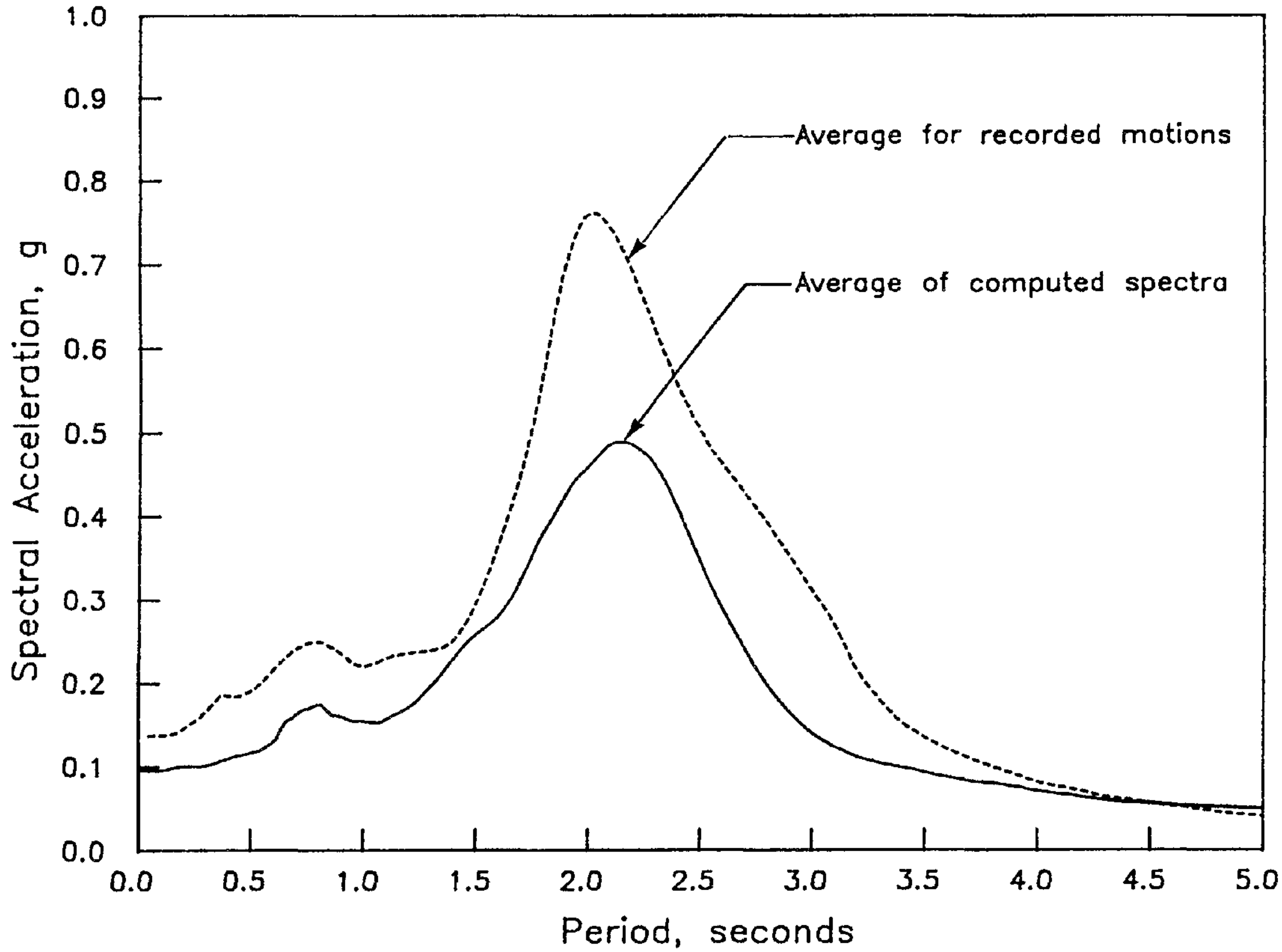


Fig. 9-5 COMPARISON OF AVERAGE RESPONSE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES USING SCALED PASADENA RECORD AS HARD LAYER OUTCROP MOTION WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT SCT SITE

