Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Effects of soft soils on design spectra

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ABSTRACT: Analytical studies with recorded and generated soft soil motions are discussed to show that ground motions can be significantly amplified in soft soils and that the strength demands for which structures have to be designed are amplified accordingly. Quantitative information on this amplification is presented, using simple SDOF soil column models whose properties are varied to cover a soil period range from 0.5 to 4.0 seconds. Spectra of strength demands are analyzed and an approach is proposed that permits an explicit incorporation of soft soil effects in the design process.

1 INTRODUCTION

The Loma Prieta, California, earthquake of October 17, 1989 has again demonstrated the great importance of local site effects on surface ground motions and damage resulting from ground shaking. The study summarized in this paper is concerned with ground motions on soft soil sites and the representation of their effects in the design of structures

Most present seismic codes include procedures that account for soil site effects, but in an empirical and nontransparent manner that does not reflect the physical phenomena that occur when a structure, which is expected to respond inelastically in severe earthquakes, is subjected to soft soil ground motions. As a consequence, presently employed design procedures, which are probably adequate in most cases, cannot provide a consistent level of protection and may be overly conservative in some cases and unconservative in others.

The objective of the discussed research is to develop procedures and information that permit an explicit incorporation of the effects of site surface geology on the seismic demands imposed on structures by design ground motions. In this research this implies consideration of the effects of source-site distance and site soil conditions on those seismic demand parameters that can be used directly for design. Thus, the research combines ground motion and structure response issues, with an emphasis on parameters that incorporate both relevant ground motion as well as structural response characteristics. These parameters form the basis for a design approach that is summarized next.

2 DESIGN BASED ON DUCTILITY AND DRIFT LIMITS

Earthquake resistant design implies that structures need to be provided with sufficient strength, stiffness, and ductility so that the available capacities exceed the expected demands with an adequate margin of safety. Design procedures based on this premise have recently been formulated (Bertero et al. (1991), and Nassar & Krawinkler (1991)). In this discussion we will summarize only those basic concepts that are necessary to put the later proposed procedure for incorporating soft soil effects into proper perspective.

We will focus only on strength and ductility issues; stiffness or drift issues, which are of equal importance, are not discussed here because of page limitations. The basic capacity parameters for structures are the strength and ductility (maximum deformation over yield deformation) of individual elements, which, when assembled into structural configurations, define the strength and ductility capacities of complete structures. Thus, a transparent design process should consist of estimating ductility capacities and deriving the strength required so that in severe earthquakes the ductility demands do not exceed the available capacities. For design this implies that ductility capacity is a predetermined target and strength is a derived quantity, which depends on the characteristics of the structure as well as on the severity and frequency characteristics of the ground motions. Thus, the required strength (inelastic strength demand) for a specified target ductility ratio becomes the primary seismic demand parameter, which needs to be evaluated with due regard to all pertinent structural and ground motion characteristics.

In the development of general design criteria, simple SDOF systems are utilized to derive strength demands that can serve as a starting point for design. Clearly, these SDOF demands must be modified in order to be applicable to real structures, which usually are complex MDOF systems. These modifications are not addressed here but are discussed in Nassar & Krawinkler (1991). For structural systems that are expected to behave elastically in severe earthquakes, an acceleration response spectrum that represents the expected response of an elastic SDOF system to near- and far-source ground motions defines the period dependent elastic strength demand, denoted here as $F_{y,e}$. For inelastic structural systems the equivalent parameter for relating seismic input to structural behavior is the SDOF inelastic strength demand, $F_y(\mu)$, for target ductility ratios μ. Spectra of $F_y(\mu)$ are representations of the system-, period-, ductility- and site-dependent required strength of structural systems.

For ground motions in rock and firm soil sites it was found by Nassar & Krawinkler (1991) that the inelastic strength demand can be related to the elastic one with

