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PREDICTING THE NUMBER OF CYCLES OF GROUND MOTION

Jonathan HANCOCK[1] and Julian J. BOMMER[2]

SUMMARY

The seismic response of any system with degrading characteristics is dependent not only on the maximum amplitude of the motion but also its duration. This is explicitly recognised in methods for estimating the liquefaction potential of soil deposits and in the HAZUS methodology for assessing potential losses in the building stock due to earthquake shaking. Many researchers have proposed that the number of effective cycles of the ground motion are better than measures of duration for determining the destructiveness of the shaking. In liquefaction studies, it is generally the number of cycles of motion that is considered. However, as is the case with strong-motion duration, there is no universally accepted approach to determining the effective number of cycles of motion, and the different methods that have been proposed can give widely varying results for a particular accelerogram.

Definitions of the effective number of cycles of motion and associated equations for predicting this quantity for future earthquakes are reviewed, classified and compared. It is found that measurement and hence predictions are particularly different for accelerograms with broad banded frequency content, which contain significant number of non-zero crossing peaks. The implications of the cycle counting method for characterising ground motion are explored and suggestions are made as to the most appropriate techniques for each application. The key parameters influencing the number of cycles of motion are also investigated in order to identify the most appropriate form for predictive equations.

INTRODUCTION

Researchers and engineers dealing with earthquake actions use cycle counting definitions for a range of applications including the design and assessment of damage to structures and for liquefaction assessment. There are many different cycle counting definitions used, although these can be grouped into five generic categories:

1. Peak counting methods
2. Level crossing counting methods
3. Range counting methods
4. Indirect estimation methods
5. Definitions based on structural response

[1] Research Student, Imperial College London, UK Email: j.hancock01@imperial.ac.uk
[2] Reader in EQ Hazard Assessment, Imperial College London, UK. Email: j.bommer@imperial.ac.uk

All of these definitions may, or may not, count motions that do not cross the zero mean between cycles. This paper explores the different ways in which the number of cycles of motion are used in earthquake engineering. The definitions are classified into groups and differences highlighted. Finally, it is emphasised that researchers should be aware of the limitations of different cycle counting methods and should report the definition used in their work.

REVIEW OF DEFINITIONS OF NUMBER OF CYCLES

Many different approaches to identify and measure the number of cycles of accelerograms have been proposed by different researchers. These definitions are reviewed and evaluated in this section.

The following three sub-sections describe the main generic techniques used for direct cycle counting. These are loosely based on categories used for classifying cycle counting definitions developed for fatigue testing (ASTM [1]). Statistical techniques proposed by some authors for estimating the number of cycles indirectly, and definitions based on structural response are discussed in the fourth and fifth sub-sections respectively. Cycle counting definitions are illustrated using a 1 second section of an accelerogram recorded in the 3.9M_w 1985 Coalinga earthquake (Figure 1).