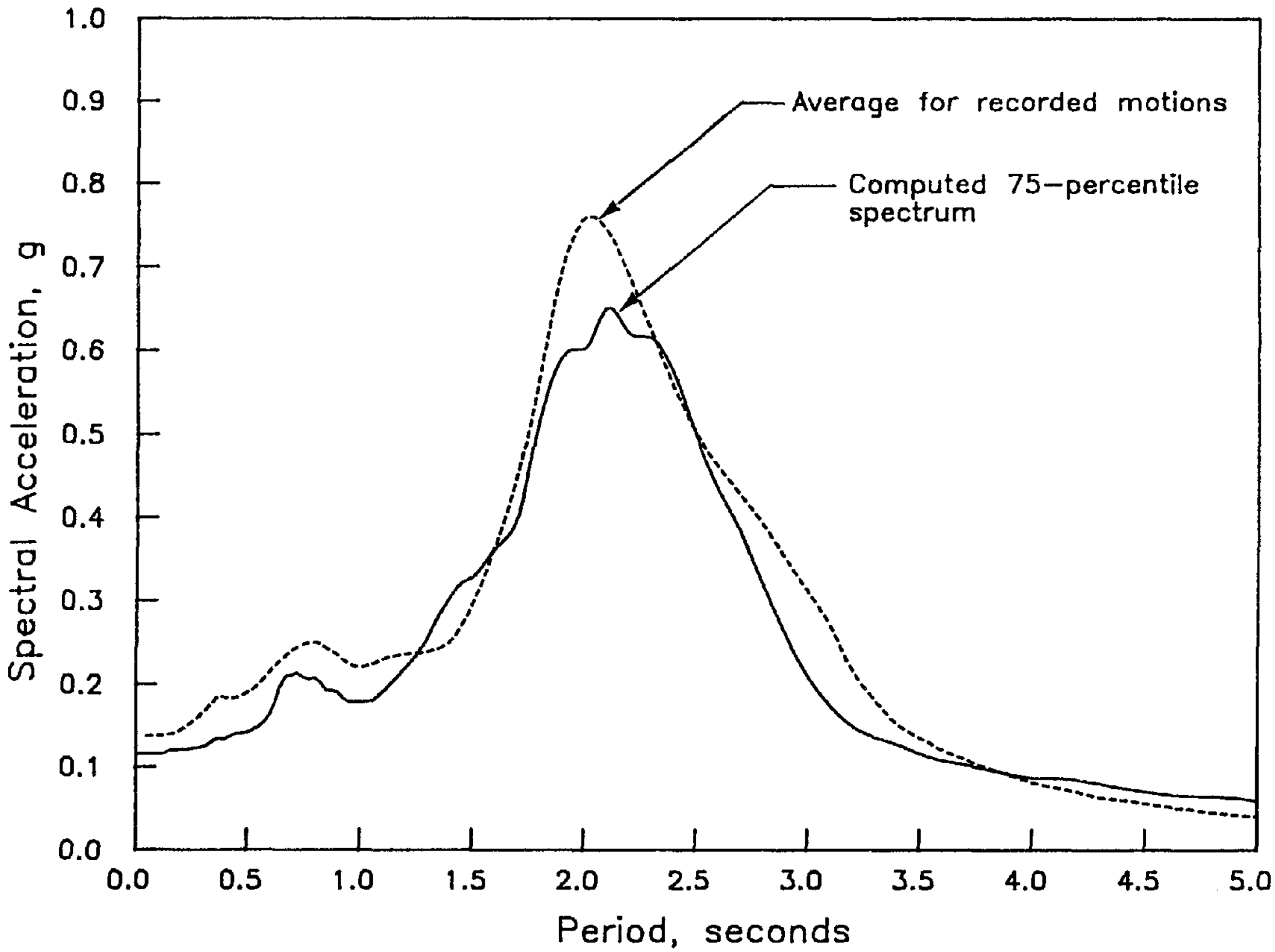


Fig. 9-6 COMPARISON OF 75-PERCENTILE SPECTRUM DETERMINED BY GROUND RESPONSE ANALYSES USING SCALED PASADENA RECORD AS HARD LAYER OUTCROP MOTION WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT SCT SITE

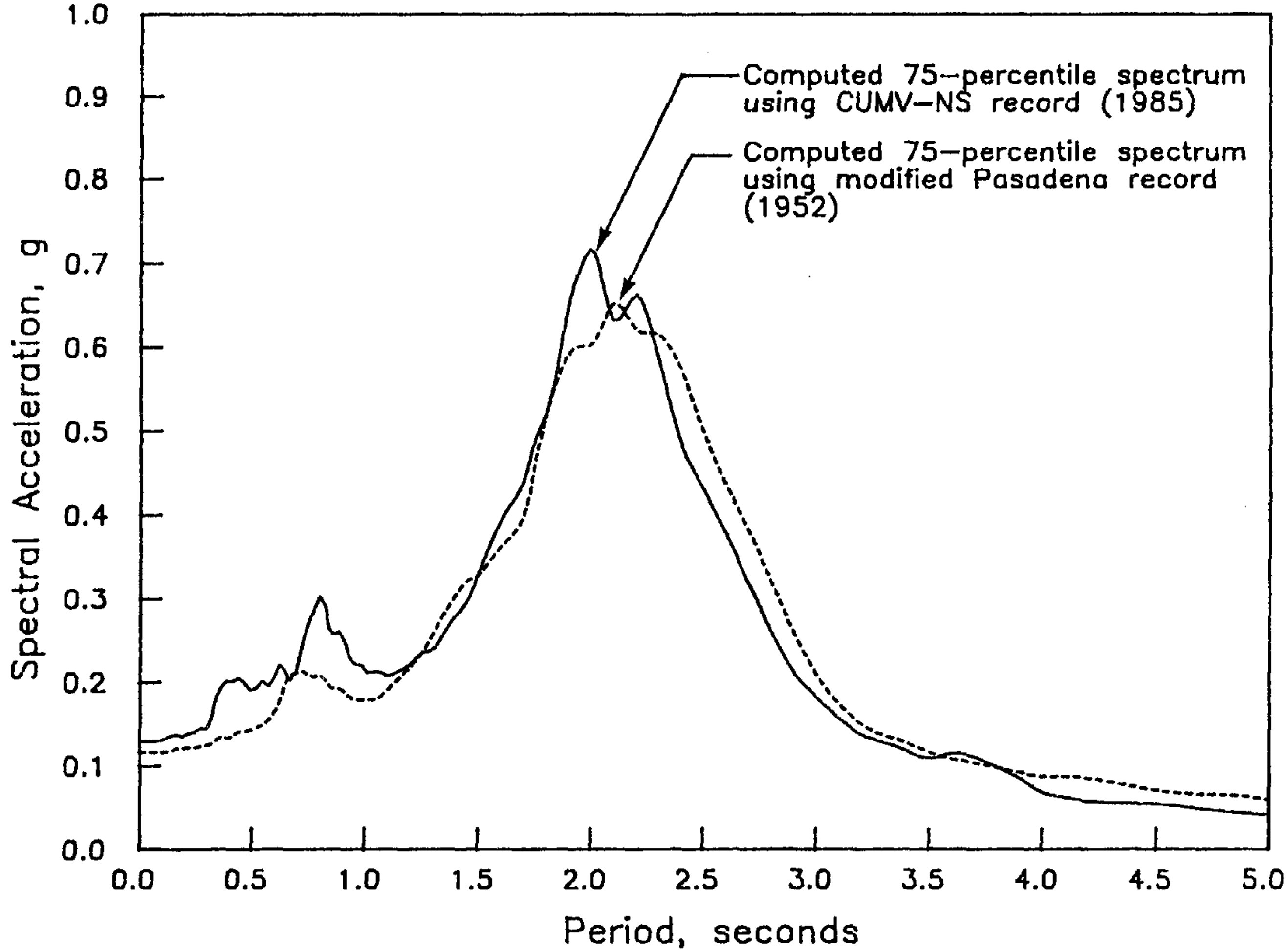


Fig. 9-7 COMPARISON OF 75-PERCENTILE SPECTRA DETERMINED BY GROUND RESPONSE ANALYSES USING SCALED PASADENA RECORD AND N-S COMPONENT OF CUMV RECORD AS HARD LAYER OUTCROP MOTIONS

there is little difference in these spectra whether the CUMV-NS record or the modified Pasadena record is used as the control motion for the analysis.

