13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1990

THE INFLUENCE OF PHASE AND DURATION ON EARTHQUAKE DAMAGE IN DEGRADING STRUCTURES

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SUMMARY

There are many parameters that are used to define the damage potential of earthquake shaking. However, no parameter is of any use unless it is empirically or analytically correlated with indices or measures of damage. Correlations between different damage parameters and the strength degradation of low to medium height masonry structures under the action of nearly 500 recorded earthquakes have been explored. Damage predictions using spectral acceleration are significantly improved by considering an average spectral acceleration over an interval from the natural period of the undamaged structure T_o to FT_o, where F is a constant to be defined. This is because as the structure degrades its stiffness decreases and effective natural period increases.

This implicitly assumes that the longer period content of the ground motion occurs after the shorter period motions that initiate stiffness degradation. This paper explores this concept by plotting response spectra including time as a third axis. This creates a 3 dimensional response spectra that has peaks at particular frequencies and times. The features on the time domain response spectra clearly show why a masonry structure can be heavily damaged by one ground motion whilst suffer virtually no damage under different ground motions with a similar 3D spectral intensity, a measure of ground motion damage proposed by Şafak [1].

INTRODUCTION

The correlation between the strength degradation of low to medium height masonry structures under the action of nearly 500 recorded earthquakes and a range of strong-motion parameters has been conducted by Bommer *et al.* [2]. Correlation between most of the parameters and strength degradation is poor. This paper investigates some of the reasons for the difficulty in predicting the damage potential of ground motions for structures with degrading stiffness. A 3D response spectra, which has time plotted as a third axis, is used to investigate the interaction between the non-stationary characteristics of the ground motion, including phase difference and duration, with the structural response. The use of 3D response spectra is not new, so existing literature employing this technique is reviewed. This reveals some of the possible causes of the different features on the 3D response spectra, and the proposals of different authors to

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predict the non-stationary characteristics of the ground motion, enabling a more realistic generation of synthetic accelerograms.

The correlation between the strength degradation of masonry structures with 0.15s initial period and the 3D spectral intensity proposed by Şafak [1] is investigated. The cause of the scatter in the predictions is explained by the time domain 3D response spectra. Finally, 3D response spectra are used to show why ground motions from two records from the same earthquake, on sites with the same site classification and at similar distances from the fault, cause completely different levels of damage to masonry structures.

3D RESPONSE SPECTRA AND TIME-FREQUENCY ANALYSIS

Existing studies using time-frequency analysis and response spectra with time or number of cycles as a third axis are reviewed in this section. This is broadly split into three subsections: the first reviews articles that discuss time domain features of 3D response spectra from recorded ground motions; papers presenting techniques for creating synthetic ground motions with designed phases are given in the second subsection; the third subsection details articles that use 3D response spectra to estimate structural damage.

Arrival Times of Seismic Waves

Plotting the response spectra in three dimensions with time as the third axis has been used by several authors. This technique is closely related to the "multiple filter technique" or "moving window analysis" and shows the frequency content of the ground motions with time. Trifunac [3] used three dimensional response spectra to aid the identification of the arrival of different seismic waves in the near field for records with closely spaced arrivals and low signal-to-noise ratio. Trifunac suggests that peaks in the spectrum generated from strong-motion recordings of the 1940 Imperial Valley earthquake are caused initially by body waves, then by Rayleigh and Love phases reflected from different crustal layers, Figure 1.

Iyama and Kuwamura [4], conduct time-frequency analysis using wavelets of the 1995 Hyogoken-Nanbu (Kobe) earthquake. They find that recordings near the source of the earthquake release energy over a short duration over all frequencies, where as recordings at greater distances have longer period motions that appear after the short period motions. Part of this may be explained by the findings of Yokoyama [4] who uses the results of wave propagation analysis to show that sedimentary surface waves developed in the Osaka plain under the action of the Kobe earthquake. The surface waves travel in the thick upper sediments at velocities approximately half that of the shear waves in the underlying soil. This created long period waves that lasted approximately 10 to 20s after the arrival of the direct seismic phases.

A pattern recognition technique has been proposed by Suzuki [6] to identify the peaks on a running power spectrum, which essentially gives the same information as a smoothed 3D response spectra. The technique uses two shape functions to describe the time and frequency characteristics of each peak in the spectrum. The process can be reversed to create artificial accelerograms from the shape functions, but no method is provided to estimate suitable shape functions for a given design scenario.