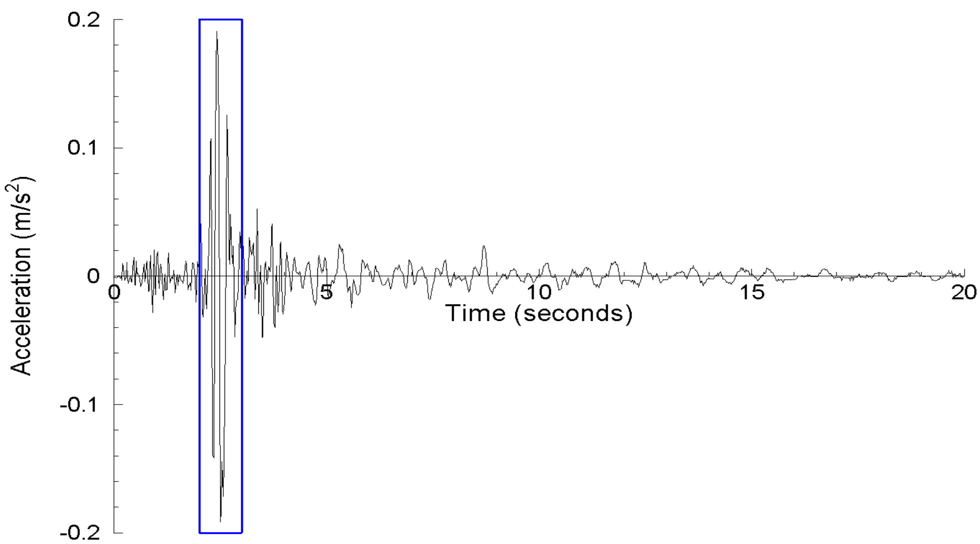

Figure 1: Accelerogram recorded for the 3.9M_w Coalinga earthquake recorded at 5.7km at Sulphur Baths. Box shows section of motion used for cycle counting examples.

To allow comparison of different cycle counting definitions, the irregular cycle amplitudes produced by each cycle counting definition are converted into a single damage parameter (D), as used by Malholtra [2]:

$$D = \sum_{i=1}^{2n} u_i^2 \tag{1}$$

where D is a measure of potential damage, u_i is the acceleration amplitude of the i^{th} half cycle and n is the number of cycles.

Before proceeding further, it is important to note the difference between cycle counting definitions and definitions of ground motion duration, reviews of which are undertaken by Bommer and Martinez-Pereira

[3] and [4]. Although the number of cycles of ground motion provide an indication of duration, most cycle counting techniques are used because they also contain a measure of the amplitude of the motion. It is also important to note that cycle counting definitions used for fatigue analysis typically measure cycle *ranges* (the distance between peak and trough), whilst those used in earthquake engineering almost exclusively count *amplitudes* (the distance between peak and the zero mean).

Peak Counting Definitions

Peak counting definitions are the most common definition used in earthquake engineering. They are used in a wide range of applications including damage estimation parameters and liquefaction potential. A cycle counting definition is classified as peak counting if it explicitly counts the number of peaks. There are several different variations of peak counting, the two main differences between definitions being:

1. Cut off level: to prevent many small peaks dominating the results some definitions do not count peaks below a low-amplitude cut off.
2. Zero crossing counting: some definitions only count the largest peaks between zero crossings, others count all peaks.

Figure 2 shows an example of a peak counting definition with no low amplitude cut off and where only zero crossing peaks are counted. The damage parameter evaluated using this definition is 0.127, if non-zero crossing peaks are included the parameter increases by 25% to 0.160.

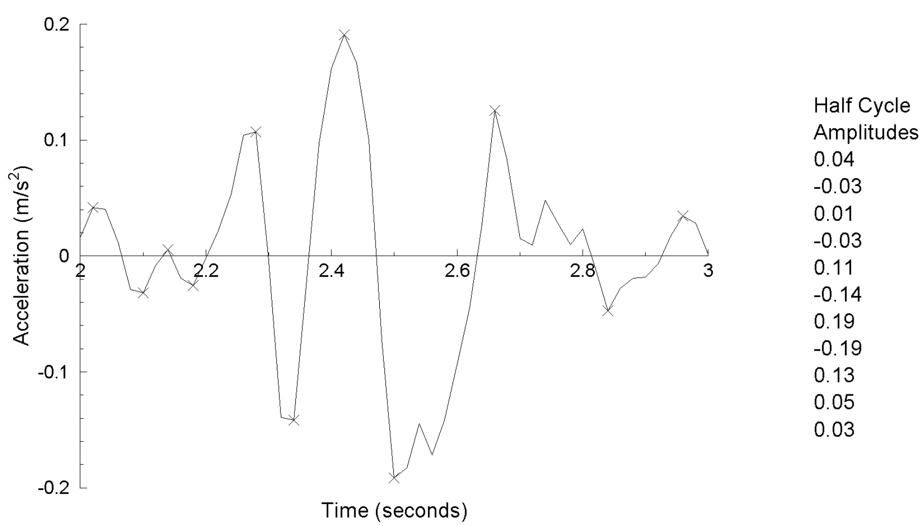

Figure 2: Peak counting example, with non-zero crossings excluded.

