THE MODELLING OF INTRAPLATE SEISMIC HAZARD BASED ON DISPLACEMENT

Nelson T K LAM[1], John L WILSON[2] And Graham L HUTCHINSON[3]

SUMMARY

The fundamental relationship between the long period components of the earthquake ground motion and the seismic moment has resulted in the maximum displacement demand to be expressed as a function of the maximum credible earthquake (MCE) and the site-source distance. Interestingly, the effect of the crustal waveguide has resulted in very moderate attenuation of medium and long period waves beyond a critical distance of 70 kilometers in Eastern North America. Consequently, the critical Moment Magnitude (M) and Distance (R) combination can be reasonably assumed to be M=MCE and R=70km. The displacement response spectrum associated with this M-R combination is defined herein as the characteristic displacement response spectrum. The effect of resonance in a flexible soil layer has been accounted for using the recently developed hand calculation procedure which is known as the "Frame Analogy Soil Amplification" (FASA) procedure. Predictions from the FASA procedure have been found to be in excellent agreement with large number of simulations using program SHAKE and limited measurements from an instrumented borehole. The displacement predictive model described in this paper is essentially generic in nature, and is therefore particularly suitable for seismic design codification in intraplate regions where indigenous earthquake record are typically lacking making the development of reliable empirical models difficult. The model subject to further modifications and development has excellent potential for worldwide application.

INTRODUCTION

Displacement, as opposed to force and acceleration, has been suggested as the preferred criterion to define the seismic performance of structures, particularly those experiencing ductile yielding. Applying the concept of a substitute structure, the displacement demand on the structure can be predicted in accordance with the elastic response displacement spectrum based on the effective natural period of the structure [Priestley, 1995; Shibata & Sozen, 1976]. This effective natural period can lengthen considerably as a result of stiffness degradation or ductile yielding. Consequently, the displacement based (DB) approach emphasizes the significance of the long period (displacement) components of the ground motion in dictating the seismic performance of a structure. The recent

shift of the engineering focus from acceleration to the consideration of displacement has the potential of causing revolutionary changes in the way in which seismic hazard is defined and modelled.

A displacement response spectrum model for Europe has been developed recently by [Bommer & Elnashai,1999] based on conventional regression analysis of strong motion accelerograms. The intrinsic deficiency of the accelerograms in accurately preserving low frequency information was recognized, and was alleviated by a low-cut frequency filter (determined by trial and error). However, the filtering appeared to have destroyed the authenticity of low frequency information contained in some of the records, and this resulted in a significant reduction in the size of the workable data. The regression analysis has nevertheless been completed,

[1] *Dept of Civil & Environmental Engineering, The University of Melbourne, Australia Email : n.lam@civag.unimelb.edu.au*
[2] *Dept of Civil & Environmental Engineering, The University of Melbourne, Australia Fax: (613)93444616*
[3] *Dept of Civil & Environmental Engineering, The University of Melbourne, Australia Fax: (613)93444616*

but this was only possible with a large strong motion database of 157 earthquakes, of magnitude 4 – 7, at epicentral distances mainly within 60km [Ambrasey,1996]. The feasibility of applying similar empirical modelling approaches to low seismicity regions, where indigenous data are typically lacking, is very much in doubt.

The seismological model originally proposed by [Brune,1970] was founded on the fundamental relationship between the seismic moment and the long period components of the earthquake ground motion. Significantly, a recent review of the Brune's Fourier amplitude spectrum source model by [Beresnev & Atkinson,1997] has discovered its close relationship with the classical displacement predictive function derived from the "point shear dislocation theory" [Aki & Richards, 1980]. (The displacement function has not been attracting a great deal of attention from engineers partly due to the traditional belief that acceleration, as opposed to displacement, is of engineering interest). The Brune model has been further developed by [Beresnev & Atkinson,1997] to model seismic shear waves radiated from a realistic finite fault source, addressing the shortcomings of the original Brune point circular source model. The latest seismological model developed by [Atkinson,1993] and [Atkinson & Boore,1995] was shown in a recent comparative study by [Atkinson & Boore,1998] to be most consistent with field observations in Stable Continental Regions amongst a number of other empirical and theoretical models. It has further been shown by [Atkinson & Silva,1997] that the empirical source spectrum derived from both Eastern and Western North America (ENA & WNA) were very consistent for wave frequency up to 1 hertz (period ≥ 1sec) despite the seemingly extreme difference in the tectonic and geological conditions of the two regions. Realistic corrections for the path and site effects in the processing of the data have contributed to an accurate representation of the source effects in WNA. The seismological model comprising the source model and the path correction model is essentially generic in nature, particularly for predictions in the medium and long period range, largely attributed to and is based on sound theoretical principles. Further, subsequent developments of the model have utilized corrected teleseismic records of large intraplate events from global networks [Atkinson,1993]. The seismological model has effectively incorporated valuable information from major earthquakes around the globe including North America, Australia, Africa and the former Soviet Union [Boatwright & Choy, 1992].