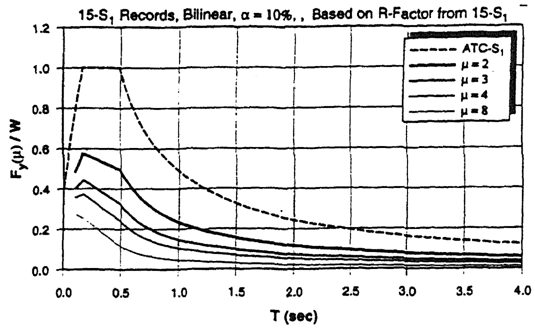

Figure 1. Inelastic strength demand spectra based on ATC S_1 ground motion spectrum

reasonable accuracy by a strength reduction factor $R = F_{y,e}/F_y(\mu)$. The following expression for R was derived from a statistical study that utilized 15 Western U.S. rock ground motion records from earthquakes ranging in magnitude from 5.7 to 7.7 (from here on referred to as the *15-S_1* data set) and bilinear SDOF systems with 5% damping:

$$R = \{c\ (\mu - 1) + 1\}^{1/c} \tag{1}$$

where $c(T,\alpha) = \frac{T^a}{1+T^a} + \frac{b}{T}$

For specific strain hardening ratios α the two regression parameters a and b are as follows:

for $\alpha = 0\%$:	$a = 1.00$	$b = 0.42$
for $\alpha = 2\%$:	$a = 1.00$	$b = 0.37$
for $\alpha = 10\%$:	$a = 0.80$	$b = 0.29$

Relationships of this type together with mean or smoothed elastic response spectra can be employed in many cases to evaluate the inelastic strength demands. This can be done with confidence for S_1 soil types, on which this relationship is based, and probably also for S_2 soil types since the R-factors were found to be insensitive to relatively small variations in average response spectra shapes. If we use this R-μ-T relationship to derive inelastic strength demand spectra from the ATC S_1 ground motion spectrum, the results shown in Figure 1 are obtained. To no surprise, the inelastic strength demands are anything but constant for periods below 0.5 sec., the range in which the elastic response spectrum has a plateau.

The simple concepts discussed so far have to be modified if site soil effects become important. The following sections address various issues that have to be considered in this modification. The discussion is based on the assumption that the inelastic strength demand for SDOF systems can be used as a basis for design and that this strength demand can be described by the following expression:

$$F_y^s(\mu) = F_y^r(\mu)\ S(T_s,\mu) = \frac{F_{y,e}^r}{R}\ S(T_s,\mu) \tag{2}$$

where $F_y^s(\mu)$ = inelastic strength demand at soft soil site

$F_y^r(\mu)$ = inelastic strength demand for bedrock motion below soft soil site

$F_{y,e}^r$ = elastic strength demand for bedrock motion below soft soil site

$S(T_s,\mu)$ = soft soil modification factor

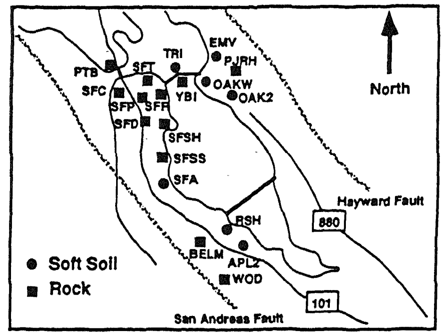

Figure 2. Locations of Loma Prieta ground motion stations used in this study

This expression implies that the strength demand at a soft soil site can be expressed by the corresponding strength demand at a rock site and a modification factor $S(T_s,\mu)$ that accounts for all soft soil effects. Thus, this S-factor is a function of many parameters, including source-site distance (if needed, see later discussion), soil period T_s, soil nonlinearity, and target ductility ratio μ. The following section focuses on several issues that affect the S-factor, and the subsequent section discusses a parameter study that provides quantitative information needed to evaluate this factor.

3 OBSERVATIONS ON SOFT SOIL EFFECTS

The following discussion is based on analytical studies performed with rock and soft soil ground motions recorded during the 1989 Loma Prieta earthquake. In these studies time history analyses were performed, using either elastic or inelastic bilinear SDOF systems with 5% damping and 10% strain hardening. The ground motion stations used in this study are shown in Figure 2. The ten rock stations marked with solid squares are designated as *10-Loma* in the following discussion.

3.1 *Characteristics of inelastic strength demand spectra for soft soil ground motions*

Elastic and inelastic strength demand spectra for a typical soft soil ground motion are shown in Figure 3, and the corresponding R-factors (ratios of elastic to inelastic strength demands) are illustrated in Figure 4. The elastic spectrum ($\mu = 1$) contains a clear signature of the soft soil on which the motion was recorded, as is evident in the large hump around a period of 1.1 seconds. It is important to note that this hump diminishes in the inelastic strength demand spectra and even disappears at large ductility ratios. As a consequence, the strength reduction factor R is strongly period dependent; it is much smaller than μ for periods of low elastic strength demands preceding the range of high elastic strength demands (hump in the elastic spectrum), and much larger than μ around the soil period of 1.1 seconds at which the elastic strength demand spectrum exhibits a large soil amplification.