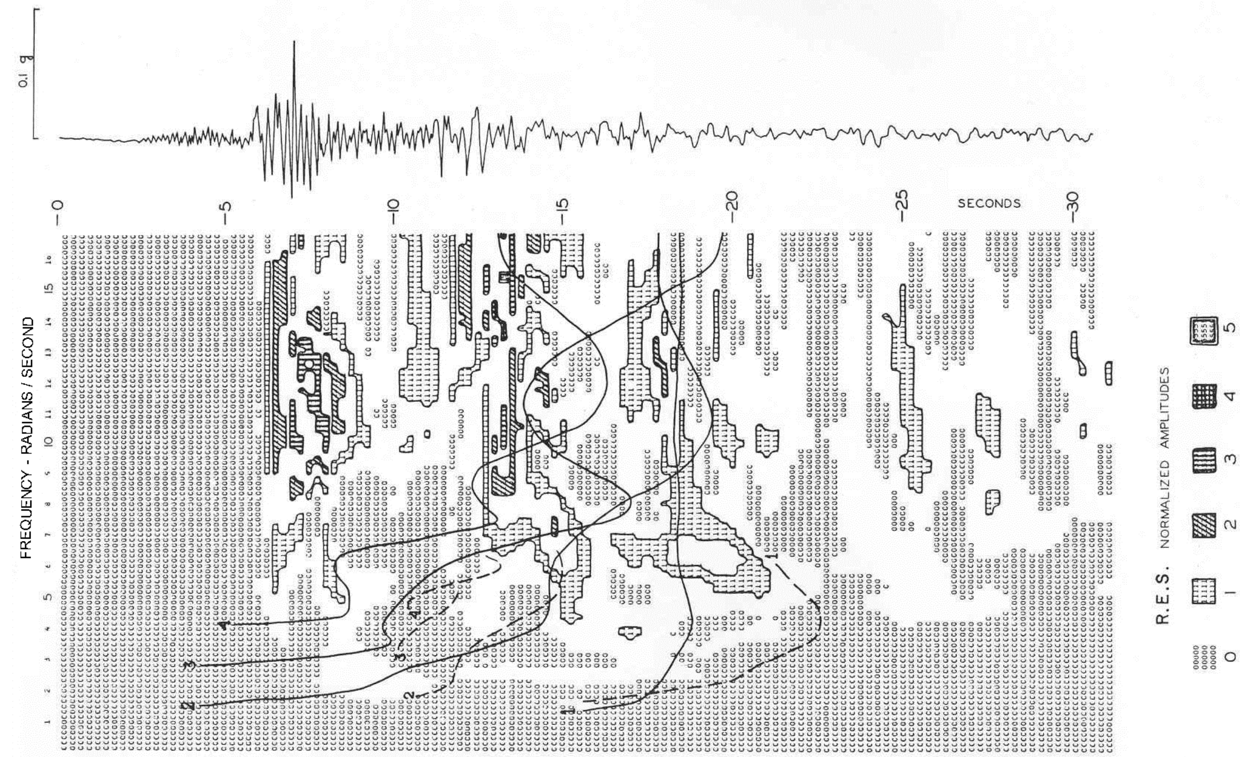

Figure 1, Response Envelope Spectrum for Event 9, NS component of an aftershock from the 1940 Imperial Valley earthquake, recorded at El Centro, 10% damping, dashed and solid lines indicate Rayleigh and Love wave arrivals respectively (Trifunac [3])

Simulation of Ground Motion

Several researchers have observed that the specification of a design response spectrum does not limit the time dependent characteristics, such as the duration and phase difference, of synthetic time histories. Tan and Chao [7] overcome this by fitting a time domain evolutionary power spectra of their synthetic ground motions to shape functions derived from recorded accelerograms.

Wong and Trifunac [8] use the arrival time of different seismic waves and the frequency dependent duration developed by Trifunac and Westermo [9] to create synthetic accelerograms. These accelerograms have realistic duration and phase content, which takes into account the local geological conditions as well as the earthquake magnitude and source-to-site distance. The synthetic ground motions produced are shown to be similar to recordings in both time and frequency domains by plotting 3D response spectra, similar to that shown in Figure 1.

The phase derivatives of the Fourier spectra of recorded ground motions are used by Boore [10] to estimate the envelope delay of different frequency ground motions. This is particularly important for estimating the ground motions with surface waves generated in sedimentary basins. An empirically derived envelope delay function is used by Boore [10] to improve stochastic ground motion simulation (Boore [11]). The empirical function developed is only applicable for a single site, and so further work would be required before a more generic model could be created. However, Thrainsson [12] and Montaldo *et al.* [13] have developed predictive relationships between magnitude and distance and phase difference using regression analysis of accelerograms from Californian and Italian earthquakes. They use these relationships to create synthetic accelerograms with realistic phase differences.

Response Spectra Including Number of Cycles for Damage Estimation

Several studies have developed elastic response spectra that show the amplitudes of vibration sustained for a given number of cycles (e.g. Perez [14], Amini and Trifunac [15], Kawashima and Aizawa [16], Gupta [17], Malholtra [18]). These spectra are developed based on the assumption that ground motions with similar spectral amplitudes will be more damaging if they contain greater numbers of cycles. Ohi *et al.* [19] find that a scale steel braced frame model responds differently to two ground motions with similar PGA. They explain the differences using a variant of the multifilter spectra, which shows that the difference is caused because the ground motions have different duration and frequency content.

Reinoso *et al.* [20] also develop response spectra for number of cycles. They suggest that ground-motion duration could be an important consideration for the design of reinforced concrete structures, particularly for buildings on sites with soft soils. They propose that a modulated harmonic function can be used to create a synthetic accelerogram to model ground-motions on soft soil sites and verify the method for the unique case of Mexico City where the deep deposits of soft soil create the formation of long duration, sinusoidal ground-motions.

The 3D spectral intensity, defined as the volume under a 3D response spectra with the number of peaks on the third axis, is proposed as a measure of earthquake destructiveness by Şafak [1]. Some authors suggest a low-amplitude cut-off should be applied to prevent residual vibration dominating the number of cycles (Mortgat [21]). Alternatively a limit to the total number of cycles counted can be used; Koliopoulos and Margaris [22] propose that the largest 20 cycles is an acceptable number. Further investigation of the 3D spectral intensity is undertaken in the next section.

The destructive power of earthquake ground motions are investigated by Nagahashi [23] by measuring the energy absorption and ductility of elasto-plastic systems. Nagahashi shows that the phase content of the ground motion controls the duration of the strong shaking, which in turn influences the energy demand on the structure.

RESPONSE OF DEGRADING STRUCTURES

Correlations between different ground-motion parameters and the strength degradation of low to medium height masonry structures under the action of nearly 500 recorded earthquakes have been explored by Bommer *et al.* [2]. The study used a strength and stiffness degrading SDOF hysteretic model developed over several years at the University of Pavia which has been calibrated against experimental tests on unreinforced and lightly reinforced masonry structural components (Calvi and Macchi [24], Magenes and Baietta [25]). The study found that the correlation between most ground-motion parameters and stiffness degradation is poor. This study uses the same structural model and 3D response spectra to investigate the reasons for the difficulty in predicting the damage potential of ground motions for structures with degrading stiffness.

The hysteretic rule used in the model accurately represents the shear-dominated failure of masonry structures. The strength and stiffness degradation, although calculated separately, are intrinsically linked because they both depend on the energy dissipated by hysteresis. Strength degradation is used as the measure of damage, although as the strength and stiffness degradation are linked, the stiffness degradation also provides an indication of damage.