Level Crossing Definitions

Level crossing definitions are not normally used to measure amplitudes of motion but are commonly used to measure the period or frequency of the motion. The most common measure is the zero mean crossing period (e.g. Vanmarke and Lai [5]), however Sarma and Srbulov [6] propose that other levels can be used. They define the frequency as half the number of excursions above a set level, divided by the duration spent above the level (the uniform duration as proposed by Sarma and Casey [7]). It is the convention in cycle counting (ASTM, [1]) to count only level crossings with positive gradient on the positive axis and crossings with a negative gradient on the negative axis (Figure 3).

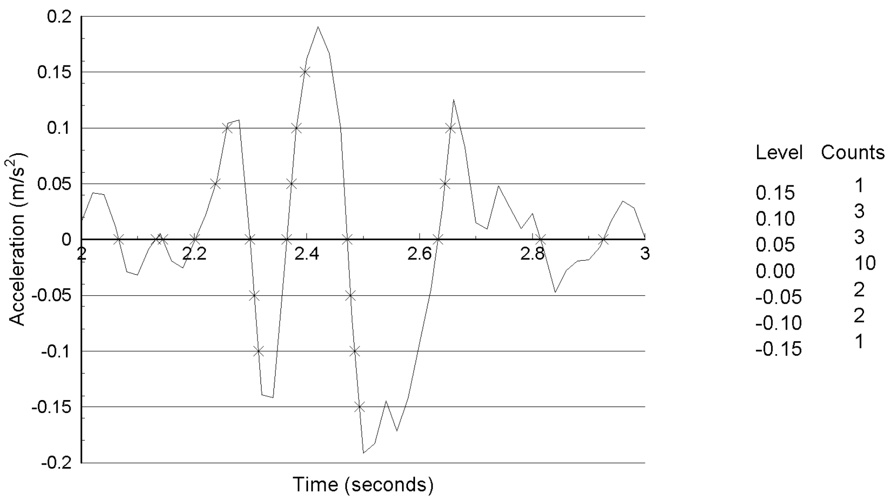

Figure 3: Level crossing example, with non-zero crossings excluded.

Range Counting Definitions

Range counting definitions are most commonly used for the analysis of fatigue. In earthquake engineering this is related to problems such as the assessment of low-cycle fatigue, typically in the joints of steel framed buildings (e.g. Calado et al. [8]; Calado et al. [9]; Mander et al. [10]; Taucer et al. [11]; Tremblay and Bouatay [13]). These principles have also been extended for use with reinforced concrete structures (e.g. Dutta and Mander [12]). The most popular range counting method is the rainflow range counting method as it counts both high-and low-frequency cycles in broad-banded signals. This procedure is used to count the number of cycles in the time series as shown in Figure 4. The rainflow counting method, as described by ASTM [1], is shown in Figure 5. It is not possible to determine peak amplitudes from cycle ranges for motions with irregular amplitude, however, for the purpose of this paper cycle ranges are converted to peaks assuming two half-cycle ranges equal one peak and one full cycle can be taken as two half cycles of half the amplitude. This gives the damage parameter calculated using rainflow counting is 0.18, a factor of 1.4 greater than that predicted by zero crossing peak counting definitions.