The reason for this phenomenon is that the effective period of an inelastic system lengthens and shifts either into or out of the period range of high elastic strength demands. As a consequence the inelastic spectra become dissimilar to and much smoother than the elastic one, the predominance of the site soil amplification decreases, and the R-factor becomes a period sensitive and highly nonlinear quantity.

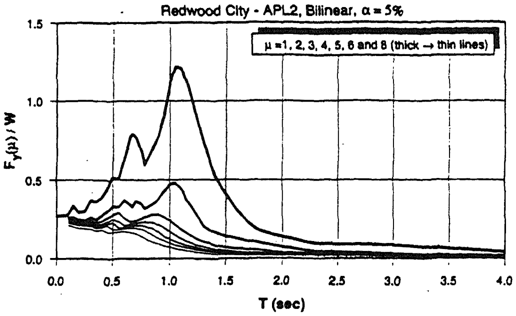

Figure 3. Elastic and inelastic strength demand spectra for APL2 soft soil record

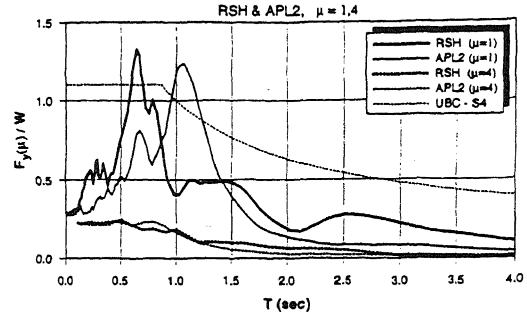

Figure 5. Elastic and inelastic strength demand spectra for two recorded soft soil motions

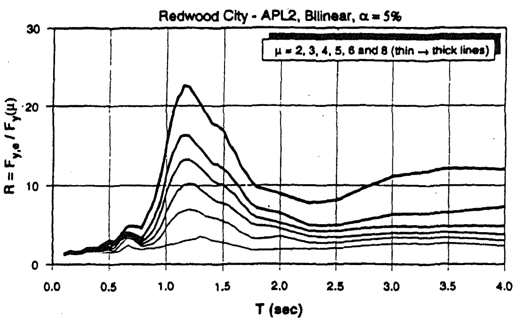

Figure 4. Strength reduction factors for APL2 soft soil record

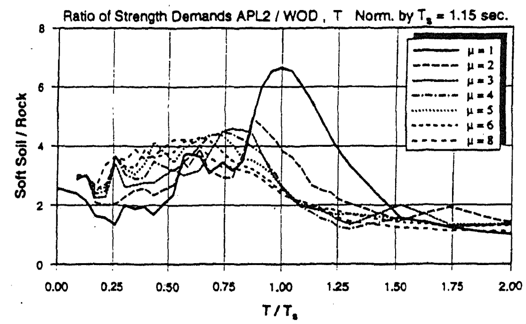

Figure 6. Amplification of strength demands obtained from a pair of nearby soft soil and rock records

This observation has significant implications for design. For structures with small ductility capacity the elastic strength demand spectrum will be an important design parameter and the required strength will be high and very sensitive to the predominant soil period. For structures with large ductility capacity the inelastic strength demand spectra, which are very different from the elastic ones, will control the design. This implies that it would be misleading to tune the structure strength to site-specific elastic response spectra and conventional R-factors and that more knowledge needs to be acquired on the magnitudes and shapes of inelastic strength demand spectra. This conclusion is reinforced in Figure 5, which shows strength demand spectra derived from two different records. The elastic spectra are very different whereas the inelastic spectra for $\mu = 4$ are similar in the range of the predominant soil periods.

