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TIME VS. FREQUENCY DOMAIN GROUND MOTION MODIFICATION: EFFECTS ON SITE RESPONSE ANALYSES AND SEISMIC DISPLACEMENTS

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ABSTRACT

Spectral matching is widely used in practice, despite being a source of controversy. Due to the recognized importance of selected ground motions in the engineering results, it is important to understand the effects of the ground motion matching technique on engineering analyses. A case of twelve ground motions selected and modified using the time domain and the frequency domain matching techniques is presented, and the effects of the modification technique on ground motion characteristics are studied. Seismic geotechnical analyses are also performed for a "soft" site and a "stiff" site. The acceleration response spectrum at the surface is found to be similar for both sets of modified ground motions, with the mean spectrum of the frequency domain matched ground motions being higher for certain frequencies. Maximum shear stress profiles are found to be similar. Newmark-type displacements are generally higher for frequency domain matched ground motions particularly for low yield coefficients, but analyses using time domain matched ground motions may yield greater displacement estimates at higher yield coefficients.

Introduction

In seismic design of major infrastructure projects, time series consistent with seismic hazard evaluation are selected for dynamic analyses. The time series used in analyses have a major impact in the results of the analyses and thus the selection of ground motions becomes a critical decision (e.g. Bray and Travasarou 2004, Athanasopoulos-Zekkos 2008). Recently, many studies have been performed (and are currently underway) to assist the engineer with the selection of "appropriate" ground motion time series (Bommer and Acevedo 2004, Watson-Lamprey and Abrahamson 2006, Kottke and Rathje 2008). Ground motions may be simply scaled or spectrally modified (or "matched"). If scaling is employed, the time series is multiplied by a constant, and the intent, many times, is for the average of the selected ground motions to be at least equal to the target spectrum within a period range of interest. Spectral modification or matching involves modifying the time series to match the target spectrum at desired (or all) spectral periods.

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Despite being controversial (Naeim and Lew, 1995), spectral matching is widely used in practice. Spectral matching typically allows the reduction of the number of time series used in analyses and makes the selection of the original time series a less critical decision (Hancock et al. 2006). Such cases may be particularly appealing in scenarios where recorded time series representative of the design earthquake are not available. Some regulations also require or encourage the use of ground motion modification techniques to modify the recorded time series. Ground motion modification is typically performed in either the time domain or the frequency domain. A review of the various ground motion modification techniques has been made by Preumont (1984) and Abrahamson (2004). Time domain (TD) methods make wavelet adjustments to recorded accelerograms at specific times until the elastic acceleration response spectrum of the modified ground motion "matches" the design spectrum. The methodology is based on Lilhanand and Tseng (1988). The technique leads to a more focused modification of the recorded ground motions thus better preserving the stationary characteristics of the original ground motion and introducing less energy during the modification. Frequency domain (FD) techniques alter the Fourier amplitude spectrum of the recorded time series based on the ratio of the target response spectrum to the time series response spectrum, but the phase of the Fourier spectrum is not altered (e.g. Rizzo et al. 1975). Frequency domain techniques have been accused for significantly altering the stationary characteristics of the original time history, disturbing the velocity and displacement time histories and resulting in unrealistically high energy content (Naeim and Lew 1995).