This result would seem to demonstrate that good evaluations of soil effects on ground response can be made even when the rock or hard layer motions must be represented by scaled records from other earthquakes, provided the scaling results in an accelerogram which reasonably represents both in acceleration level and frequency content, the characteristics of the anticipated rock outcrop motions.

10. Predictions of Ground Motions at Sites of Special Interest

The ultimate goal of the field investigations and analyses performed in this study is the development of an ability to predict, with some level of confidence, the nature of the ground motions which are likely to have occurred at critical sites or in critical zones of Mexico City where major damage occurred but where no instrumental records were obtained. Typical examples are presented below.

CUPJ Site

One such site for example is the CUPJ site, near the location of much of the very heavy damage and building collapses during the September 19, 1985 earthquake (see Fig. 10-1). Clearly a first step in making an evaluation of the ground motions which led to the collapse of this building is a determination of the soil conditions at this particular site. The results of a soil exploration program showed that the soil conditions at this site consist of a 4 m thick layer of sand, underlain by about 26 m of clay containing thin seams of silt and fine sand, followed by a 9 m thick layer of sand and stiffer clay, followed by the hard layer. The variation of measured shear wave velocities with depth is shown in Fig. 10-2, and an interpreted profile of the site conditions based on all of this data is shown in Fig. 10-3.

It is immediately apparent from the results presented that this soil profile at the CUPJ site, shown in Fig. 10-3, is very similar to that for the SCT site. A comparison of the interpreted soil profiles is shown in Fig. 10-4. In view of the very close similarity in the soil conditions it would be reasonable to conclude by observation that the earthquake motions at these two sites would also be closely alike.