An additional post-processing routine has been added to the masonry model for this work so that the increase in the period of the structure from stiffness degradation is output at each time step. This period is plotted on the elastic 3D response spectra for the ground-motion under consideration. The 3D response spectra are created by plotting the spectral acceleration time histories of multiple elastic SDOF systems with natural periods ranging from 0 to 3s. A 2D response surface is created from the time histories using CoPlot graphics package (CoHort [26]). The elastic 3D response spectra is used to show how the frequency content of the ground motion evolves with time and is calculated independently from the response of the masonry structure.

An example time domain response spectra is presented in Figure 2. This shows the frequency content of the ground motion from 1992 Landers Earthquake, recorded 26km from the fault at Fun Valley. The 3D response spectrum reveals the arrival of two, essentially separate, seismic phases that are not easily isolated on the original accelerogram. The first strong arrivals occur 8 to 10 seconds after the start of the record and have a predominant period of 0.3s. The second arrivals start about 28 seconds from the start of the record and have a predominant period of 0.7s.

The influence of the different seismic phases on the response of masonry structures with different periods is shown on Figure 2 by solid black lines that track the increase in period as the stiffness degrades. As the ground motion contains only low-amplitude spectral acceleration at 0.1s period the masonry structure with this initial period suffers little damage or stiffness degradation. However, the structure with 0.2s initial period is damaged by the first wave train, which lengthens the period of the structure making it more susceptible to damage from the second wave train. Had the wave groups arrived in the opposite order, which would not be expected for recorded ground motions, the damage to the shorter period structures would be less, although the spectral amplitude of the ground motion would be the same. This provides anecdotal evidence as to the importance of using ground motions with realistic phase content for the analysis of stiffness degrading structures.

Figure 2 also shows that the amount of damage sustained by the masonry structures is strongly dependent on the period of the ground motion and the period of the structure. As both of these can change with time it is particularly challenging to derive a simple parameter which expresses the damage potential of the ground motion. Pomonis *et al.* [27] conduct shake table tests of full-scale masonry walls and find that the frequency-dependent characteristic intensity I_{char} has a good correlation with damage.

$$I_{char} = RMSA^{1.5} * \sqrt{D_s} \tag{1}$$

where D_s is the significant duration defined by Trifunac and Brady [27] and is the time interval between attaining 5% and 95% of the total Arias intensity. *RMSA* is the frequency-dependent RMS acceleration between 0.1 and 0.3s:

$$RMSA = \left[\int_{3Hz}^{10Hz} PSD(f) df \right]^{0.5} \tag{2}$$

where $PSD(f)$ is the power spectral density of the record. The characteristic intensity also recognises that the duration of the strong shaking influences the damage potential of the ground motion. This is logical as the repeated application of loading progressively causes damage. This phenomenon can be seen in the stiffness degradation of the structure with 0.2s initial period, which is progressively damaged as the strong shaking continues throughout the ground motion (Figure 2).

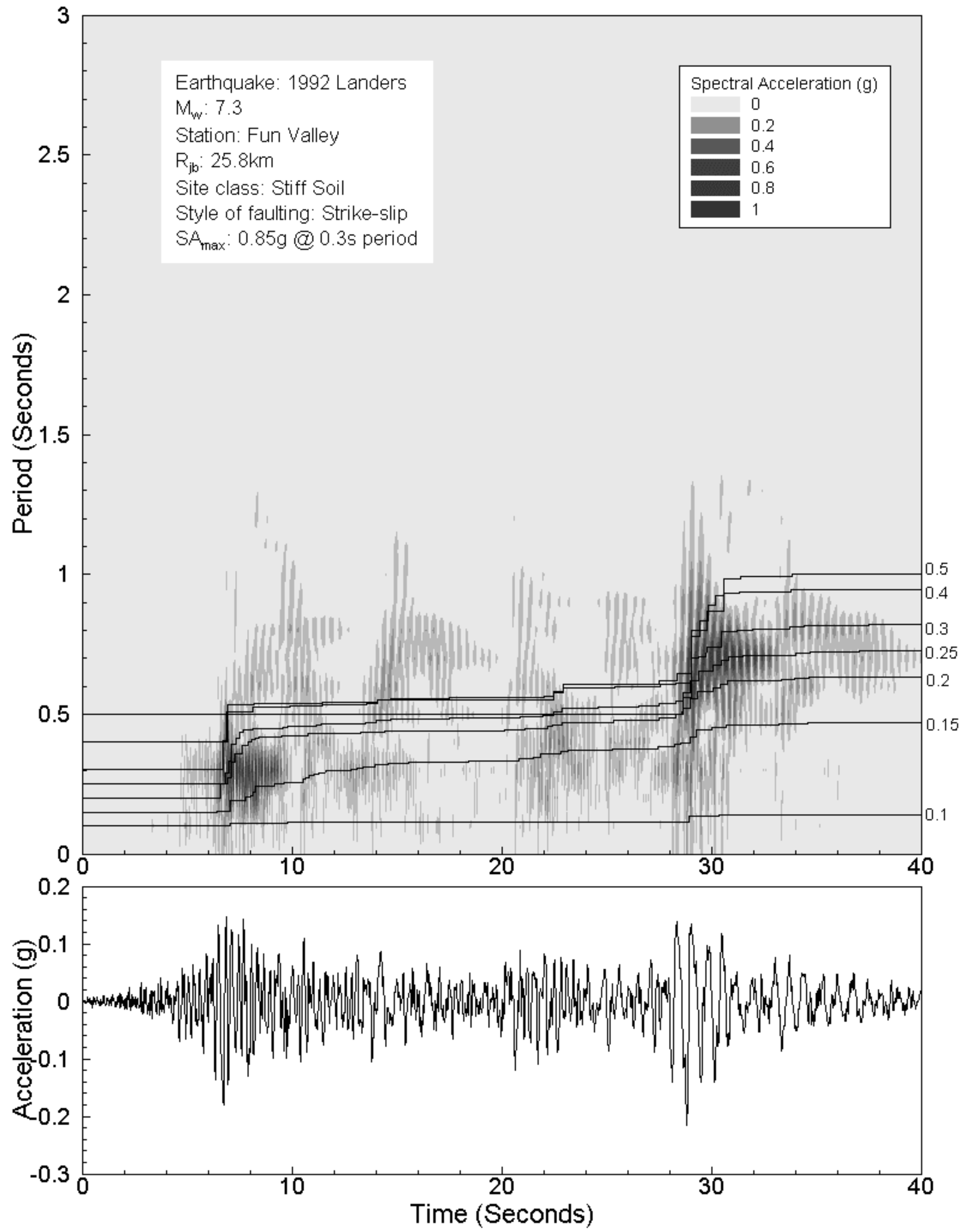

Figure 2: 3D response spectra for 1992 Landers earthquake (7.3M_w), recorded 26km from the fault rupture at Fun Valley. Solid black lines on response spectra show stiffness degradation of masonry structures with 0.1, 0.15, 0.2, 0.25, 0.3, 0.4 and 0.5s initial period.