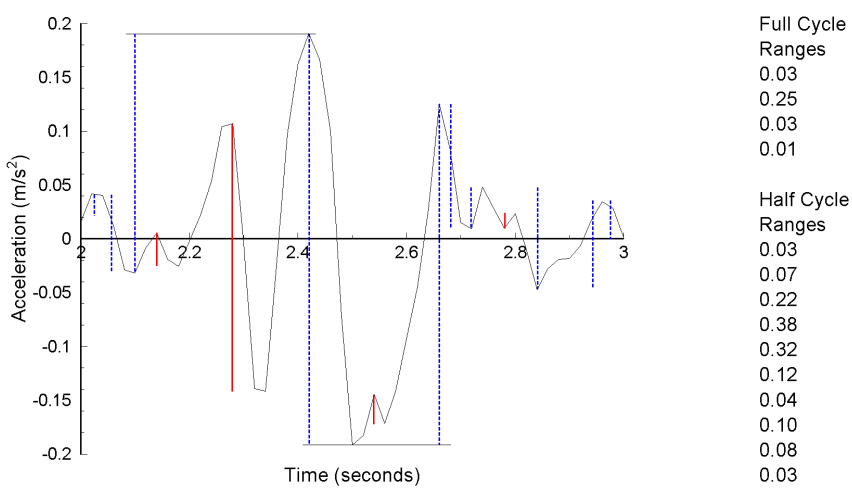

Figure 4: Range counting example using rainflow counting technique, solid lines show full cycles, dashed lines show half cycles.

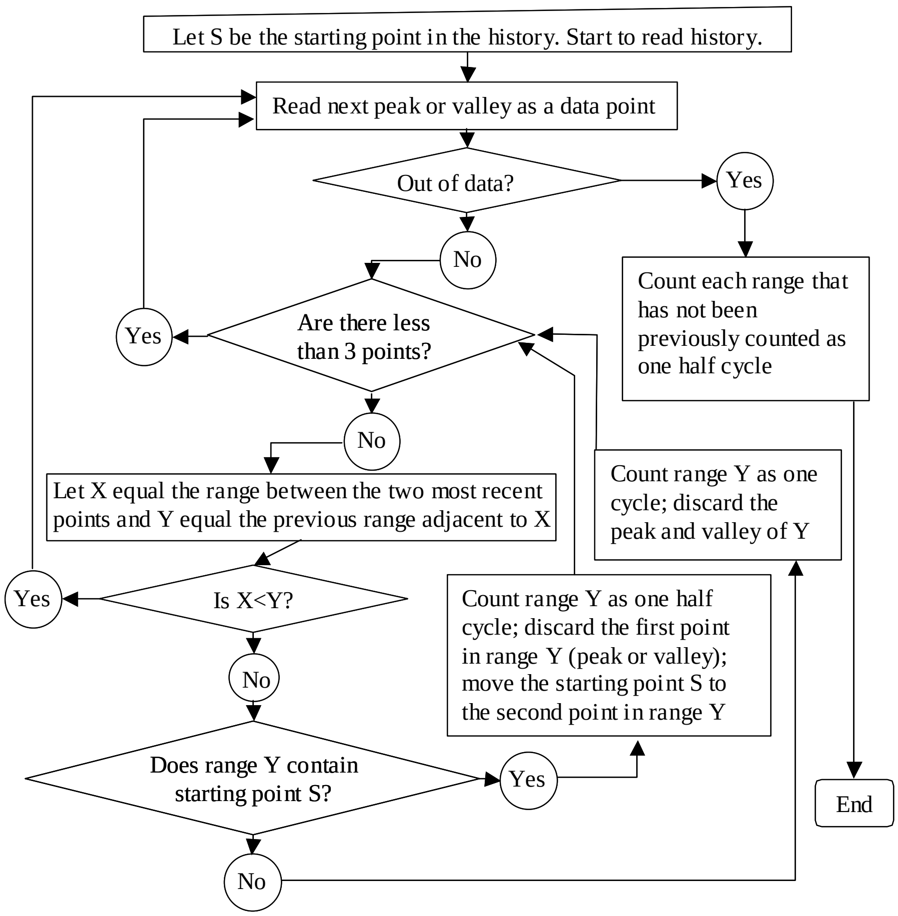

Figure 5: Rainflow counting procedure

Indirect Counting Methods

Indirect counting methods are those that do not count the number of cycles directly from a time series, but use statistical techniques to approximate the number of cycles. The most common are definitions based on random vibration theory, which use spectral moments to determine the predominant frequency and hence the number of extreme peaks per unit time (e.g. Boore [14]). Most of these definitions assume that the peaks are not strongly correlated and are part of a stationary process. The method given by Boore [14] to determine the number of extreme responses, N, in time interval T is:

$$N = 2\tilde{f}T \tag{2}$$

where $\tilde{f}$ is the predominant frequency, given by:

$$\tilde{f} = \frac{1}{2\pi}\left(m_4 / m_2\right)^{1/2} \tag{3}$$

m_2 and m_4 are the second and fourth spectral moments respectively, given by:

$$m_2 = \frac{1}{\pi}\int_0^\infty \omega^2 \left|A(\omega)\right|^2 d\omega \tag{4}$$

$$m_4 = \frac{1}{\pi}\int_0^{\infty} \omega^4 |A(\omega)|^2 d\omega \tag{5}$$

where ω is the circular frequency and $A(\omega)$ is the acceleration spectrum. Almini and Trifunac [15]; Gupta [16] and [17]; Gupta and Trifunac [18] and [19] point out that real accelerograms are non-stationary and use order statistics to derive the effective peak acceleration of a stationary accelerogram. Elghadamsi *et al.* [20] over come this issue by modelling strong ground motion with a stationary component plus a non-stationary envelope function.

Definitions Based on Structural Response

A number of authors measure a parameter related to structural response and use this to determine a number of effective cycles of motion. This is usually based on the approach suggested by Zahrah and Hall [21] who determine the equivalent number of yield cycles n_{eq} by dividing the total hysteretic energy (E_H) by the equivalent energy that would be absorbed had the structure been loaded monotonically to the same maximum displacement. This definition of the number of equivalent cycles can be defined using an elasto-plastic model and used as a comparative index to assess the severity of ground-motion:

$$n_{eq} = \frac{E_H}{F_y.(x_{\max} - x_y)} \tag{6}$$

where F_y is the yielding force, x_{max} is the maximum displacement and x_y is the yield displacement. The physical concept of this parameter is illustrated in Figure 6. Manfredi *et al.* [22] find that the number of equivalent cycles defined in this way increases with distance from the fault although the peak demand decreases.

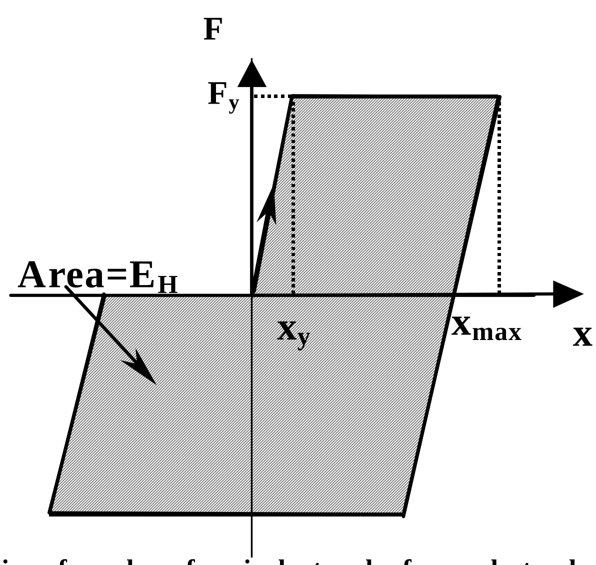

Figure 6: Illustration of number of equivalent cycles for an elasto-plastic system.

Table 1 contains a summary of different cycle counting definitions used by different authors.