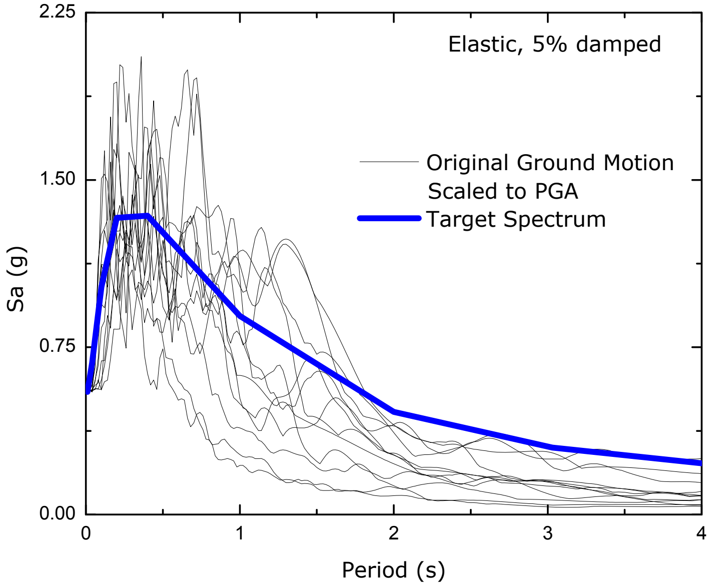

Figure 1. Recorded ground motions scaled to target PGA

Methodology

Whereas changes to the amplitude and frequency content of the original time series are necessarily made in all spectral matching techniques, it remains unclear what the impact of these modifications is in engineering analyses. A set of 12 ground motions were selected as part of the design of a critical facility in a subduction zone. The target spectrum (elastic, 5% damped) that was developed for the Safe Shutdown Earthquake using both deterministic and probabilistic approaches according to the seismic design provisions of the 2006 National Fire Protection

Association (NFPA 2006) 59A is shown in Fig. 1. The acceleration response spectrum of the selected ground motions, scaled to the target Peak Ground Acceleration (PGA) are also shown. Each selected ground motion was separately modified in the time domain and in the frequency domain generating two sets of ground motions that both match the target spectrum. The time domain matching technique was implemented using the software program RSPM99 (Abrahamson 1992, 1998) and the Frequency domain matching technique was implemented using proprietary software referred herein as "Freqmatch".

The changes in the ground motion characteristics during matching were investigated. These included Peak Ground Velocity (PGV), Bracketed Duration, Significant Duration, and Arias Intensity. Subsequently, 1-D equivalent-linear seismic response analyses were performed using the computer program SHAKE2000 (Ordoñez 2007). Site soil parameters were developed for a "stiff" soil site, and a "soft" soil site. Newmark-type analyses were then performed for shallow, intermediate and deep sliding masses and seismic permanent displacements were calculated. The results of the analyses are presented.

Ground Motion Characteristics

The characteristics of the original (scaled to target PGA) and matched time series were computed. The mean (μ) and standard deviation (σ) ratios of the modified to original (scaled to PGA) ground motion characteristics are shown in Table 1. The mean peak ground velocity (PGV) was affected similarly, increasing by a factor of 1.5 to 1.6. Time domain modification appears to have resulted in slightly greater PGV than frequency domain ground motion modifications. Bracketed and significant duration were not significantly affected by the modification process using either the time domain or frequency domain approach. Time domain matching did not affect the mean Arias Intensity, but frequency domain matching appeared to increase Arias Intensity by 40% on average.

Table 1. Summary of ratios of modified to original ground motion characteristics

		TD/ Original	FD/ Original
PGV (m/s)	μ	1.6	1.5
	σ	0.9	1.0
Bracketed Duration (s)	μ	1.1	0.9
	σ	0.3	0.1
Significant Duration (s)	μ	1.0	1.1
	σ	<0.1	0.1
Arias Intensity (m/s)	μ	1.0	1.4
	σ	0.1	0.3

Fig. 2 presents the changes in Arias Intensity caused by the modification techniques when compared to the original, scaled to PGA, ground motions. Ground motion modification using the time domain approach resulted in small increases or small decreases of the Arias Intensity. Six of the twelve ground motions experienced an increase in Arias Intensity of 50% or more using the frequency domain approach.

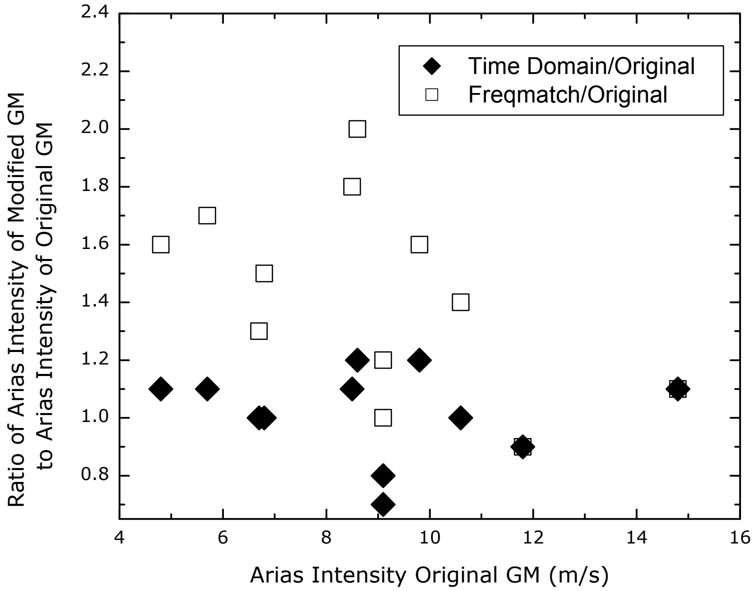

Figure 2. Ratios of Arias Intensity for modified to original ground motion (GM)