The spectral periods used to evaluate the characteristic intensity proposed by Pomonis *et al.* [27] is based on the expected natural period of one to three storey buildings (Spence *et al.* [29]). As the period of masonry structures increases with damage an improved damage prediction may be obtained by considering the spectral accelerations to a period about three times the initial period of the structure (Bommer *et al.* [2]).

The correlation between the 3D spectral intensity as proposed by Şafak [1] and the damage of masonry structures with 0.15s initial period is conducted using the same strong ground-motion database as Bommer *et al.* [2]. The 3D spectral intensity is calculated using the largest 20 cycles (Koliopoulos and

Margaris, [22]). The parameter is evaluated using both spectral velocity and spectral acceleration, but only the results using spectral acceleration are reported here as they give consistently better correlations.

The 3D intensity is evaluated between 0 to 5s period limits, the same period range used by Şafak [1], and for a period range from the initial period of the structure T_o to T_oF, where F equals 3, as proposed by Bommer *et al.* [2]. The 3D intensity evaluated between 0 to 5s period is poorly correlated to strength degradation, resulting in correlation coefficients of 0.47 (Figure 3). Evaluating the parameter over a period range from 0.15 to 0.45s significantly improves correlations, with the correlation coefficient increasing to 0.8 (Figure 3). However, the scatter is still significant and ground motions with essentially the same 3D spectral intensity create damage ranging from null to exceedance of the ultimate limit state (Figure 3).

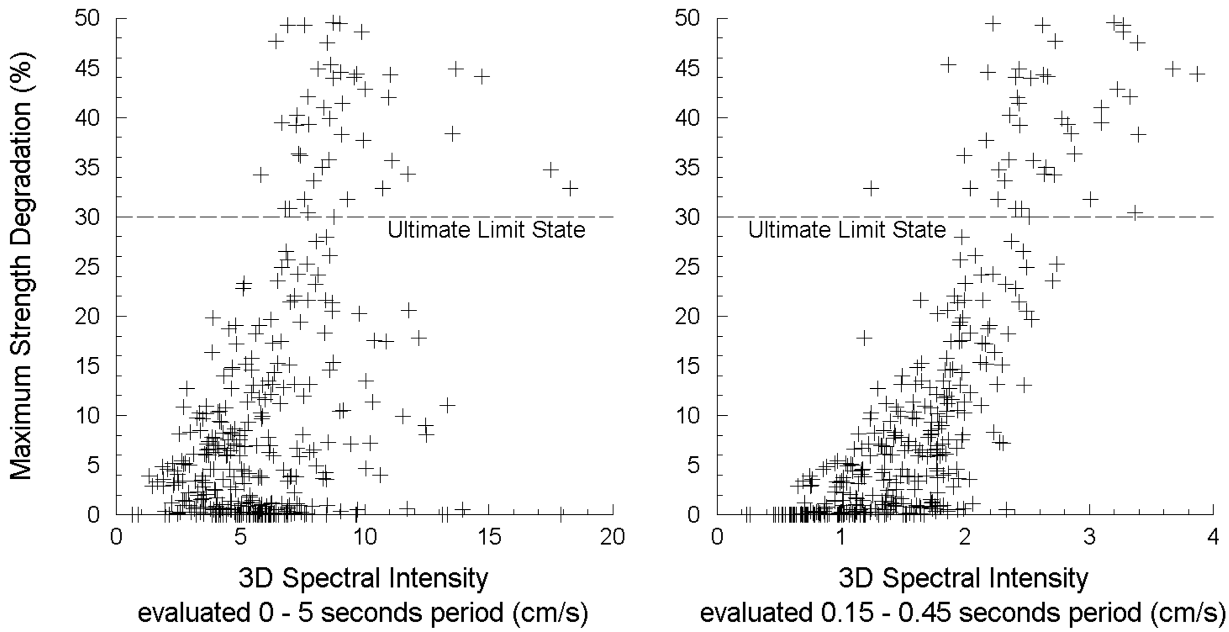

Figure 3: Correlation between 3D spectral intensity proposed by Şafak [1] and the strength degradation of masonry structures with 0.15s initial period. Intensity evaluated for period ranges 0 to 5s (left) and 0.15 to 0.45s (right).

To investigate scatter in the damage estimates from the 3D spectral intensity, time domain response spectra are plotted for two ground motions with similar 3D intensity but different damage levels. The first ground motion is from the 6.7M_w 1994 Northridge earthquake recorded 87km from the fault rupture on soft soil downstream of the Prado dam (Figure 4). This ground motion has a 3D spectral intensity, evaluated between 0.15 and 0.45s period, of 2.33 cm/s and causes a strength degradation of less than 1% in the masonry model with natural period of 0.15s. The 3D response spectrum shows that although this ground motion contains many cycles of motion these are only of damaging amplitude for a narrow period range between about 0.2 and 0.5s. The spectral acceleration at 0.15s is not sufficient to damage the structure.

The second ground motion is from the 6.3M_w 1984 Morgan Hill earthquake recorded at 11km from the fault rupture on stiff soil at Gilroy 6 (Figure 5). This ground motion causes 49% strength degradation and has a 3D spectral intensity, evaluated between 0.15 and 0.45s period, of 2.22 cm/s. The 3D response spectrum shows that this ground motion is particularly damaging because the high frequency arrivals are followed by strong accelerations with longer period, which continue to damage the more flexible weakened structure.