The computer program GENQKE [Lam, 1998] has been developed by the authors based on this seismological model to generate synthetic earthquake accelerograms for a range of seismological parameters [Lam *et al*,2000a]. Unlike real accelerograms, these synthetic accelerograms are not limited by the long period resolution of the recording instruments. (Note, the accuracy of the seismological model has been confirmed up to a natural period of 5 seconds [Atkinson & Boore, 1998]). Consequently, a large number of response spectra spanning the natural period range of 0.01 – 5.0 seconds (which cover the effective period of most structures) have been obtained from the generated accelerograms [Lam *et al*,2000b]. These response spectra and the associated ground motion parameters have been found to be consistent with empirical models developed independently in Western North America, Europe, China and Australia. (Details are described in technical papers which are expected to be published in international earthquake engineering journals in the coming months). The generic nature of the seismological model has been further confirmed.

The generic displacement attenuation model developed recently by the authors using ground motion simulations in accordance with the seismological model is summarized in Section 2. The relationship between displacement parameters, moment magnitude (M) and site source distance (R) is defined in the model for the generic "rock" and "hard rock" conditions [Boore&Joyner,1997]. Interestingly, the critical displacement response spectrum is typically associated with a unique critical M-R combination in which M is the Maximum Credible Earthquake (MCE) and R is approximately 1.5 times the thickness of the earth crust (1.5D) as a result of the crustal wave-guide effect [Somerville,1999]. The displacement response spectrum associated with such critical M-R combination is defined herein as the "characteristic displacement response spectrum" [Section 3]. The effect of soil resonance on the displacement spectrum has also been modelled using the FASA procedure which has been developed recently by the authors [Section 4]. Finally, the characteristic displacement response spectra for rock and soil sites for low and moderate seismicity regions have been unified into one model.

GENERIC DISPLACEMENT ATTENUATION MODEL

The proposed displacement spectrum model is bi-linear comprising a "flat" part which is defined by the maximum response displacement spectral (SD_{max}), and a "sloping" part which is defined by the corner period (T_2) and SD_{max} as shown in Figure (1). Note, the corner period of the displacement response spectrum is not to be confused with the corner period of the acceleration response spectrum (T_1).

SD_{max} can be expressed in the following form:

$SD_{max} = SD^* \alpha_D(M)\, \beta(R)\, \gamma_D(M,R)$ (units in mm) (1)
where SD^* = 14mm (which is associated with the reference M-R combination : M=6 and R=30km)

The magnitude factor $\alpha_D(M)$ is defined by :
$\alpha_D(M) = 0.20 + 0.80\,(M-5)^{2.3}$ (2)

The distance factor , β, is defined by :
$\beta = 30/R$ (R is in km) (3)

The crustal factor, $\gamma_D(M,R)$ for the generic "rock" crust representing the geological conditions of "young" heavily folded regions (e.g. Western North America (WNA)) is defined by :

$\gamma_D(M,R) = 1.6 + (30-R)/200 + (6-M)/10$ (R is in km) (4)

For the generic "hard rock" crust representing the geological conditions of "old" stable continental shield regions (e.g. Eastern North America (ENA)), $\gamma_D(M,R)$ is equal to unity, by definition.

The variation of SD_{max} with M for a constant value of R is shown in Figure (2). Equation (5), which predicts the Corner Period (T_2), has been obtained by fitting a straight line through computed results for both generic "hard rock" and "rock" conditions as shown in Figure (3).

$T_2 = (M-4)/2$ (5)

The values of SD_{max} and T_2 have been presented in Table 1 for M-R combinations which are considered to be representative of low and moderate seismicity regions. Table 1 indicates that SD_{max} is typically controlled by the magnitude 7 earthquake in the far field. By contrast, the gradient of the "sloping" part, which depends on the corner period (T_2) is controlled typically by the magnitude 5 earthquake in the near field. Note, T_2 increases by half a second for every unit increase in the moment magnitude.