Stiff Site Analyses

Equivalent linear site response analyses were performed for a "stiff" sandy soil site. The soil profile and soil parameters are shown in Figure 3. The shear wave velocity in the upper 30 m (V_{s30}) is equal to 248 m/s, classifying the site as Site Class "D - stiff soil profile" according to the 2000 International Building Code. The Darendeli and Stokoe (2001) shear modulus and material damping curves for a soil with PI=0 and representative confining stresses were used to represent the dynamic soil properties of each soil layer. The Imai and Tonouchi (1982) correlation was used to estimate the small strain shear wave velocity (V_s) from the N_{60} blowcount and the small strain shear modulus was calculated from the density and V_s. The V_s of the half space (at 30 m and deeper) was equal to 610 m/sec (2,000 ft/sec).

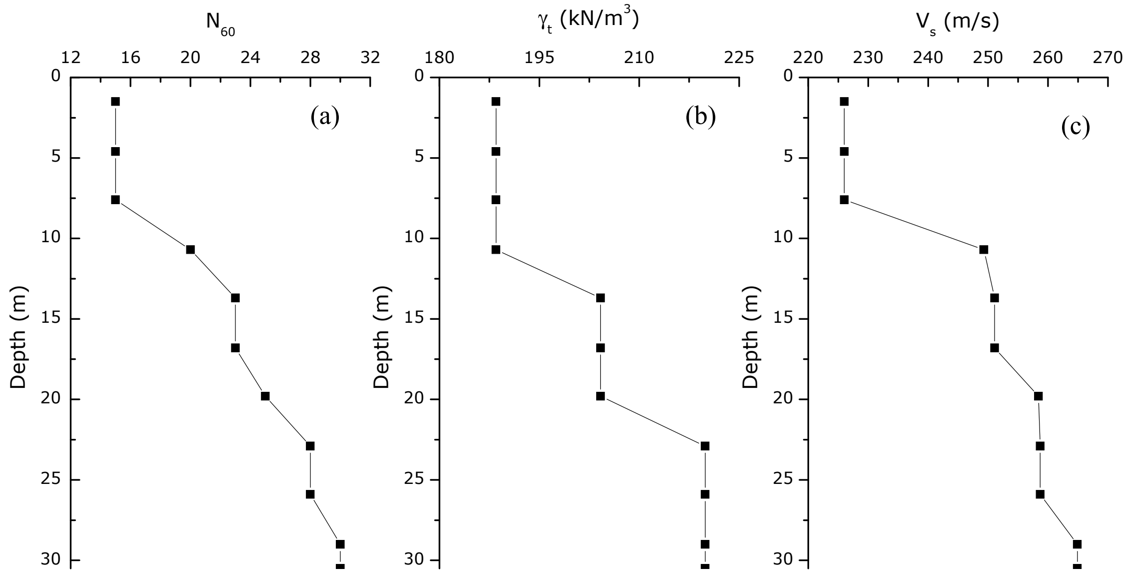

Figure 3. Stiff soil profile properties: (a) SPT blowcount; (b) total unit weight, and (c) shear wave velocity.

The matched ground motions were used as input in the site response analyses. Figure 4 compares the maximum shear stress profile calculated for the time domain and the frequency domain matched ground motions. The maximum shear stresses were similar for the time domain and frequency domain matched ground motions. The maximum shear stress profiles diverged at a depth of approximately 24.4 m, where the mean of the maximum shear stress profile using the time domain approach slightly exceeded its counterpart using the frequency domain technique.