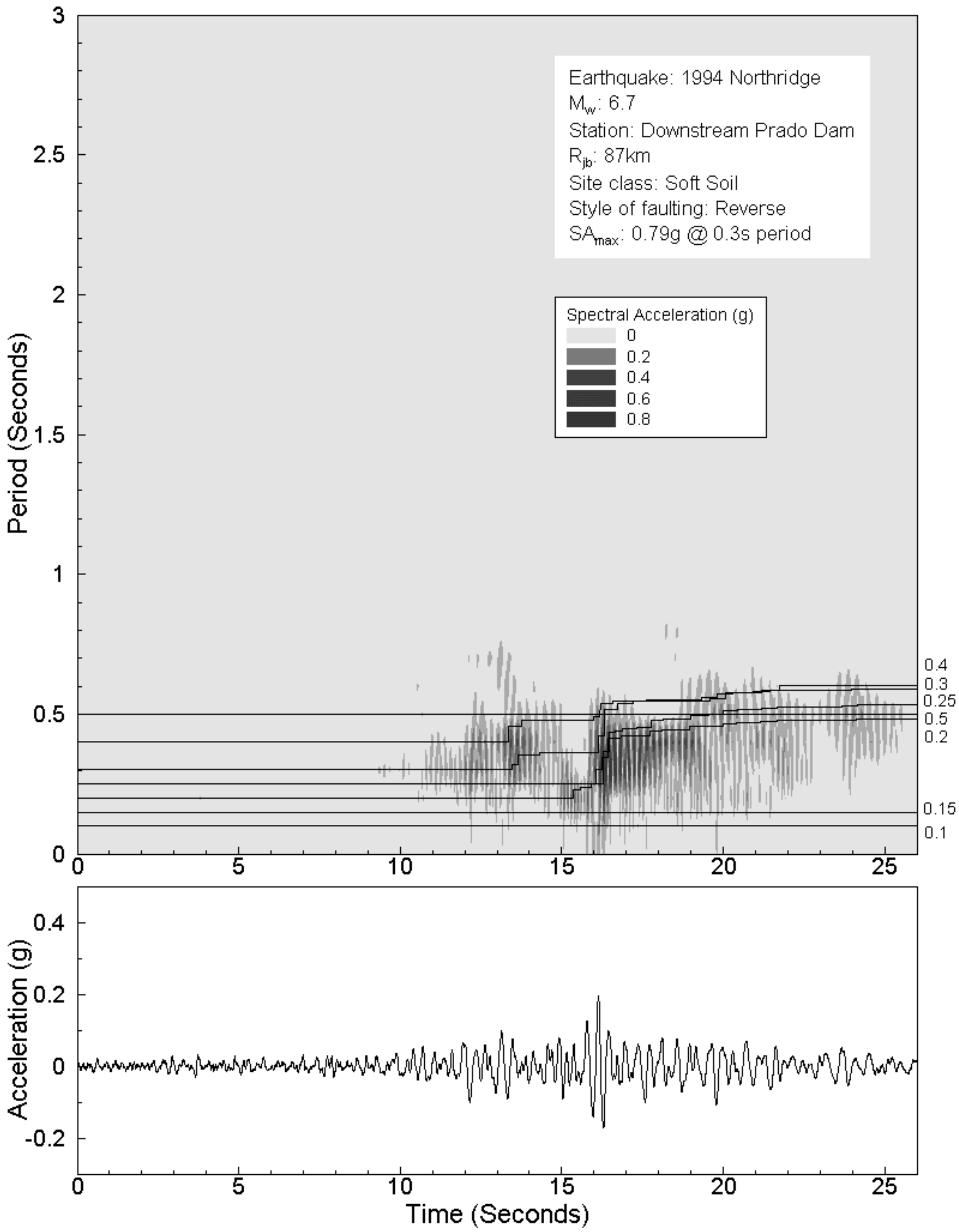

Figure 4: 3D response spectra for 1994 Northridge (6.7M_w) earthquake, recorded at 87 km from the fault rupture on soft soil downstream of the Prado dam. Solid black lines on response spectra show stiffness degradation of masonry structures with 0.1, 0.15, 0.2, 0.25, 0.3, 0.4 and 0.5s initial period.