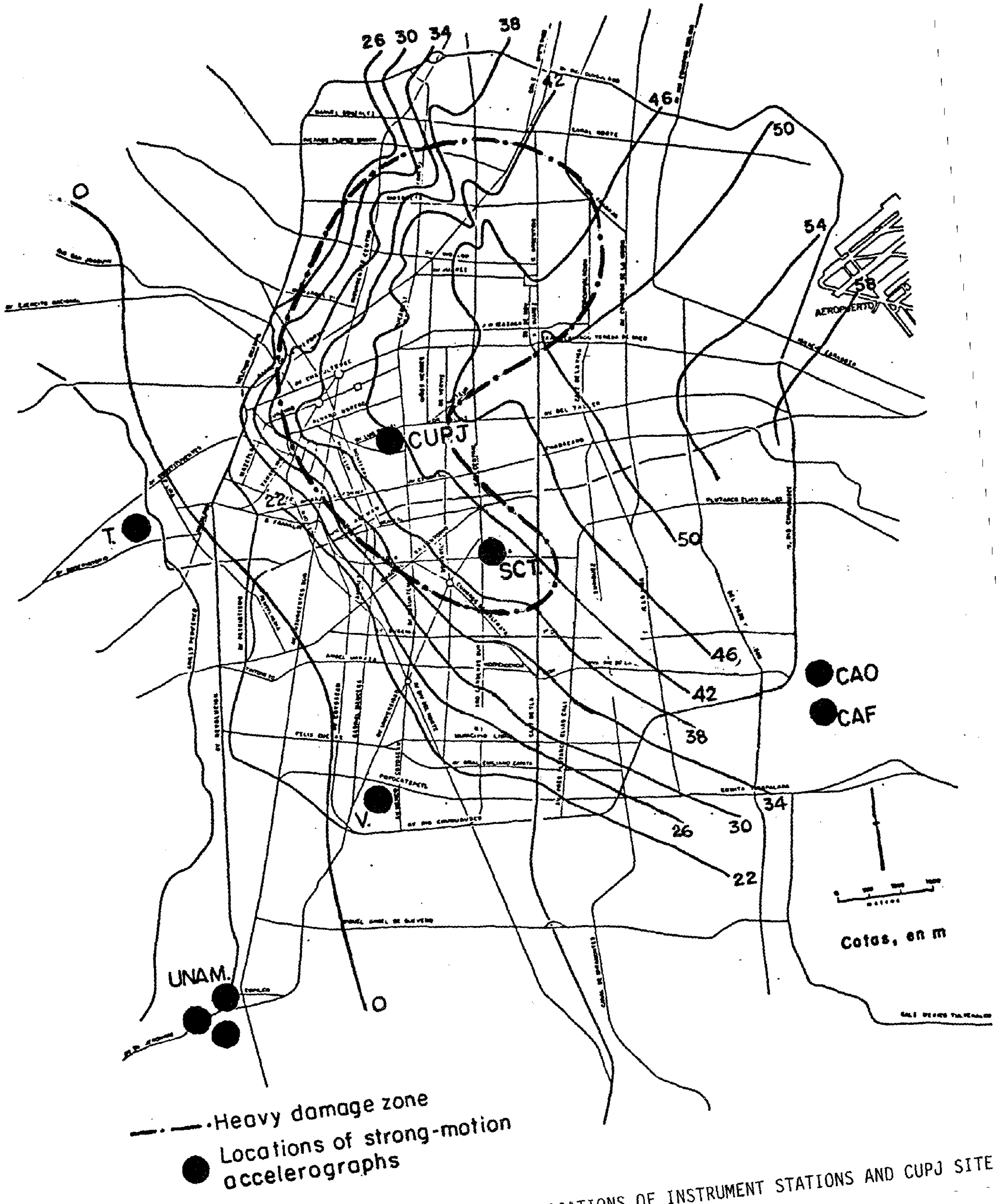


Fig. 10-1 PLAN OF MEXICO CITY SHOWING LOCATIONS OF INSTRUMENT STATIONS AND CUPJ SITE

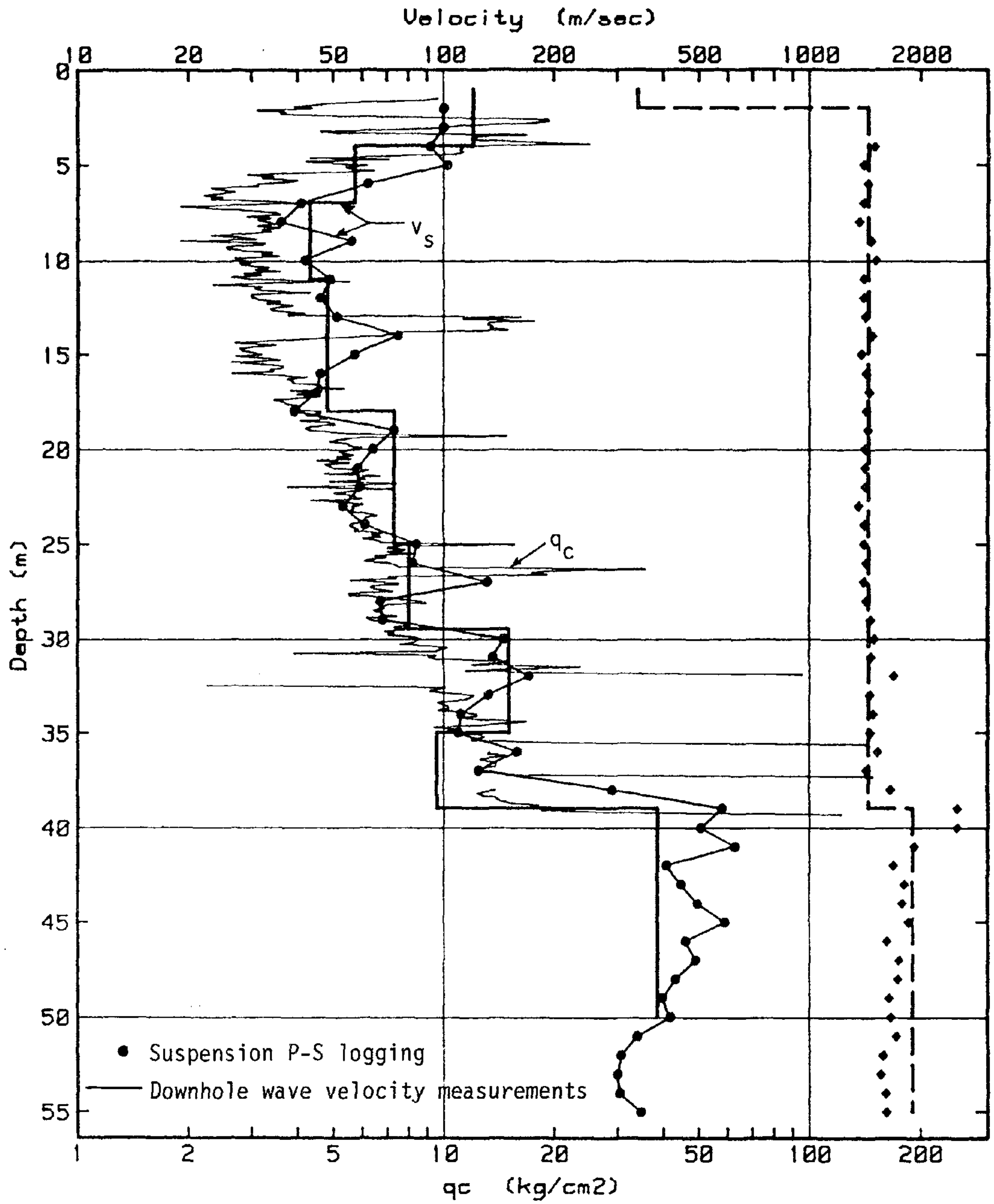


Fig. 10-2 MEASURED SHEAR WAVE VELOCITIES AT CUPJ SITE

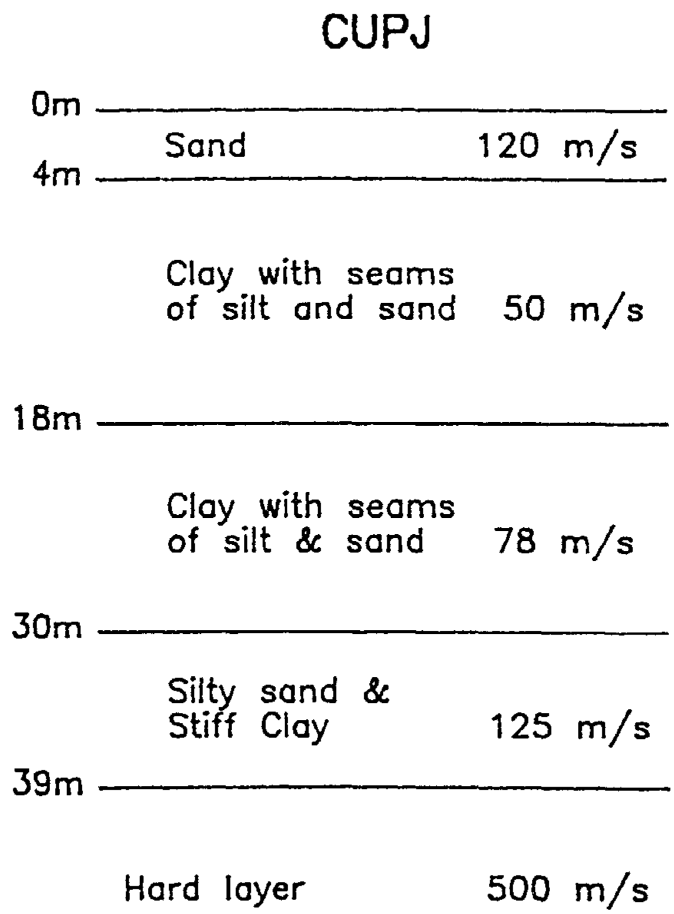


Fig. 10-3 INTERPRETED SOIL PROFILE AT CUPJ SITE BASED ON SOIL BORINGS AND SHEAR WAVE VELOCITY MEASUREMENTS

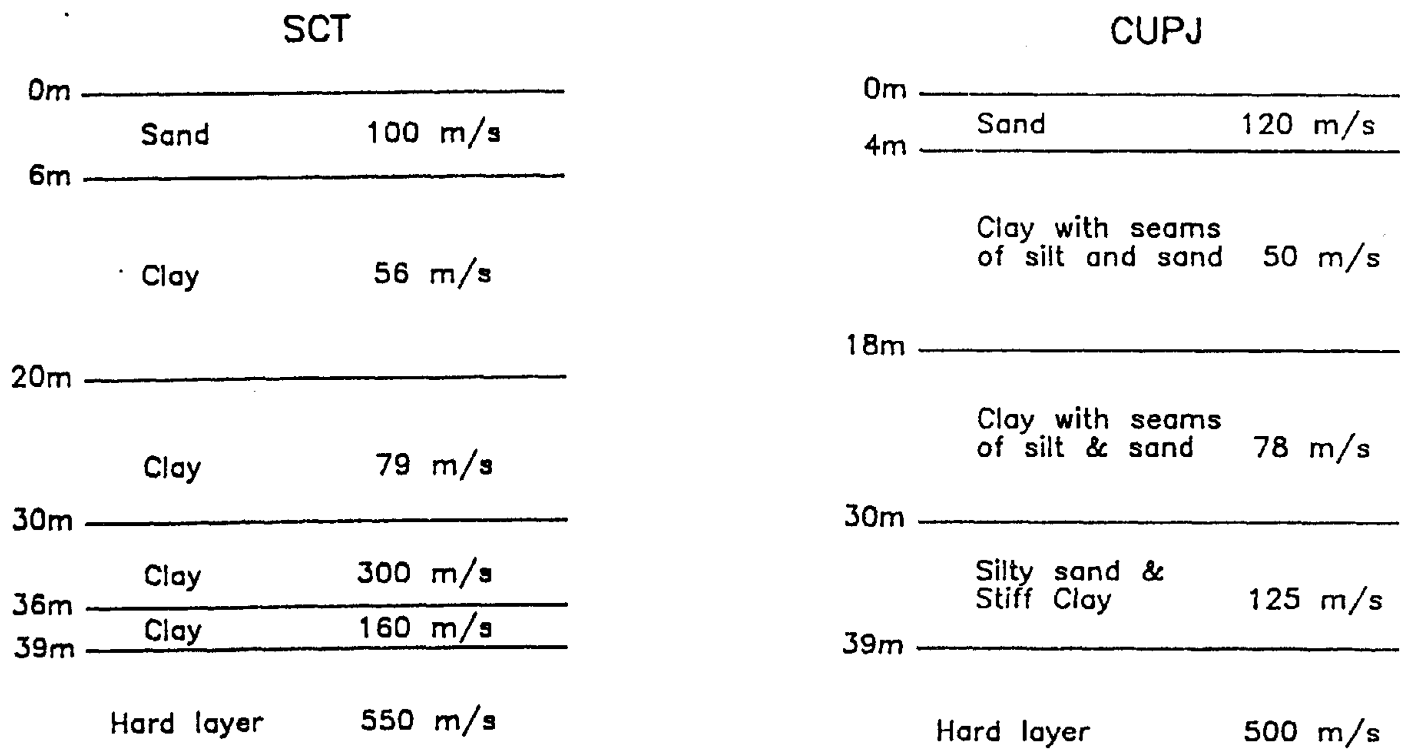


Fig. 10-4 COMPARISON OF INTERPRETED SOIL PROFILES AT SCT AND CUPJ SITES

To confirm this observation, a series of ground response analyses were made for the conditions at the CUPJ site following the same procedures as those used for the SCT site. The basic profile used for analyses is that shown in Fig. 10-3, but allowance was made for variations in soil properties and hard-layer excitation as follows

Shear wave velocities:	Varied by ±10%
Amplitude of hard layer motions:	Varied by ±20%
Predominant period of hard layer motions:	Varied by ±10%

The results of these analyses are shown in Figs. 10-5. Fig. 10-5 shows the upper and lower bounds of the spectra determined from the computed surface motions, emphasizing again the wide range of computed motions which may result from small changes in soil characteristics and input motions for such soil conditions. Fig. 10-6 shows the 75-percentile spectrum for the set of computed motions and a comparison of this spectrum with that computed for the SCT site and the average of the recorded motions at the SCT site. The similarities in these results leaves little doubt that the motions at the CUPJ site were likely to have been very similar to those at the SCT site in the September 19, 1985 earthquake.

Heavy Damage Area

An area of major interest in the earthquake of Sept. 19, 1985 is the very heavy damage area shown in Fig. 1-2. It is not possible to explore in detail the soil conditions at all building locations in this area but sufficient studies have been made to indicate that the clay deposits are generally similar to those at the SCT site but they vary considerably in depth to the hard layer with such depths ranging from about 24 to 44 m.