Table 1: Summary of cycle counting definitions proposed by different authors

Generic Category	Level Crossing		Peak Count		Range Count		Indirect/ Structural
Non-zero Counted	Yes	No	Yes	No	Yes	No	Method
Reference:							
Ambraseys and Sarma [31]				x			
Lee and Chan [29]			o	o			
Trifunac and Westermo [32]							x
Joannon *et al.* [33]							x
Mortgat [34]			o	o			
Vanmarke and Lai [35]		x					
Araya and Saragoni [36]		x					
Amini and Trifunac [15]							x
Bolt and Abrahamson [25]				x			
Boore [14]							x
Zahrah and Hall [21]							Δ
Saragoni [37]		x					
ASTM [1]	x	x	x	x	x		
Kawashima and Aizawa [38]			o	o			
Sarma and Yang [39]				x			
Jeong and Iwan [23]				x			x
Joyner and Boore [40]							x
Siddharthan [41]					x		
Saragoni [42]		x					
Gupta [16]							x
Gupta [17]; Gupta and Trifunac [43]							x
Manzocchi *et al.* [44]				x			
Mander *et al.* [10]					o	o	
Gupta and Trifunac [45]							x
Safak [46]	o	o					
Basu and Gupta [47]	o	o					x
Calado *et al.* [48]					x		
Sarma and Srbulov [6]	o	o					
Gupta and Trifunac [18]	x	x					x
Schwarz [26]			o	o			
Bursi and Caldara [49]					x		
Perera *et al.* [50]					x		
Taucer *et al.* [11]					o	o	
Liu *et al.* [30]			x				
Manfredi [51]							Δ
Stewart *et al.* [52]			x				
Calado *et al.* [9]					x		
Erberik and Sucuoglu [53]				x			
Tremblay and Bouatay [12]					x		
Malhotra [2]			o	o			Δ
Manfredi [22]							Δ

o = zero crossing counting method not specified, Δ =Structural method

USES OF CYCLE COUNTING

Structural Applications

Low cycle fatigue damage measures are widely used in earthquake engineering (e.g. Jeong and Iwan [23], Mander *et al.* [10], Malholtra [2]). Fatigue based damage measures accumulate damage as the structure displaces, recognising that failure can be caused by a single large amplitude motion or several smaller amplitude motions. An example of a simple damage measure of this type is that used by Malhotra [2], (Equation 1).

Effective peak ground motion definitions based on the amplitude of secondary cycles of ground motion have been developed by several authors (e.g. Mortgat [24], Bolt and Abrahamson [25], Schwarz [26]). The effective peak of motion is a better measure of the destructiveness of the shaking than the maximum amplitude, because it provides a more realistic estimation of damage of near-field ground motions from small magnitude earthquakes. The high acceleration peaks of these events are only sustained for a few cycles, the energy content is low, and properly designed structures experience little or no damage. The HAZUS methodology for assessing potential losses in building stock to earthquake shaking also recognises that the number of cycles of motion is important and makes use of a magnitude correction to reduce the influence of small magnitude events (Kircher *et al* [27]).

Liquefaction Applications

Cyclic loading of saturated or partially saturated granular soil during an earthquake causes pore water pressure to increase with each cycle. With sufficiently severe loading conditions some soil types reach a critical state where the pore water pressure are so high that the effective stress is reduced to critically low levels. This results in a dramatic loss of strength, liquefaction of the soil and constitutes a serious hazard to any overlying structures or slopes.

Current techniques used to assess liquefaction potential are based on results from laboratory testing of soils under uniform cycles of loading and on observations of soils in the field after earthquakes (Youd and Idriss [28]). Techniques similar to those used in fatigue analysis are used to convert irregular ground motions to uniform amplitude cycles, enabling the results of laboratory tests to be used to interpret field observations of liquefaction (e.g. Lee and Chan [29] and Liu *et al.* [30])

PREDICTING THE NUMBER OF CYCLES OF MOTION

This section describes the parameters that influence the number of cycles of ground motion. The cycles of motion are expressed in terms of the number of effective cycles (N_{cy}), as used by Malholtra [2] to enable easy comparison of results:

$$N_{cy} = \frac{1}{2}.\sum_{i=1}^{2n}\left(\frac{u_i}{u_{\max}}\right)^2 \tag{7}$$

where u_{max} is the amplitude of the largest half cycle, u_i is the amplitude of the i^{th} half cycle and n is the total number of cycles.

Ground Motions with Broad-banded Frequency Content

Non-zero crossings in any time history, including ground and structural motions, occur when the signal has broad banded frequency content. As discussed in the previous section, the presence of non-zero crossings is particularly important as it causes differences in the number of cycles estimated by different cycle counting definitions.