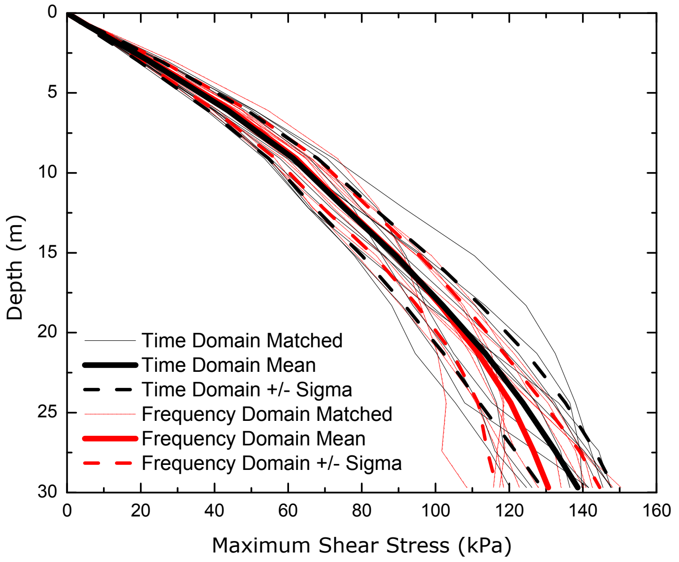

Figure 4. Maximum shear stress profiles for time domain and frequency domain matched ground motions

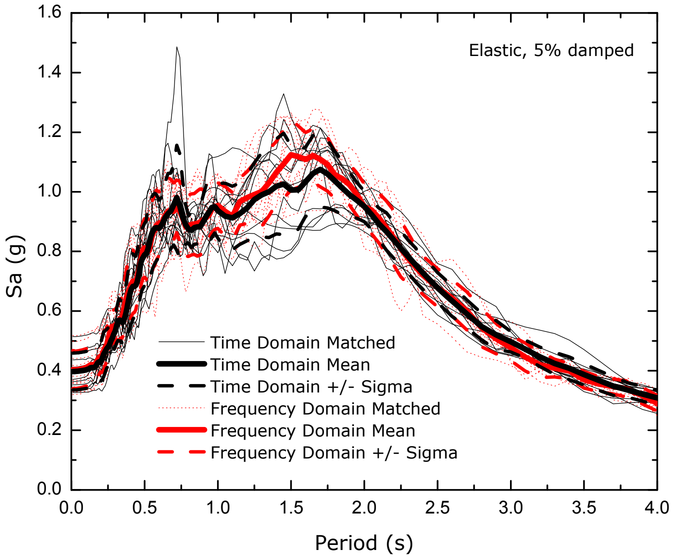

Figure 5. Surface response spectra for time domain and frequency domain matched ground motions

Figure 5 compares the acceleration response spectra (elastic, 5% damped) at the surface of the stiff soil site using the time domain and frequency domain matched ground motions. The mean response spectra at the surface were similar, except between periods of 1.2-2 s, where the time domain mean acceleration response spectrum fell a bit short (approximately

10%) of the frequency domain mean acceleration response spectrum. In general, the response spectrum at the surface does not seem to be significantly affected by the ground motion modification technique.

Figure 6 presents the estimated Newmark-type displacements due to the modified ground motions for three different sliding masses. For surficial (1.5 m thick) sliding and yield coefficient up to 0.18, the mean Newmark-type displacements were greater for the frequency domain modified ground motions than time domain modified ground motions. For "intermediate" (13.7 m=45 ft) sliding, the displacements were greater for frequency domain matching for $k_y \leq 0.15$. For "deep" (29 m=95 ft) sliding, the mean displacements were greater for frequency domain modified ground motions for values of $k_y \leq 0.10$. Beyond these k_y values, the displacements using the time domain were slightly greater.