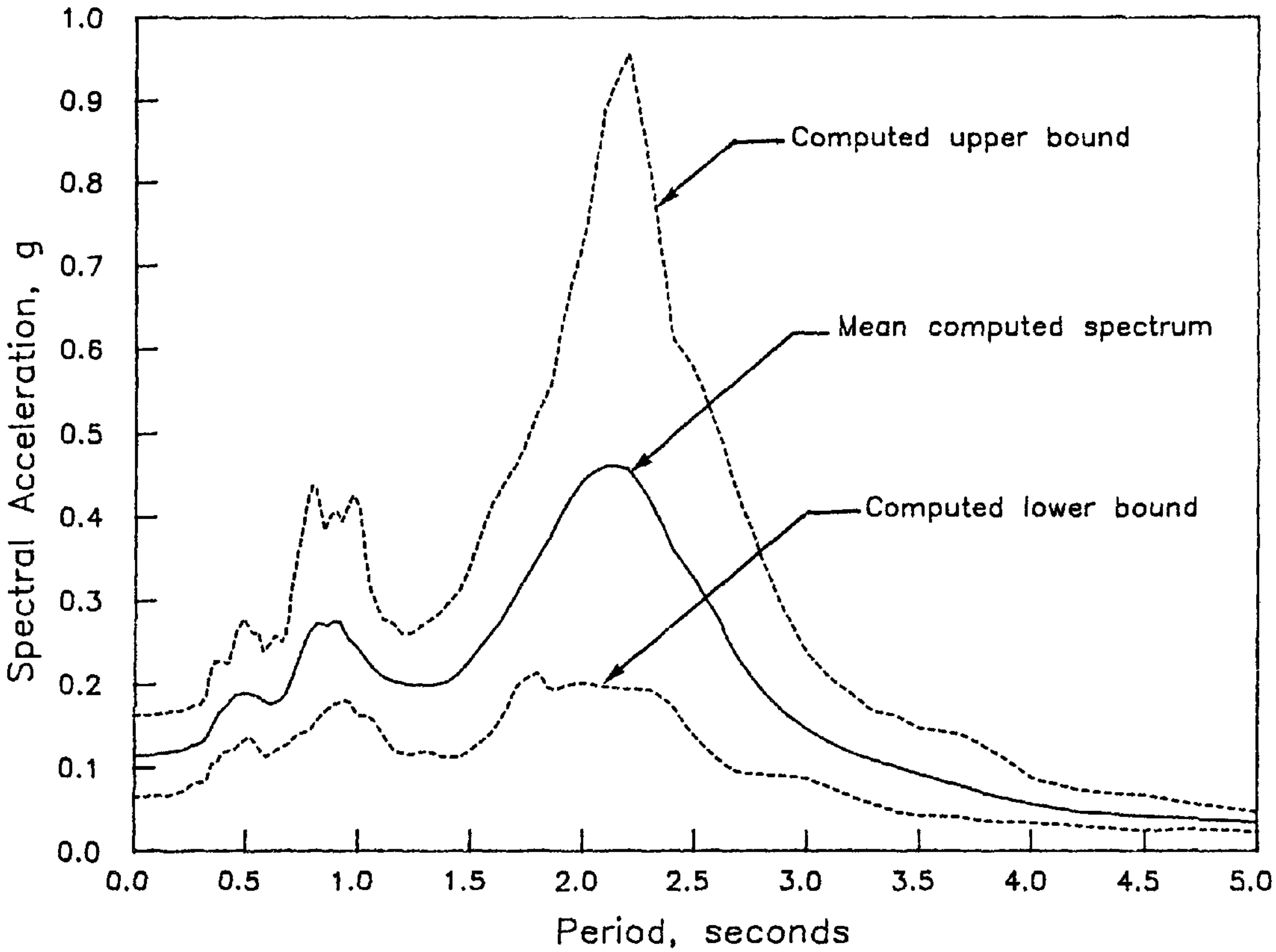


Fig. 10-5 RESULTS OF GROUND RESPONSE ANALYSES FOR CUPJ SITE BASED ON SHEAR WAVE VELOCITIES INTERPRETED FROM FIELD MEASUREMENTS--ACCELERATION RESPONSE SPECTRA FOR COMPUTED MOTIONS