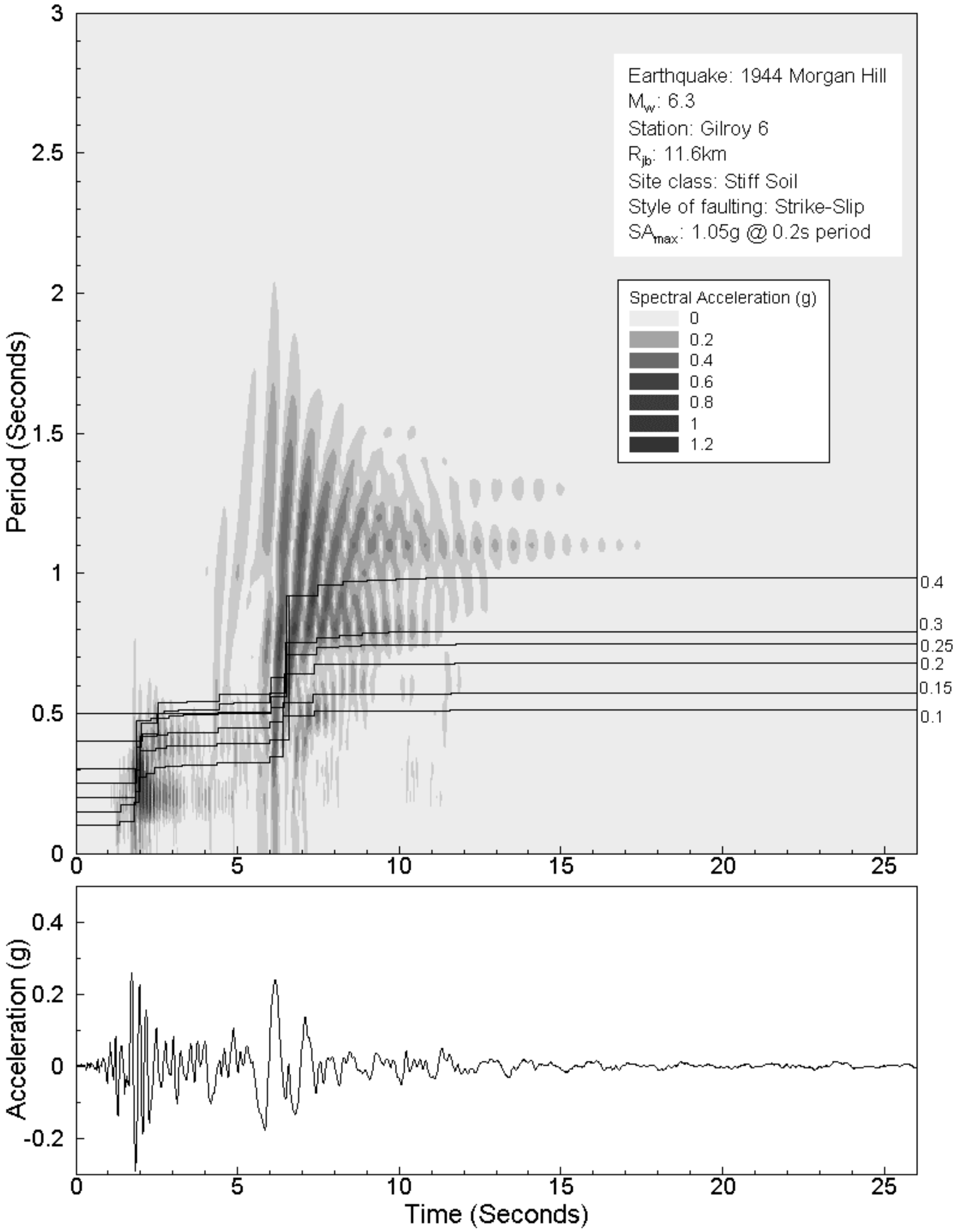

Figure 5: 3D response spectra for 1984 Morgan Hill (6.3M_w) earthquake, recorded at 11 km from the fault rupture on stiff soil at Gilroy 6. Solid black lines on response spectra show stiffness degradation of masonry structures with 0.1, 0.15, 0.2, 0.25, 0.3, 0.4 and 0.5s initial period. Analysis of 0.5s structure halted after 2% drift limit exceeded.

Ground motions containing strong velocity pulses are known to be particularly damaging. These pulses are characteristic of forward rupture directivity, where strong short duration pulses of ground motion are caused by the constructive interference of the seismic radiation as the fault rupture propagates towards the site (Sommerville *et al.* [30], Bommer *et al*. [31], Mavroeidis and Papageorgiou [32], Somerville [33]).

The reason that these motions are so destructive is explored by plotting a 3D response spectra of one such motion, the 6.7M_w 1994 Northridge earthquake, recorded at 2 km from the fault at West Pico Canyon Road (Figure 6). The most striking feature of this ground motion is the extent to which the strong accelerations progress into the longer periods. This is particularly damaging for masonry structures, as there is no decrease in loading as the period of the structure increases with progressive damage. The damaging potential of ground motions with large energy pulses is also recognized by Araya and Saragoni [34] who propose the parameter P_D to measure the potential for damage:

$$P_D = \frac{\int_0^{to} a_g^2 dt}{\nu_0^2} \tag{3}$$

where $\int_0^{to} a_g^2 dt$ is the Arias Intensity of the whole record and ν_0 is the frequency of zero crossings per second. Unfortunately, the P_D parameter was designed using stationary stochastic simulations and does not always behave as intended with recorded accelerograms. This is because the frequency of zero crossings in recorded ground motions varies with time (Joannon *et al.* [35]).

The difference between ground motions which produce completely different strength degradation, but are both recorded from the 6.7M_w 1994 Northridge earthquake on rock approximately 20km from the fault ruptures are investigated. The first ground motion was recorded at Castaic old ridge route and has forward directivity. This record has significant spectral accelerations which progress into the long period causing significant damage to structures over a range of initial periods (Figure 7). The second ground motion was recorded at Monte Nido fire station and has backward directivity. This ground motion has approximately twice the number of effective cycles than the motion with forward directivity (Hancock and Bommer [36]), but half the spectral acceleration, which is limited to lower periods (Figure 8). The low spectral amplitudes result in only slight damage, indeed the most heavily damaged structure with 0.1s initial period only has 6% strength degradation.

CONCLUSIONS

Plotting response spectra with time as a third axis has been used in the past to show the arrival of different seismic phases. This concept is extended and used to show that each group arrival progressively damages masonry structures. The severity of the loading and hence damage to structures with stiffness degrading characteristics is shown to be governed by the spectral amplitude of the ground motions. However, as masonry structures exhibit stiffness degradation the period of the critical spectral acceleration changes with time and is influenced by the phase difference and duration of the strong shaking.

The amplitude and frequency of the ground motions is shown to be critical to the level of damage. The 3D spectral intensity evaluated over a wide period range is poorly correlated to damage. Correlations are significantly improved by evaluating this parameter over the interval from the initial period of the structure T_o to T_oF, where F equals 3, as proposed by Bommer *et al.* [2]. Investigation of the remaining scatter in the predictions using 3D response spectra, show that differences occur as the 3D spectral intensity does not accurately capture the influence of the increase in period of structure as damage progresses.