3.2 *Amplification of strength demands in soft soils*

As proposed in Eq. 2, soil effects are described here by a modification factor that relates the strength demand for soft soil motions to the strength demand for rock motions by a soil modification factor S. This concept can be applied to elastic as well as inelastic strength demands. If the soft soil motion and the rock motion at the base of the soil layers were known, this modification factor could be obtained directly as the ratio of the strength demands of soft soil to rock motions. To this date no recordings are available that permit a direct assessment of this amplification of strength demands. However, during the Loma Prieta earthquake several soft soil motions as well as nearby rock surface motions were recorded. The ratios of strength demands derived from these recordings are used in this study to provide basic information on soft soil amplification, even though it is recognized that rock surface motions differ somewhat from bedrock motions and may vary significantly within short distances.

Typical results for amplification factors obtained from a pair of recorded nearby motions are shown in Figure 6. The time axis is normalized by the soil period $T_s = 1.15$ seconds estimated at the soft soil APL2 site. The results show a clear pattern, with the largest amplification evident for the elastic strength demand at $T/T_s = 1.0$ and a decrease in amplification and shifting in maximum amplification to $T/T_s < 1.0$ evident for inelastic strength demands. This pattern was consistent for almost all the pairs of records analyzed, even though the magnitude of the amplification factor varied significantly between record pairs.

3.3 *Validity of one-dimensional soil column model*

Simple one-dimensional soil column models are used widely by researchers and engineers to evaluate soil amplification effects. Most researchers agree that such a model is a gross oversimplification of a complex three-dimensional problem in which wave form, direction, reflection and refraction, impedance contrast, as well as 3-D topographical effects play a major role.

In support of one-dimensional soil column models it can be said that they capture most of the global soil amplification characteristics important for design in a quantitative (but not always accurate) manner. This is illustrated in Figure 7, which shows elastic strength demand spectra obtained from recorded and predicted soft soil motions at the Treasure Island (TRI) site. The predictions are based on the use of the nearby YBI rock record as input to 1-D soil column models. The widely

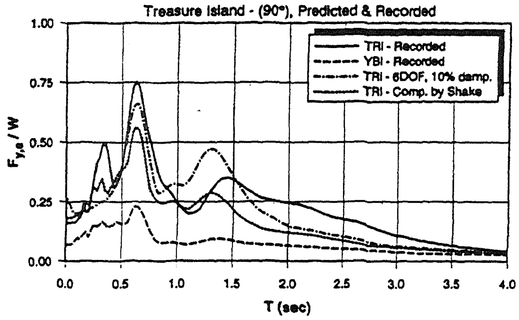

Figure 7. Elastic strength demand spectra obtained from recorded and predicted soft soil motions

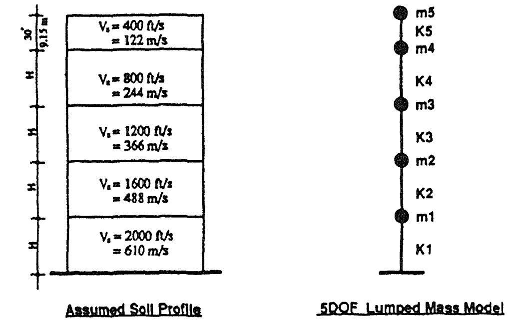

Figure 8. Soil column models used in parameter study

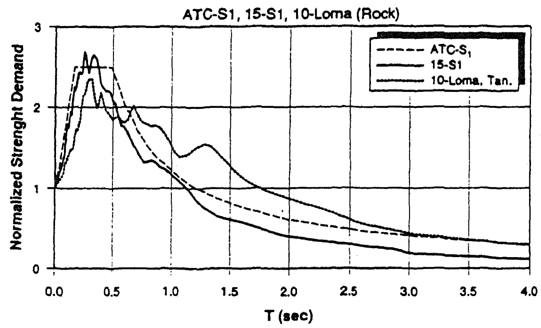

Figure 9. Means of normalized elastic spectra of *15-S_1* and *10-Loma* rock records

used SHAKE program as well as a 6DOF structural model are used to predict soft soil motions. Both the SHAKE and structural models give comparable predictions that capture most of the main features of the actual spectrum. However, the spectral amplitudes for periods exceeding the predominant soil period (around 1.5 seconds in this case) are severely underestimated in the case shown here and in all other cases studied. Thus, it must be concluded that spectra derived from soil motions based on 1-D soil columns will lead to poor predictions of the elastic and inelastic strength demands for periods exceeding the predominant soil period.