Table 1 - Predicted values of S_D and T_2

M	5	5.5	6	6.5	7
R(km)	10	20	30	50	70
$S_{D\,(mm)}$ ("hard rock")	8	8	14	19	25
$T_{2\,(sec)}$ ("hard rock")	0.50	0.75	1.0	1.25	1.5
$S_{D\,(mm)}$ ("rock")	15	13	22	27	32
$T_{2\,(sec)}$ ("rock")	0.50	0.75	1.0	1.25	1.5

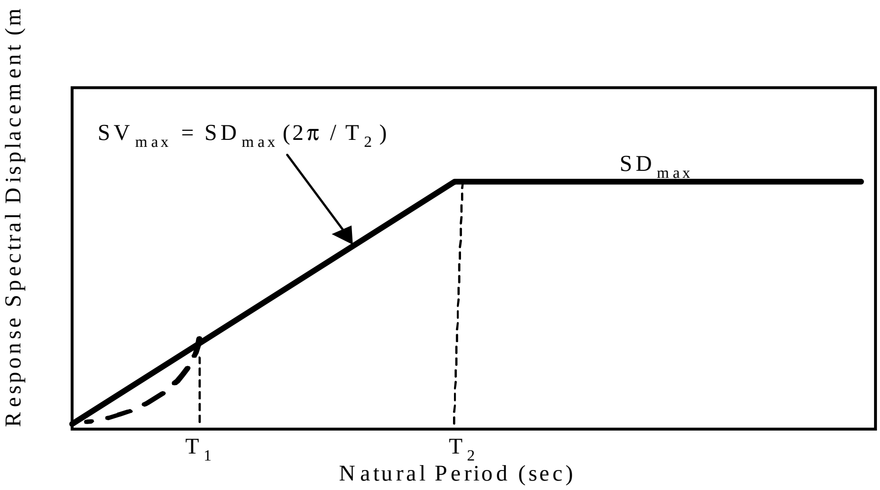

Figure 1 The Bi-linear Displacement Response Spectrum

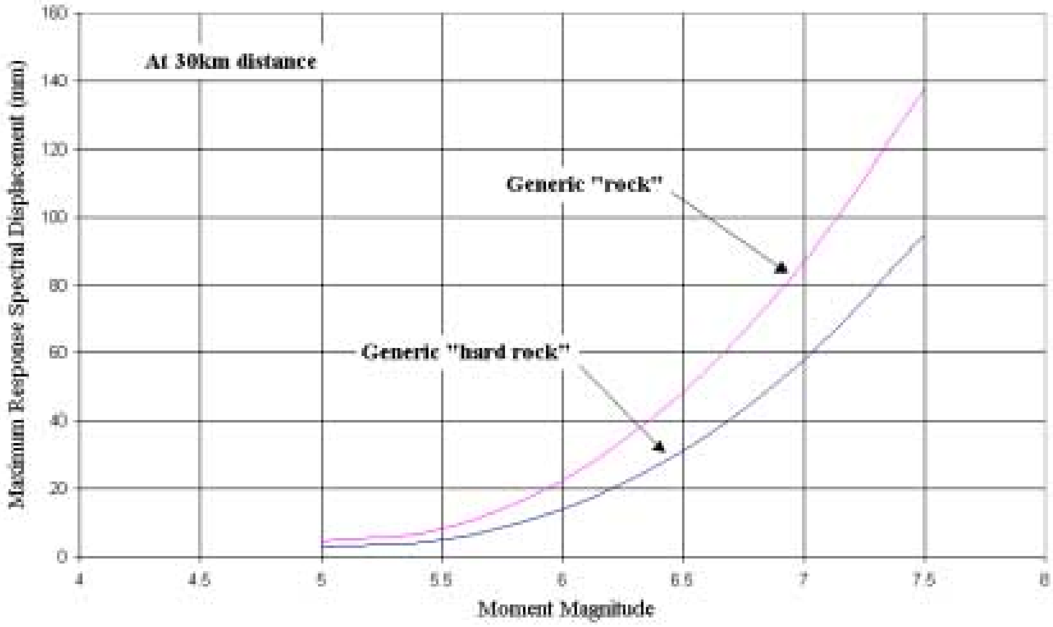

Figure 2 Correlations of Maximum Response Spectral Displacement with Moment Magnitude