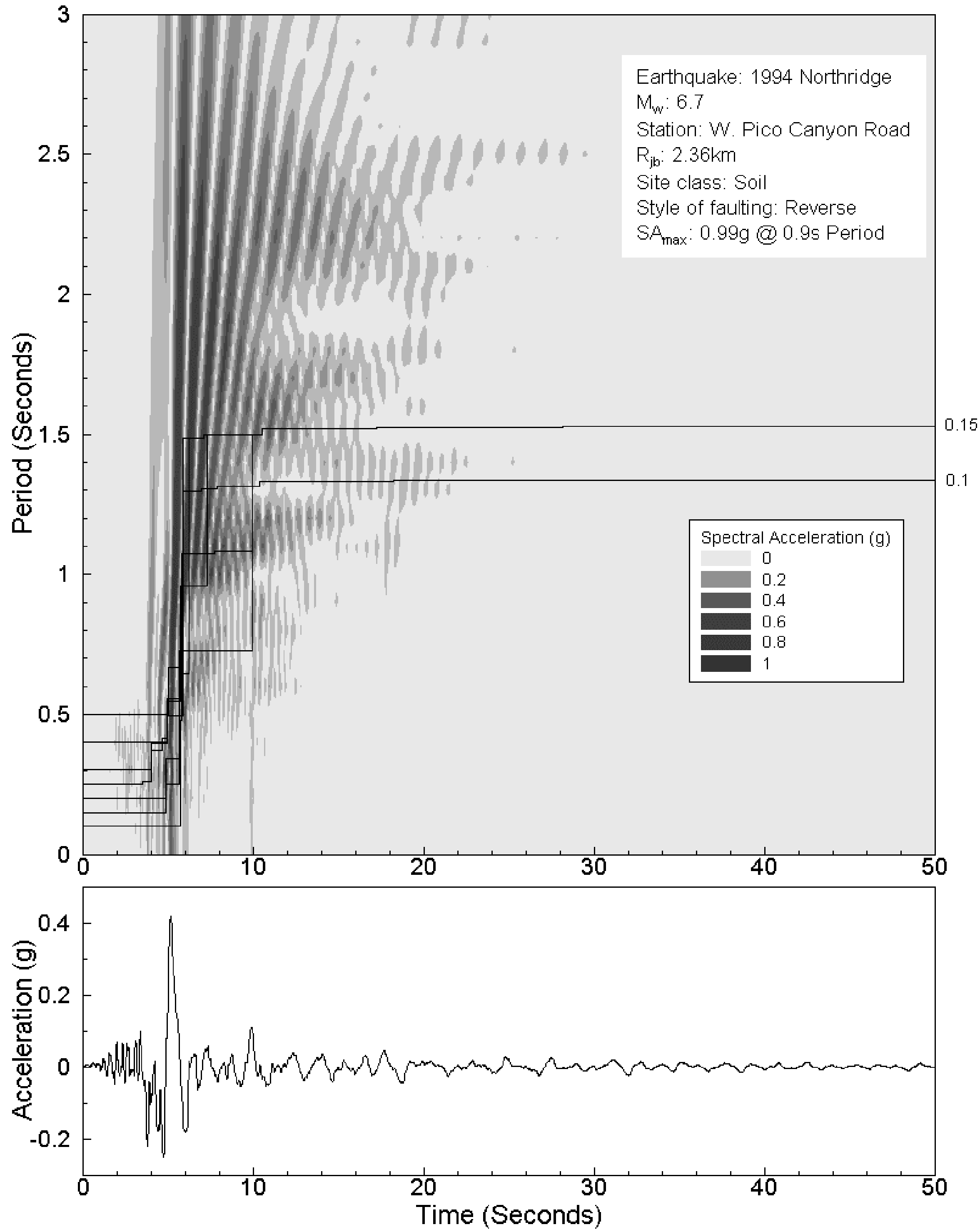

Figure 6: 3D response spectra for 1994 Northridge (6.7M_w) earthquake, recorded at 2 km from the fault rupture at West Pico Canyon Road. Solid black lines on response spectra show stiffness degradation of masonry structures with 0.1, 0.15, 0.2, 0.25, 0.3, 0.4 and 0.5s initial period. Analysis of 0.2-0.5s structures halted when 2% drift limit exceeded.