4 EVALUATION OF SOFT SOIL AMPLIFICATION

Because of the lack of records on pairs of soft soil and rock motions, it was necessary to generate soft soil motions from available rock records. Despite the previously discussed shortcomings of one-dimensional wave propagation models, simple 1-D soil column models are used in this study to generate soft soil motions and acquire a basic understanding of the effects of soil amplification on seismic strength demands. The reasons are that a simple model is needed to evaluate these effects and that no realistic and more complex models of general validity are available at this time.

The soil column is modeled as a five layer system with increasing shear wave velocities as shown in Figure 8. For all models the top layer is of constant thickness, whereas the thickness H of all other layers is varied in a manner that results in first mode soil periods of $T_s = 0.5$, 0.75, 1.0, 1.25, 1.5, 2.0, 3.0, and 4.0 seconds. For the eight soil systems so generated, the ratios of the first three modal periods are close to 1:0.5:0.33. These soil column models are converted to elastic 5DOF lumped mass models with 10% damping in each mode. These structural models are subjected to bedrock motions, and the computed response histories at the top level are designated as soft soil motions for which soil amplification can be evaluated.

Two sets of bedrock motions are used in this study; the *15-S_1* record set representing typical S_1 records (see Section 2) and the *10-Loma* record set representing far-source records obtained from the Loma Prieta earthquake. From the second set the tangential (w.r.t. epicenter) components of the records are used in order to establish a consistent directional pattern. The results from these two record sets, which have significantly different mean elastic spectra (see Figure 9), are evaluated separately in order to assess the effects of rock spectral shapes on soil amplification.

Thus, a total of 25 rock records are used as input to the 8 soil column models, resulting in 200 soft soil records. For these 200 soft soil records and the 25 rock records the strength demand spectra are computed (using bilinear SDOF systems), and the soft soil amplifications are evaluated from the ratios of soft soil to rock spectra. In this paper only mean values are discussed.

Typical results obtained from this parameter study are shown in Figures 10 to 15. Figure 10 shows the mean elastic strength demand spectra for the 8 soil column models together with the mean spectrum of the *10-Loma* rock motions. Figures 11 and 12 present results for amplification factors (soil spectra over rock spectra) for elastic and inelastic strength demands for $\mu = 4$, plotted versus period T normalized by the soil period T_s. Figure 13 shows a diagram similar to Figure 6, but in this case the results are mean values obtained from predicted soft soil records. Figure 14 illustrates the dependence of the maximum amplification of elastic strength demands on the soil period T_s, and Figure 15 shows the dependence of maximum amplification on the target ductility ratio μ.

From these figures and others not shown here the following observations can be made:

1. The elastic strength demand spectra of the soft soil motions exhibit clear humps in the vicinity of the first soil period and noticeable humps in the vicinity of the second soil period. The width of the humps increases with an increase in soil period T_s.

2. The shapes of soil inelastic strength demand spectra are much smoother than those of the corresponding elastic spectra and the peaks of these spectra no longer occur at the soil column periods. The humps of the inelastic spectra are much wider than those of the elastic spectra.

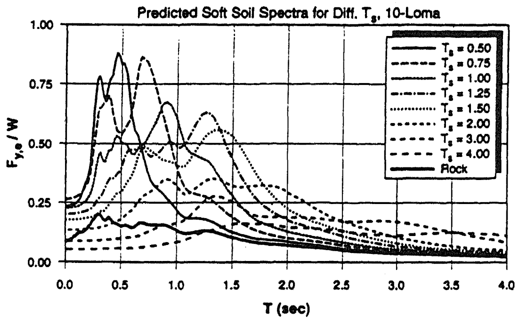

Figure 10. Mean elastic strength demand spectra for soft soil and rock motions, *10-Loma* record set

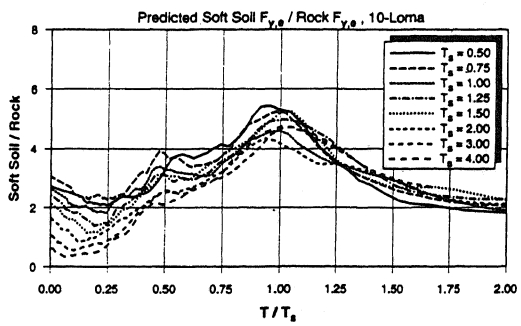

Figure 11. Mean amplification of elastic strength demands, *10-Loma* record set

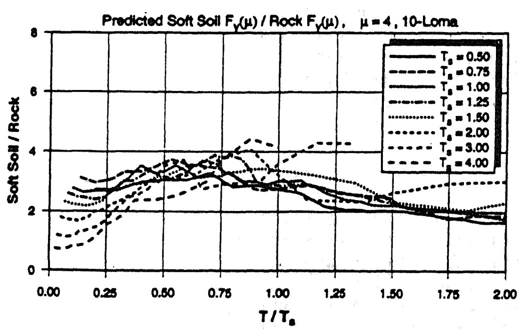

Figure 12. Mean amplification of inelastic strength demands for $\mu = 4$, *10-Loma* record set