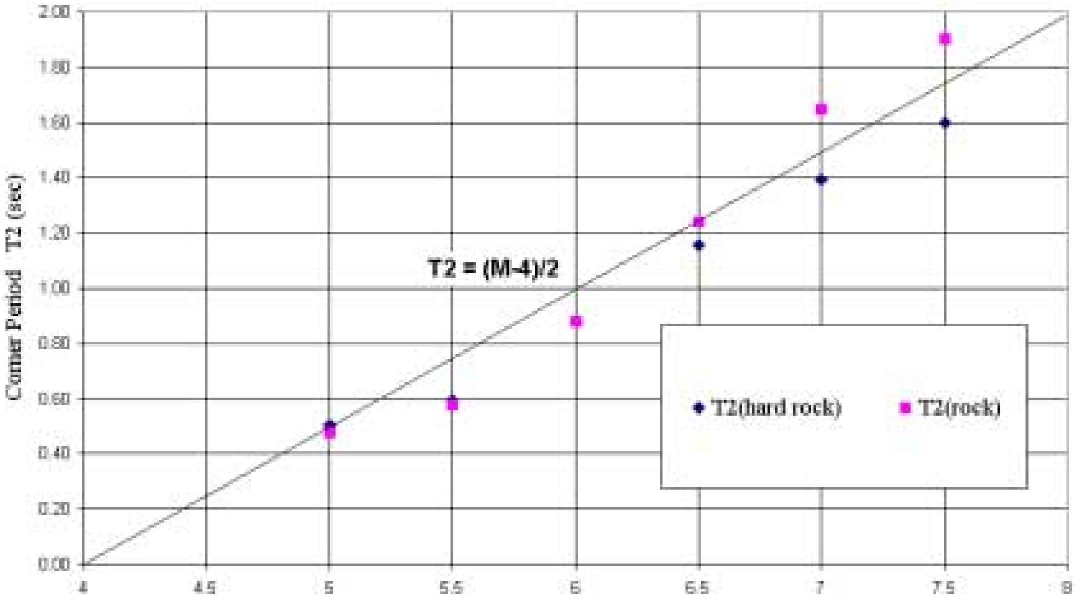

Figure 3 Corner Period of Displacement Response Spectrum

THE CHARACTERISTIC DISPLACEMENT RESPONSE SPECTRUM

From Table 1, the maximum response spectral displacement is typically associated with a large magnitude event in the far field. Thus, the value of R associated with the maximum credible earthquake (MCE) is of particular interest. It has been shown that in low and moderate seismicity regions, earthquakes of magnitude 7 or greater, typically, have a 50% chance of occuring further than 50-70km away from a site during an exposure period of up to 1000 years [Lam *et al, 2000b]*. According to the recently established "tri-linear" geometrical attenuation relationship which can be explained by the crustal waveguide effect [Somerville,1999], "zero attenuation" is assumed between approximately 70km (~1.5D) and 130km (~2.5D) from the source of the earthquake for a crustal thickness (D) of around 40-50km [Figure 4]. Further, earthquake ground motions at distances greater than 130km from the site will have a lower overall rate of attenuation than those initiated from within the 70km limit, due to the nature of the geometrical attenuation relationship. It can be shown that the response displacement caused by an earthquake at a 200km distance will only be about 20% lower than that caused by an earthquake of a similar magnitude at a 70km distance. Consequently, all earthquakes initiated outside the 70km limit can be conservatively, and reasonably, represented by a constant effective distance of 70km for the purpose of predicting displacement demand.

The critical M-R combination (or the characteristic M-R combination), assuming a maximum credible earthquake magnitude of 7 and a crustal thickness of 40-50km (comparable to that of ENA), is M=7 and R=70km. The corresponding characteristic displacement response spectrum has a peak response spectral displacement and corner period of 25mm and 32mm respectively for the generic "hard rock" and "rock" conditions according to equations (1-4) [refer also Table 1]. The corner period in both cases is 1.5 seconds according to equation (5). However, a conservative 1.0 second is recommended to ensure that the characteristic spectrum envelopes all other spectra associated with different M-R conbinations. The resulting characteristic displacement response spectra for both types of crustal condtions are shown in Figure 5.