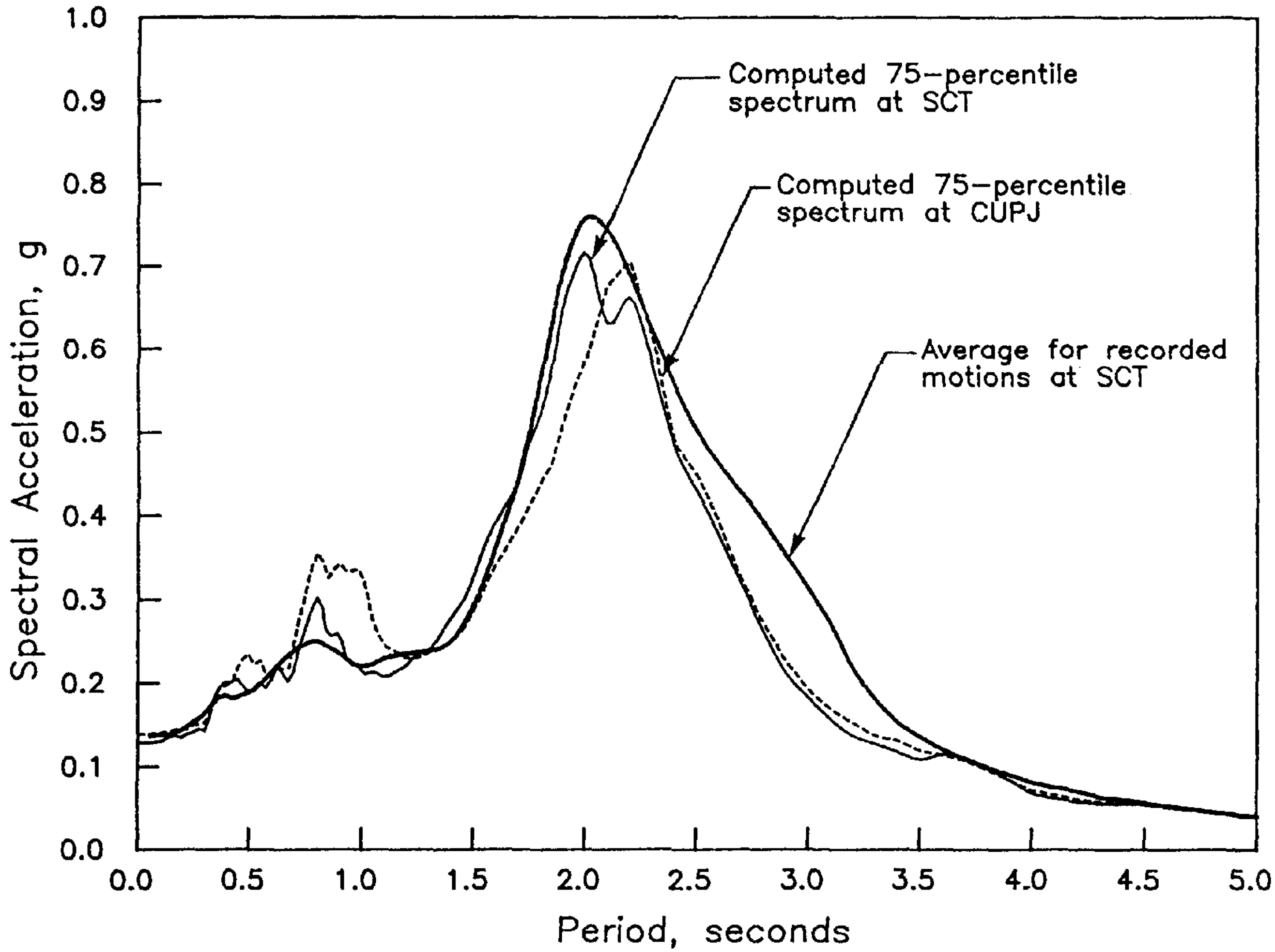


Fig. 10-6 COMPARISON OF 75-PERCENTILE SPECTRA FOR COMPUTED MOTIONS AT SCT AND CUPJ SITES WITH AVERAGE SPECTRUM FOR RECORDED MOTIONS AT SCT SITE

In order to explore the probable nature of the ground motions in this large area, a series of ground response analyses were performed using the soil properties deduced from the earthquake motions and shown in Fig. 4-1. These properties have already been shown to lead to response spectra in good agreement with the recorded motions at the SCT site when they are incorporated in a ground response analyses using the UNAM average motion as a control motion.

Thus to explore the possible variation in motions throughout the heavy damage area, a series of analyses were made using the soil profile shown in Fig. 4-1, using the N-S component of motions recorded at the UNAM-CUMV site as outcrop excitation, but varying the depth to the hard layer; analyses were made for hard layer depths ranging from 25 to 45 m.

The results of these analyses are shown in Fig. 10-7. It may be seen that because of the different depths of clay in the area, ground motions are likely to have varied significantly in different locations, though they are generally quite high throughout the entire zone. Based on these results a representative average spectrum for the entire zone has been indicated in Fig. 10-6. This average spectrum might be appropriate in efforts to relate the overall damage in this zone to the nature of the motions producing it and could be considered useful for such generalized studies. For particular building locations, however, it is clear that more site-specific motions should be used in damage evaluations.