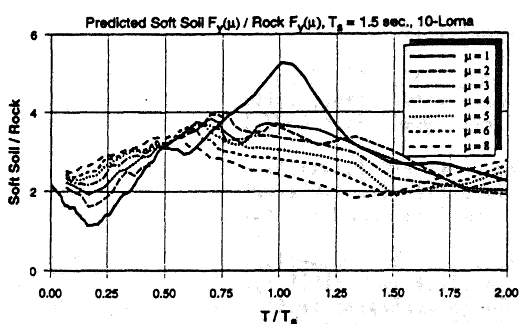

Figure 13. Mean amplifications of elastic and inelastic strength demands for $T_s = 1.5$ sec.; *10-Loma* record set

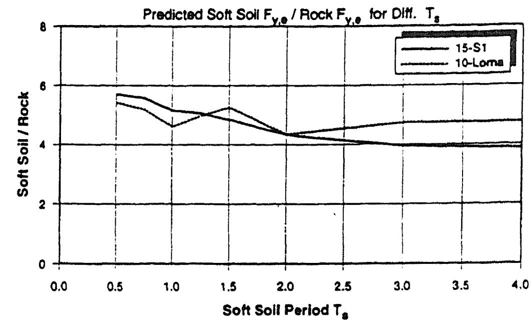

Figure 14. Variation of maximum amplification of elastic strength demand with T_s and record set

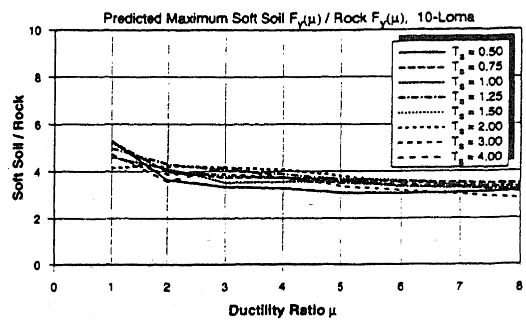

Figure 15. Variation of maximum amplification of strength demands with ductility ratio μ, *10-Loma* records

3. The maximum soft soil amplifications are only weakly dependent on the period of the soil column.

4. The maximum soft soil amplifications are larger for elastic systems than inelastic ones, but differ only little for systems with ductility ratios between 2 and 8. For inelastic systems the maximum amplifications occur at T/T_s ratios smaller than 1.0. The larger the target ductility ratio, the smaller is the T/T_s ratio at which maximum amplification occurs.

5. The soft soil amplifications of elastic and inelastic strength demands do not depend strongly on the rock motion spectral shape. In general, the results obtained from the *15-S_1* record set are close to those obtained from the *10-Loma* record set. This does not apply, however, to the amplification of PGA as discussed next.

An interesting side result was obtained from the study of spectral amplifications. The factors shown in Figure 11 for $T/T_s = 0$ are means of soil amplification factors for peak ground accelerations, PGA. Values of these factors, plotted against the soil T_s are shown in Figure 16 for both the *15-S_1* and *10-Loma* record sets. These plots show a large dependence of PGA amplification on both the soil column period and the rock record set. For the *15-S_1* set the PGA gets amplified for motions in soft soils with a period smaller than 2.0 seconds, whereas for the far-source *10-Loma* records amplification of PGA occurs in soft soils with periods smaller than 3.2 seconds. The relevance of this observation will be discussed in the conclusions. It must be emphasized that these results are obtained from studies with simple soil columns with all the shortcomings discussed previously. Nevertheless, PGA amplification factors obtained from pairs of nearby soil and rock records (individual data points shown in Figure 16) fall rather close to the predicted curve.