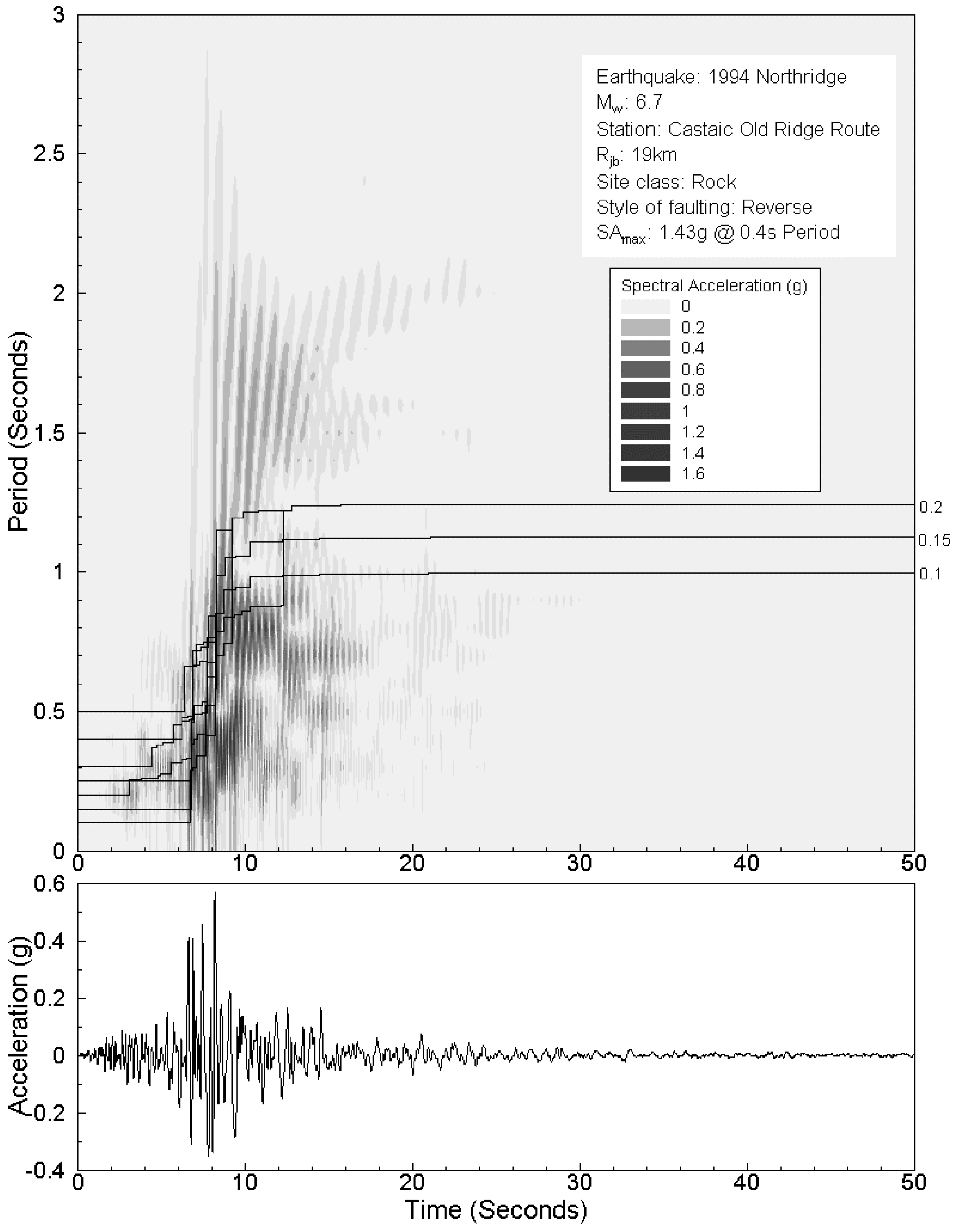

Figure 7: 3D response spectra for 1994 Northridge (6.7M_w) earthquake, recorded 19 km from the fault rupture at Castaic Old Ridge Route. Solid black lines on response spectra show stiffness degradation of masonry structures with 0.1, 0.15, 0.2, 0.25, 0.3, 0.4 and 0.5s initial period. Analysis of 0.25-0.5s structures halted after 2% drift limit exceeded.

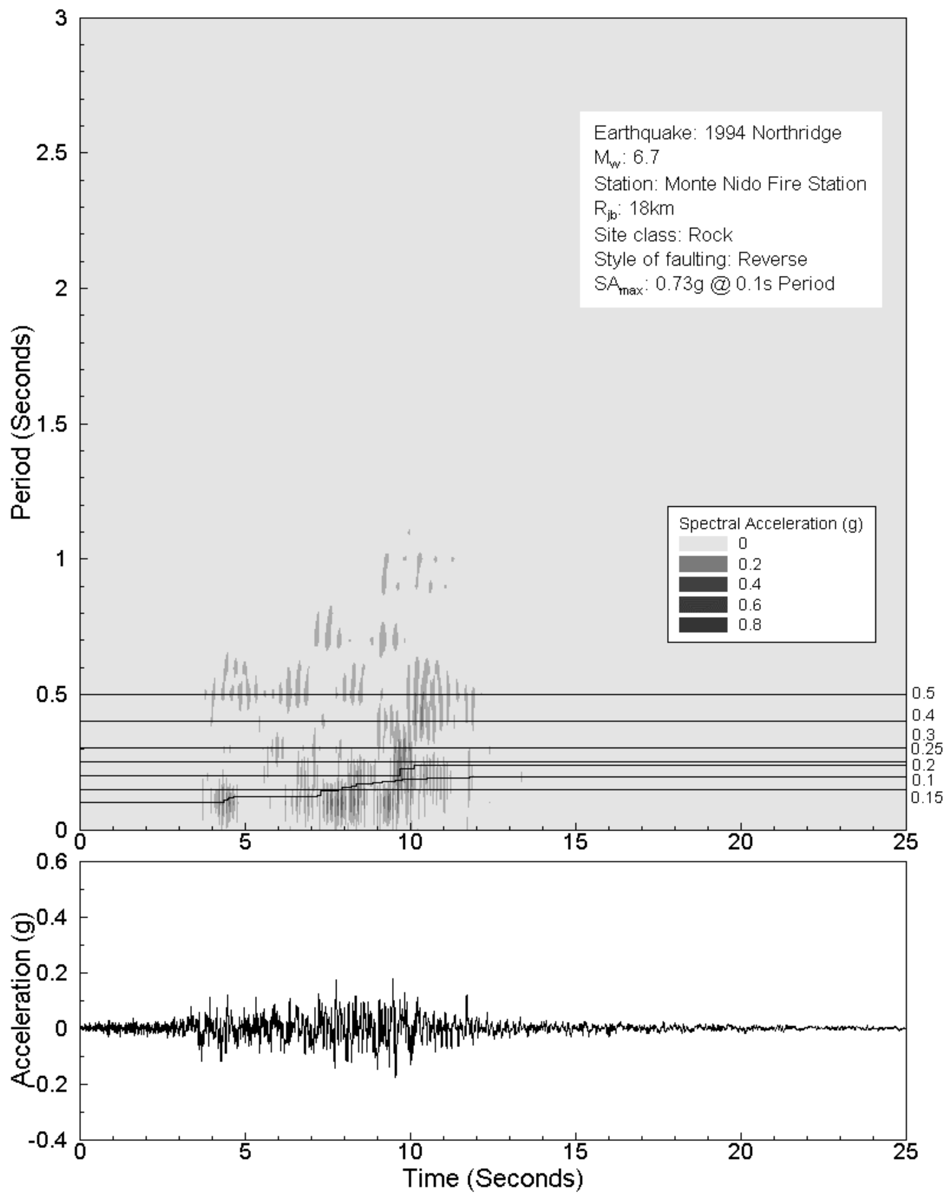

Figure 8: 3D response spectra for 1994 Northridge (6.7M_w) earthquake, recorded 18 km from the fault rupture at Monte Nido fire station. Solid black lines on response spectra show stiffness degradation of masonry structures with 0.1, 0.15, 0.2, 0.25, 0.3, 0.4 and 0.5s initial period.

From inspection of the 3D response spectra from many recorded ground motions it is seen that the phase, or difference in arrival time, of different seismic waves is not a significant issue when selecting *recorded* ground motions for analysis of degrading structures. This is because the high frequency waves in recorded ground motions invariably arrive before the long period waves, progressively loading the structure as its stiffness degrades. However, it is advisable that the phase content and duration of synthetically created ground motions have similar characteristics to that observed in recorded ground motions if they are to be used in the analysis of structures with degrading stiffness.

ACKNOWLEDGEMENTS

The authors are grateful to for Dr Guido Magenes for his computer program used to calculate the response of the masonry structures. The work of the first author is supported by a doctoral training grant from the EPSRC.

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