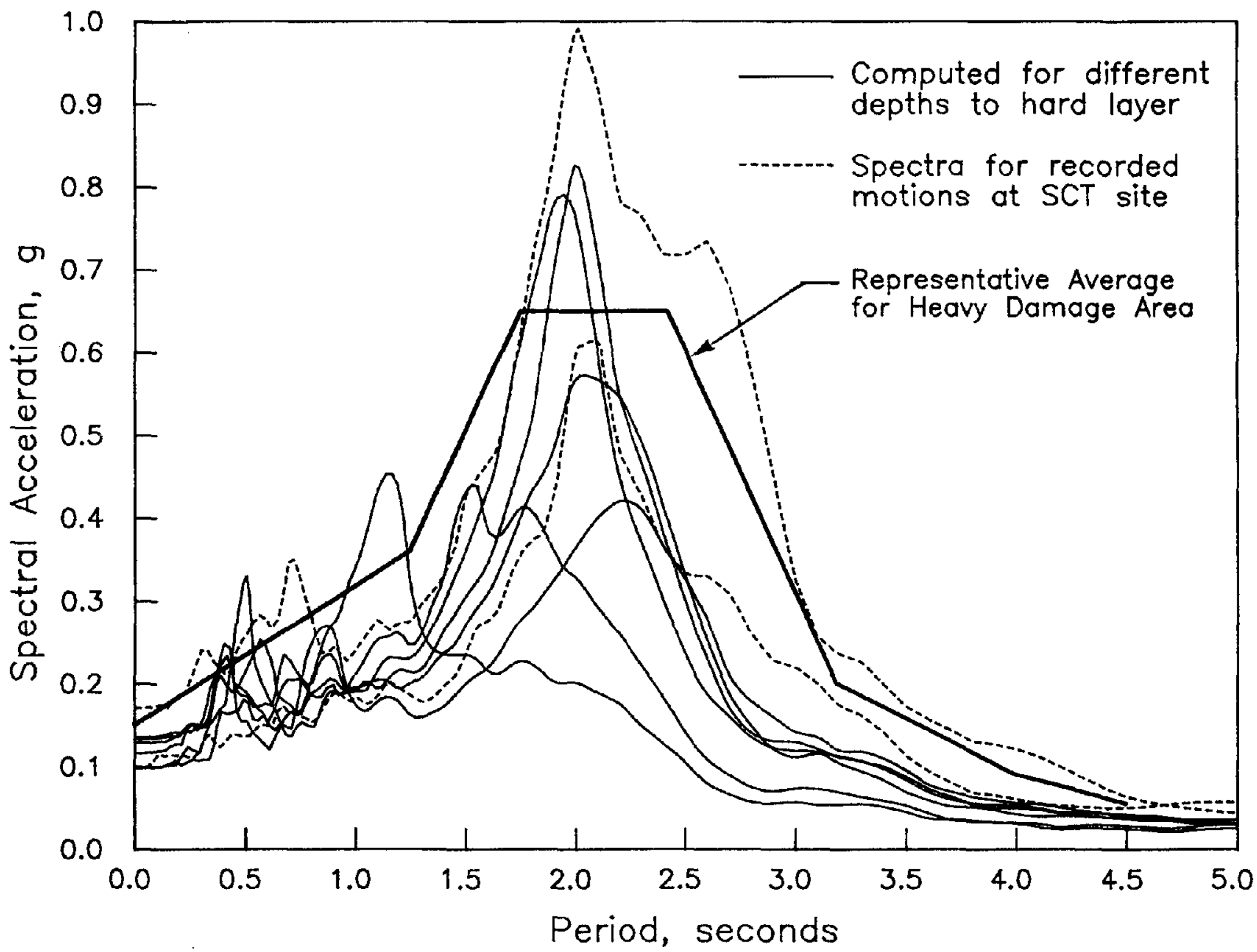


Fig. 10-7 COMPUTED SPECTRA FOR HEAVY DAMAGE AREA FOR SOIL DEPTHS RANGING FROM 25 TO 45 M. AND EVALUATION OF REPRESENTATIVE AVERAGE SPECTRUM FOR HEAVY DAMAGE AREA

11. Conclusions

On the basis of the data and analyses presented in the previous sections of this report, it appears reasonable to draw the following conclusions:

1. The characteristics of earthquake ground motions varied widely in Mexico City in the Sept. 19, 1985 earthquake with marked differences in motions occurring

    (a) in different zones of the city such as the hard and rock-like areas, the transition zone, and the area of the old lakebed underlain by deep clay deposits.

    and (b) in the lakebed area itself where markedly different motions were recorded at sites underlain by different depths of clay.

2. The characteristics of the ground motions recorded at sites underlain by clay showed generally similar frequency characteristics in the main shock and in the aftershock, indicating that these characteristics were controlled mainly by the local soil conditions rather than the source characteristics of the earthquake (see Fig. 2-7).
3. The records of ground motions recorded at different locations of the city underlain by Mexico City clay show that the characteristics of the motions were very sensitive to small changes in the shear wave velocities of the clay. Thus although the soil conditions at the SCT and CAF sites appeared to be generally similar, the motions recorded at these sites had quite different frequency characteristics (see Fig. 6-7).
4. The ground surface motions computed by ground response analyses using the same control motion on a hard layer outcrop also indicate that a

small change in shear wave velocity of the clay in the soil profile will have a significant influence on the frequency characteristics of the motions (see Fig. 8-21).

5. The dynamic stiffness of the clay in Mexico City can be determined by means of borings (to establish the general soil profile) and the use of recorded motions to determine the characteristic site period and the average shear wave velocity of the clay in the soil profile. The use of soil properties determined in this way in ground response analyses in which the average recorded motions on the hard layer in the UNAM area are used as control motions provides good predictions of the effect of local soil conditions on the characteristics of the motions recorded at the SCT, CAO and CAF sites in Mexico City.

6. The characteristics of the clay at the SCT, CAO, CAF, TLB and TLD sites have also been determined by in-situ downhole shear wave velocity measurements and by P-S Suspension Logging procedures. The values of shear wave velocity determined by these procedures are slightly lower than the values interpreted from the frequency characteristics of the ground motion records, probably because small errors associated with the in-situ wave velocity measurement procedures tend to lead to somewhat lower values than the actual wave velocities.

7. To allow for the uncertainties in (a) the accuracy of shear wave velocity measurements and (b) the characteristics of the control motions on the hard layer outcrop, which must be used in predicting ground response by wave propagation theory, in cases where the results are very sensitive to small changes in these parameters, as in Mexico City, it is desirable to use a probabilistic approach to ground response prediction. Thus in computing the effects of local soil conditions on

ground response in Mexico City it was considered desirable to allow for possible uncertainties in these parameters as follows:

Possible uncertainty (error) in shear wave velocity:	±10%
Possible uncertainty in hard layer motion amplitude:	±20%
Possible uncertainty in predominant period of hard layer motion:	±10%

8. Using the probabilistic approach outlined above to compute the effects of local soil conditions on ground motion characteristics, it was found that:

   (a) in most cases the average spectra for the recorded motions at the SCT, CAO, CAF, TLB and TLD sites in Mexico City lie within the bounds of the spectra computed by ground response analyses.

   and (b) the agreement between the average spectra for the recorded motions at each of the five sites located on the lake-bed clay deposits (SCT, CAO, CAF, TLB, TLD) and the 75-percentile spectra for motions computed by the probabilistic ground response analyses described above, ranged from Fair to Very Good, with the overall assessment being rated as Good (see Table 8-1).

9. On the basis of the results of the ground motion studies, it would appear that if allowance is made for possible small deviations from the best average deterministic ground response analysis parameters, and ground response is considered on a probabilistic basis, ground response analyses can provide very useful data for assessing the influence of local soil conditions on the characteristics of the ground motions likely to develop at sites underlain by clays, similar

to the conditions existing in the old lake-bed area of Mexico City where motions vary widely depending on the depth and stiffness of the clay deposits.

10. Even in cases where a record of motions in a hard layer is not available, good predictions of the effects of local soil conditions on ground motions characteristics can be made provided a hypothetical motion or scaled earthquake record having appropriate frequency characteristics is used for the control motion in ground response analyses (see Fig. 9-7).

11. Because of the generally good results obtained in using ground response analyses for the five sites at which motions and soil characteristics are known in Mexico City, the same procedures can be expected to provide a good basis for predicting motions at sites where motions were not recorded in the September 19, 1985 earthquake. Typical examples are the CUPJ site (Fig. 10-5) and the heavy damage area (Fig. 10-6). Also it can be expected that these procedures may provide a good basis for predicting ground motions at sites in the lake-bed zone due to other earthquake sources and source mechanisms.

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