DISPLACEMENT RESPONSE SPECTRUM ACCOUNTING FOR RESONANCE EFFECT IN SOIL

In this section, the effect of resonance in soft soil is considered. Resonance is particularly significant where "young" and soft sedimentary or marine deposits overlie a much harder sedimentary, metamorphic or crystalline volcanic material (eg. granite). Such conditions are commonly found in coastal cities and in delta areas. The sharp impedance contrast at a well defined interface between soil and bedrock is the ideal condition for resonance to develop in an earthquake. The effects of soil resonance can be modelled by shear wave analysis using, for example, the well known computer program SHAKE (originally written by [Schnabel *et al*,1972] and further developed at the University of California at Berkeley). Soil displacement response spectra generated by SHAKE have been found in a recent comparative study to be consistent with field observations [Cheng *et al*, 1999]. However, the preparation of input data to execute SHAKE for design purposes is generally not a straightforward process and requires special expertise particularly in obtaining representative accelerograms to define the bedrock excitations.

An alternative procedure, which is simple to apply and easily programmed into a spreadsheet for design applications, has been developed to predict the maximum response spectral accelerations which accounts for the effects of resonance in the soil. The procedure has been named the 'The Frame Analogy Soil Amplification" (FASA) procedure as it is based on the analogy with the response behaviour of a moment resisting frame to predict the peak ground accelerations and the maximum response spectral accelerations on soil sites. According to the FASA model, the maximum response spectral acceleration of the soil response spectrum (Sa_{max}) is proportional to the response spectral acceleration of the bedrock response spectrum (Sa_i) at the natural period of the site (which is also the corner period of the soil response spectrum). A paper describing the development and validation of the FASA procedure will be published shortly. In the interim, refer [Lam *et al*,1996] for a brief description of an early version of the model. The procedure has been extended recently to model displacement response spectra. The maximum response spectral displacement (SD_{max}) of the bi-linear displacement response spectrum may be predicted by the following expression:

$$SD_{max} = 3.6\ Sd_i\ \lambda_1\ \lambda_2\ \beta \qquad (8)$$

Where Sd_i is the response spectral displacement of the bedrock excitation at initial site period (T_i), and λ_1 is the height dependent higher mode factor which is defined by the following relationship :

λ_1 = 1.0 + 0.03(H−15) or equal to unity whichever is the greater (9)
(H is the total depth of the soil)

λ_2 is the period shift correction factor in a bi-linear displacement spectrum, and is defined by :

$\lambda_2 = T_g / T_i$ (for $T_i < T_2$) (10a)
$\lambda_2 = 1$ (for $T_i \geq T_2$) (10b)

where T_g is the shifted site natural period which coincides with the corner period of the bi-linear displacement spectrum. A (T_i / T_g) ratio of 0.8 has been recommended by [SEAOC,1977] for low seismicity areas, and this recommendation is in agreement with results obtained from a recent analytical study by [Lam & Wilson,1999].

β is the damping correction factor (β) which is equal to unity, by definition, if soil damping is 5%. (An iterative procedure is contained in the FASA procedure to predict soil damping based on the predicted average shear strain in the soil.)

The trend implied by the FASA procedure described above is shown diagrammatically in Figure 6. Clearly, the level of the displacement spectrum on a soil site depends largely on both the site natural period and the shape of the characteristic displacement response spectrum of the underlying bedrock.

CONCLUSION

1. A generic displacement attenuation model has been developed from the latest seismological model for the generic “hard rock” and “rock” sites as defined by [Boore & Joyner,1997]. In the model, the displacement parameter can be predicted for any given moment magnitude (M) – distance (R) combination.

2. A characteristic displacement response spectrum accounting for the effects of the crustal waveguide has been obtained for rock sites and bedrock, assuming a maximum credible earthquake magnitude of 7 and a crustal thickness of 40-50km. [Figure5]

3. The FASA model, which accounts for the effects of resonance in soil, has been developed to predict the maximum response spectral acceleration and displacement.

4. The level of the displacement spectrum on a soil site depends largely on both the site natural period and the shape of the characteristic displacement response spectrum of the underlying bedrock. Both the rock and the soil response spectrum predictive procedures have been unified in one model. [Figure 6]