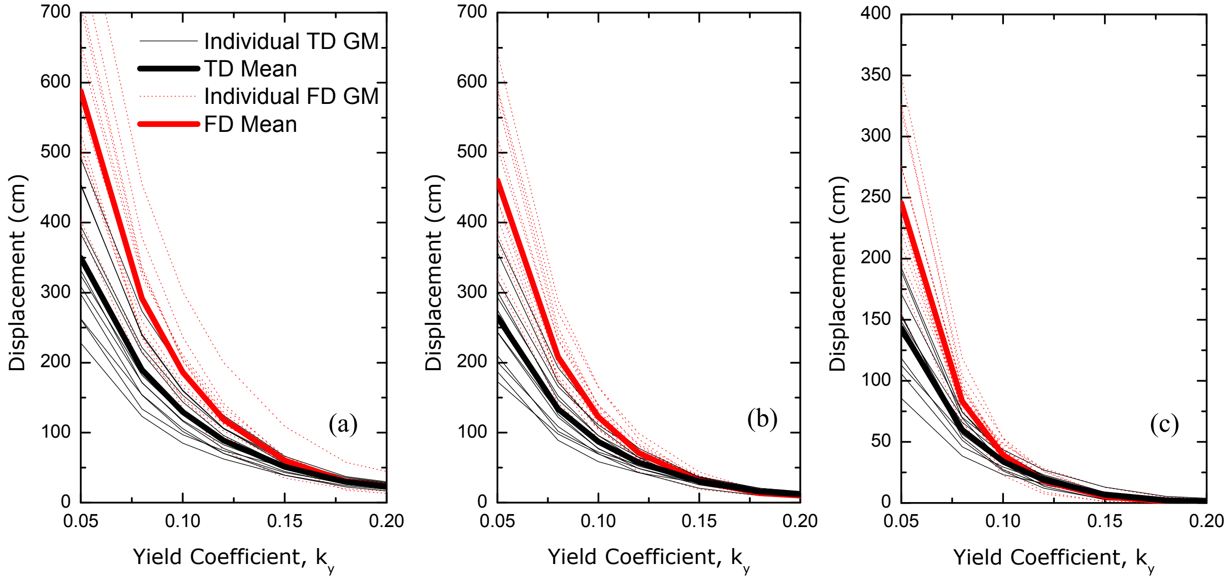

Figure 6. Newmark-type displacement estimates for (a) surface sliding, (b) "intermediate" sliding, and (c) "deep" sliding for the stiff site

Soft Site Analyses

The soft soil profile and soil parameters are shown in Figure 7. This site would be representative of a 30 m thick San Francisco Bay Mud site. The Vucetic and Dobry (1991) shear modulus and material damping curves for soil with a PI = 30% were used. The Dickenson and Seed (1994) empirical equation was used to calculate the shear wave velocity from the undrained shear strength of the Young Bay Mud. The V_{s30} for this site is 169 m/s, which classifies the site as Site Class "E - soft soil" profile according to the 2000 International Building Code.

Modified ground motions using the time domain technique and the frequency domain technique were used in the analyses. The combination of high intensity ground motion and soft soils indicate that non linear effects would be pronounced and equivalent linear site response analyses may not be as appropriate. Indeed, the maximum shear stress was found to exceed the shear strength of the clay. To account for soil non-linearity and clay shear strength exceedance in a simplified manner, the shear modulus reduction and material damping curves were "modified" at larger strains by increasing material damping and decreasing the shear modulus of the clay.

Modification of the dynamic curves was identical for all ground motions in an effort to isolate the variability in seismic response due to the input ground motions only.

Figure 8 compares the maximum shear stress profile for ground motions modified using the time domain technique and the frequency domain technique. The mean maximum shear stresses for frequency domain using frequency domain and time domain matching were very similar. Analyses using the frequency domain matching technique exhibited higher variance than the time domain matched ground motions. Overall, there was more variability in shear stresses than the stiff site profile.