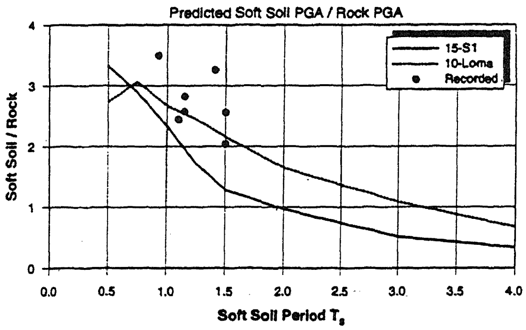

Figure 16. Mean amplifications of PGA computed from *15-S_1* and *10-Loma* record sets

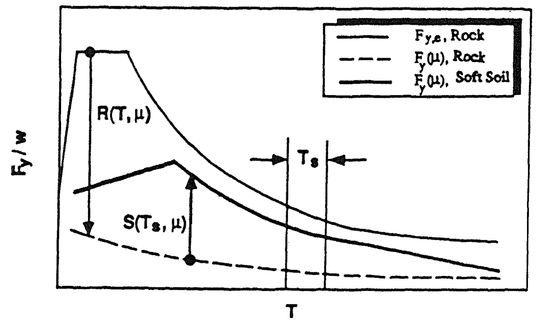

Figure 17. Suggested process for modification of SDOF strength demands for soft soil effects

5. IMPLICATIONS FOR SEISMIC DESIGN

The study summarized here has shown that soft soil effects cannot and should not be lumped into a constant and ductility independent soil factor (such as S_3 and S_4 in the 1991 UBC). Rather, it appears to be feasible to relate the strength demand (elastic or inelastic) for a soft soil motion to that of the motion in the underlying rock by a modification factor $S(T_s,\mu)$ as shown in Eq. 2. This factor can be derived from the kind of information presented in the previous section, which provides quantitative values for amplification factors and shows that large amplification occurs over a wide period range and is dependent on the period of the soil column and the target ductility ratio. It is observed from the mean data that the amplification is not very sensitive to the shape of the rock spectrum.

Considering that soil periods can be determined only with significant uncertainty, some enveloping of amplification of strength demands is recommended. This enveloping can be based on either a narrow band of estimated T_s or on a broad band that gives more credit to the uncertainties in the determination of soil periods and to the shortcomings of data derived from one-dimensional wave propagation models. The suggested process of modifying the SDOF strength demands is illustrated in Fig. 17. As in design for structures located on rock, the need exists to modify SDOF strength demands for MDOF effects. Appropriate modifications need to be developed through further research.

It must be emphasized that the results presented in Section 4 are not final answers in many cases. They are based on linear soil column models with 10% damping in each mode. This damping is supposed to account for light nonlinearities in the soil stress-strain properties. Different soil damping will lead to somewhat different results. Most important, however, is the recognition that soft soils, when subjected to high accelerations, will respond highly nonlinear and are not capable of transmitting accelerations larger than those associated with the soil shear strength. Thus, soft soil amplification decreases as the rock motion approaches a magnitude that causes high nonlinearity in the soil. Idriss (1991) estimates that at rock PGAs exceeding 0.4*g* no soft soil PGA amplification occurs. Thus, the soil amplifications need to be capped depending on the severity of the rock motions and the anticipated soft soil PGA amplification (see Figure 16). The effects of high nonlinearities in the soil can be evaluated with the 5DOF structural model used in this study and are under investigation by the authors.

6. CONCLUSIONS

Quantitative information on spectral amplifications has been developed based on simple 5DOF soil column models whose properties are varied to cover a soil period range from 0.5 to 4.0 seconds. For soft soils without strong nonlinearities the amplification in the vicinity of the soil period is approximately 5 for elastic strength demands, and between 3 and 4 for inelastic strength demands. This amplification of strength demands is approximately the same for soil columns of all periods, whereas the amplification of PGA is strongly soil period dependent. In fact, the PGA gets deamplified in soil columns with long periods. Thus, the PGA of soft soil motions is a very poor indicator of the spectral demands in the vicinity of the soil period and, consequently, an assessment of soft soil effects must be based on spectral amplifications and not on PGA amplification.

ACKNOWLEDGEMENTS

This research is supported by the John A. Blume Earthquake Engineering Center at Stanford University, the Stanford/USGS Institute for Research in Earthquake Engineering and Seismology, and a grant given by Kajima Corporation and administered by CUREe. The support provided by these organizations is gratefully acknowledged.

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