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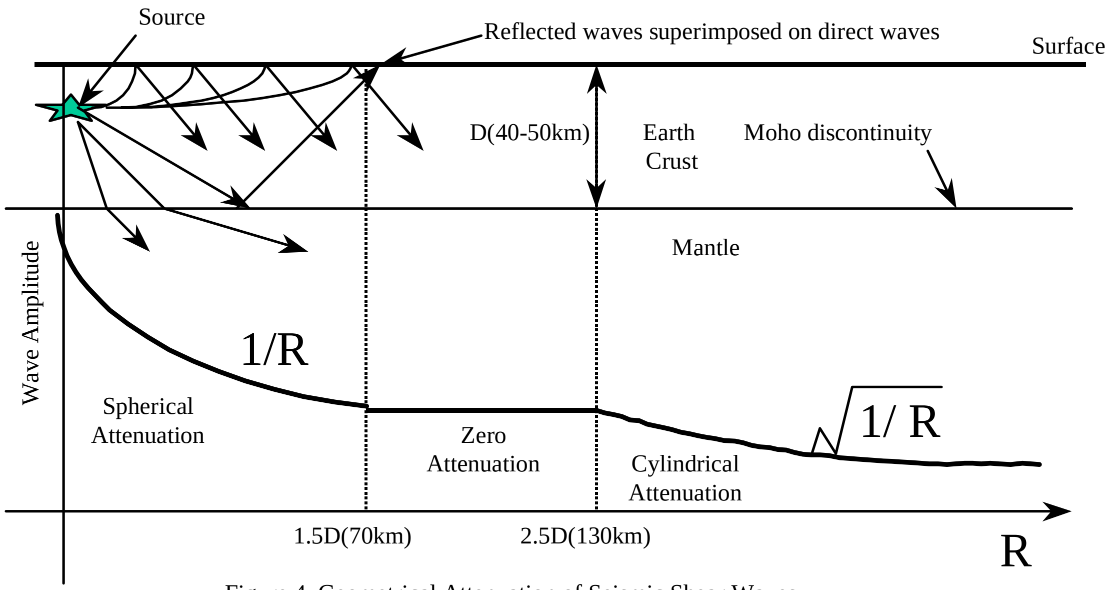

Figure 4 Geometrical Attenuation of Seismic Shear Waves

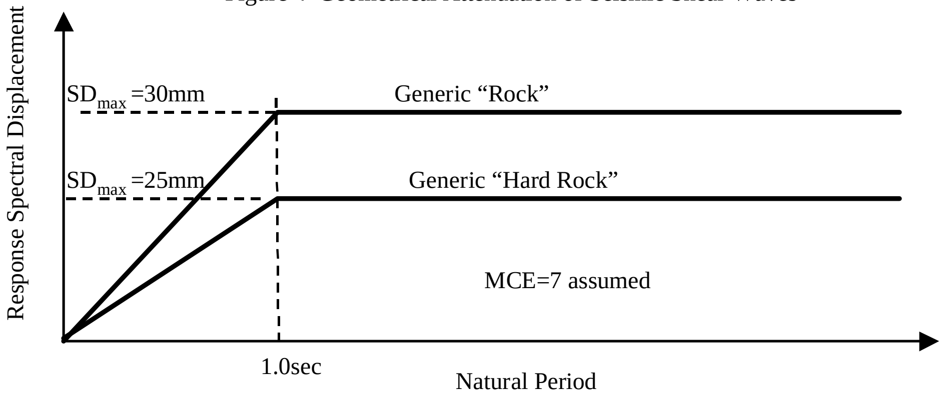

Figure 5 Characteristic Displacement Response Spectra for Generic Rock Sites

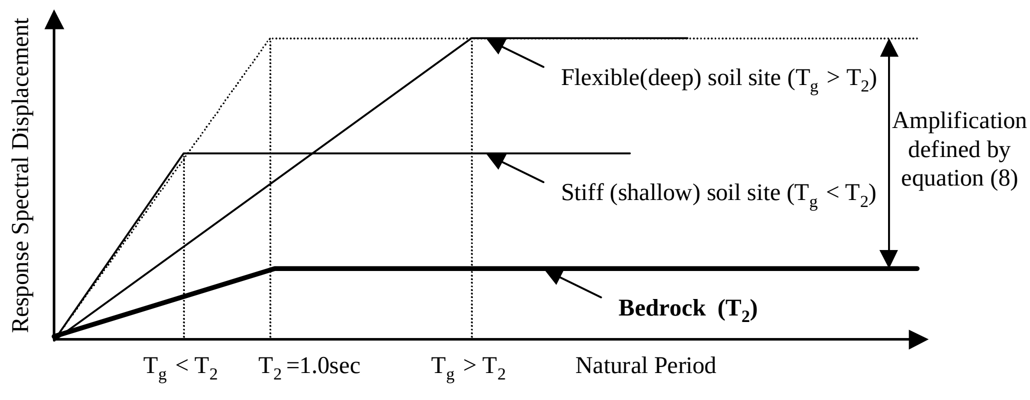

Figure 6 Unified Displacement Response SpectrumModel for Rock and Soil Sites

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