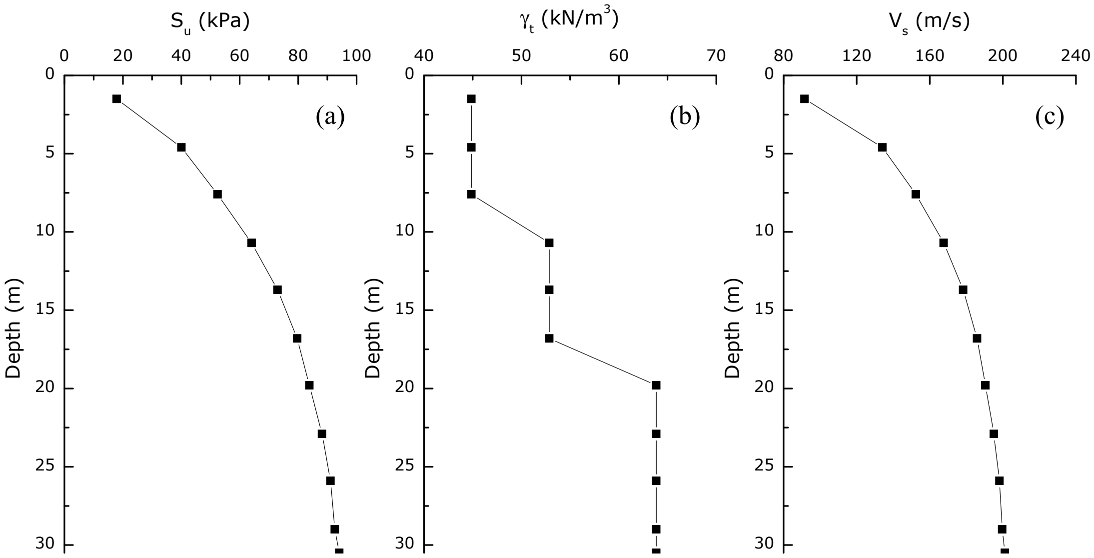

Figure 7. Soft soil profile properties: (a) undrained strength; (b) total unit weight, and (c) shear wave velocity.

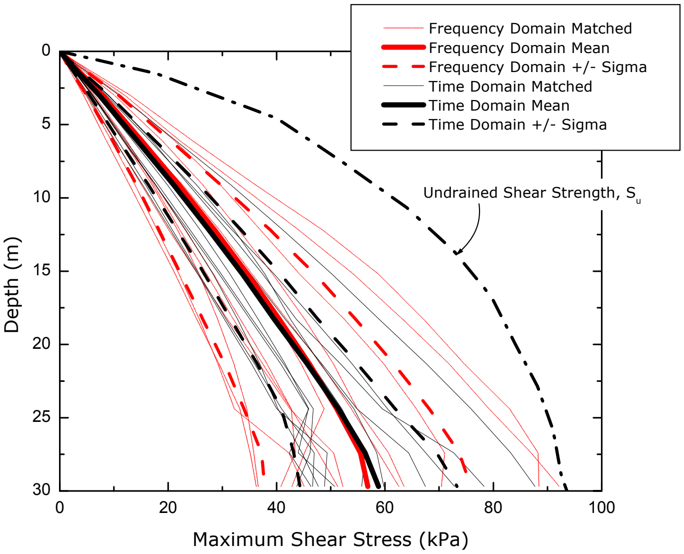

Figure 8. Maximum shear stress distributions for time domain and frequency domain matched ground motions

Figure 9 compares the acceleration response spectra (elastic, 5% damped) at the surface of the soft soil site for the time domain and frequency domain matched ground motions. Frequency domain and time domain modified ground motions have similar acceleration response spectra at the surface, with greater variance than the stiff site. The mean acceleration spectrum of the time domain matched ground motions fell below its counterpart of the frequency domain matched ground motions for most periods. Average Newmark-type displacements shown in Figure 10 were greater for the frequency domain modified ground motions than for the time domain modified ground motions for all yield coefficients.

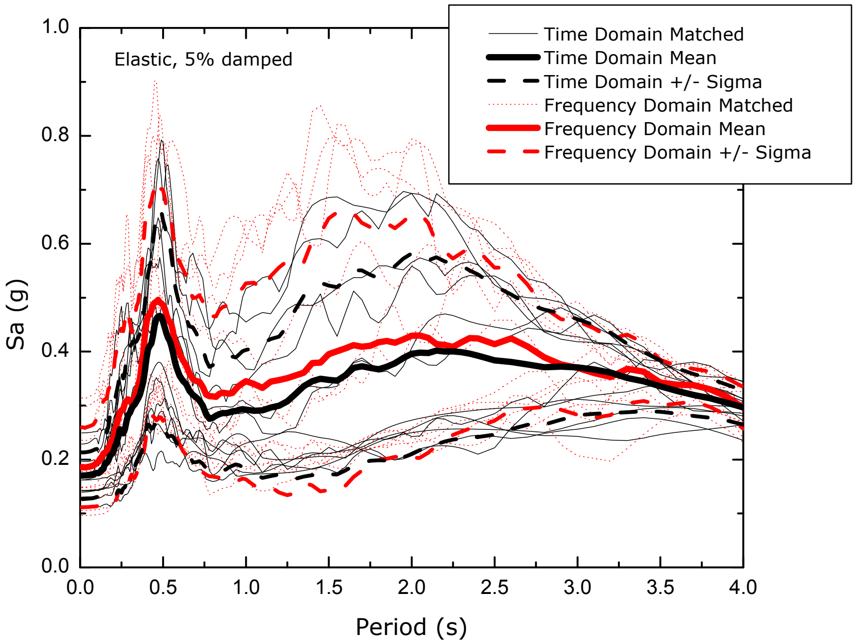

Figure 9. Response spectra at the surface for time domain and Frequency domain matched ground motions

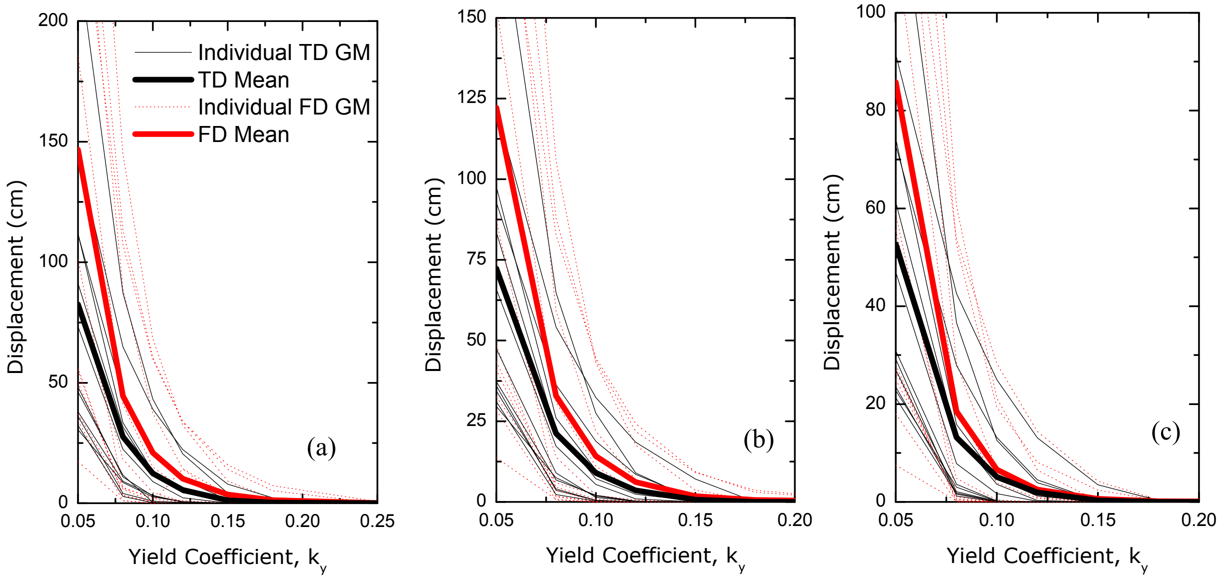

Figure 10. Newmark-type displacement estimates for (a) surface sliding, (b) “intermediate” sliding, and (c) “deep” sliding for the soft site profile

Conclusions

A case of twelve selected ground motions modified using the time domain and separately the frequency domain technique is presented. The effects of ground motion characteristics are studied. The PGV of the time domain modified ground motions was somewhat greater than the PGV using frequency domain matched ground motions, whereas the Arias Intensity of the frequency domain modified ground motion was significantly higher than its time domain counterpart. Seismic geotechnical analyses were subsequently performed and the results for a "soft" site and a "stiff" site are presented. Based on the findings of this investigation, it is concluded that the results will depend on a number of factors such as the original ground motion, the ground motion modification technique and site conditions. The mean acceleration response spectrum at the surface is found to be similar for both sets of ground motions, with the mean spectrum of the frequency domain ground motions being higher for certain frequencies. Maximum shear stress profiles are on average similar, but the scatter in the shear stress profiles may be significant depending on the matching technique employed. Newmark-type displacements are generally higher for frequency domain matched ground motions, particularly for very low yield coefficients, but analyses using time domain matched ground motions may yield greater displacements at higher yield coefficients, depending on site conditions and the sliding mass.

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