Several researchers have developed response spectra including the number of cycles of motion (e.g. Safak [46], Malholtra [2], Kawashima and Aizawa [38]). These spectra show the amplitude of the secondary peaks of motion as well as the maximum peak traditionally displayed on a response spectra. As the response spectra are produced from the motion of elastic single degree of freedom (SDOF) systems some authors have suggested that the motion will be narrow banded, containing only zero crossing peaks. However, examination of the actual motion shows that only the response of SDOF systems with periods lower than the dominant period of the ground motion are narrow banded. This is illustrated in Figure 7 which shows the displacement time histories of 2.5s and 0.5s SDOF systems with 5% damping under the action of ground motions recorded 32km from the fault at Shelter Cove 2 from the 1992 7.1M_w Cape Mendocino (Petrolia) earthquake. The motion of the 0.5s SDOF system has few non-zero crossing peaks, while the 2.5s SDOF system has many. The Fourier transform of the motions (Figure 8) shows that the motion of the 2.5s SDOF system retains the broad-banded frequency content of the ground motion whist 0.5s SDOF system effectively filters out the broad-banded content of the ground motion.

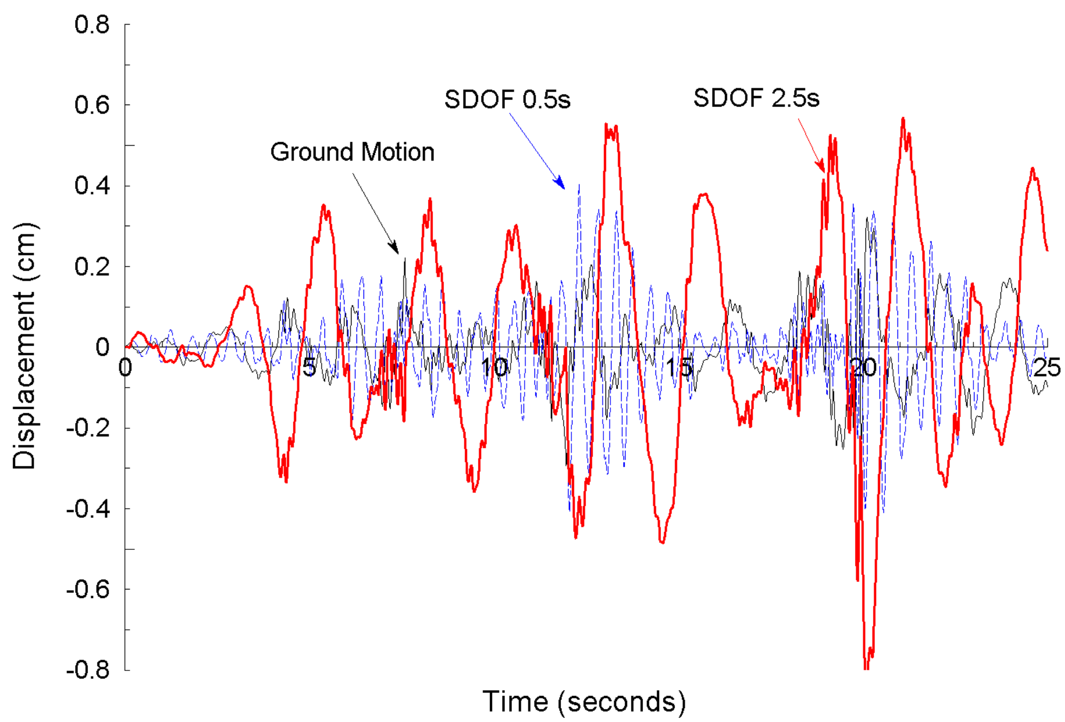

Figure 7: Displacement time histories of 2.5s and 0.5s SDOF systems with 5% damping under the action of 1992 7.1M_w Cape Mendocino (Petrolia) earthquake ground motions recorded 32km from the fault at Shelter Cove 2 (stiff soil).

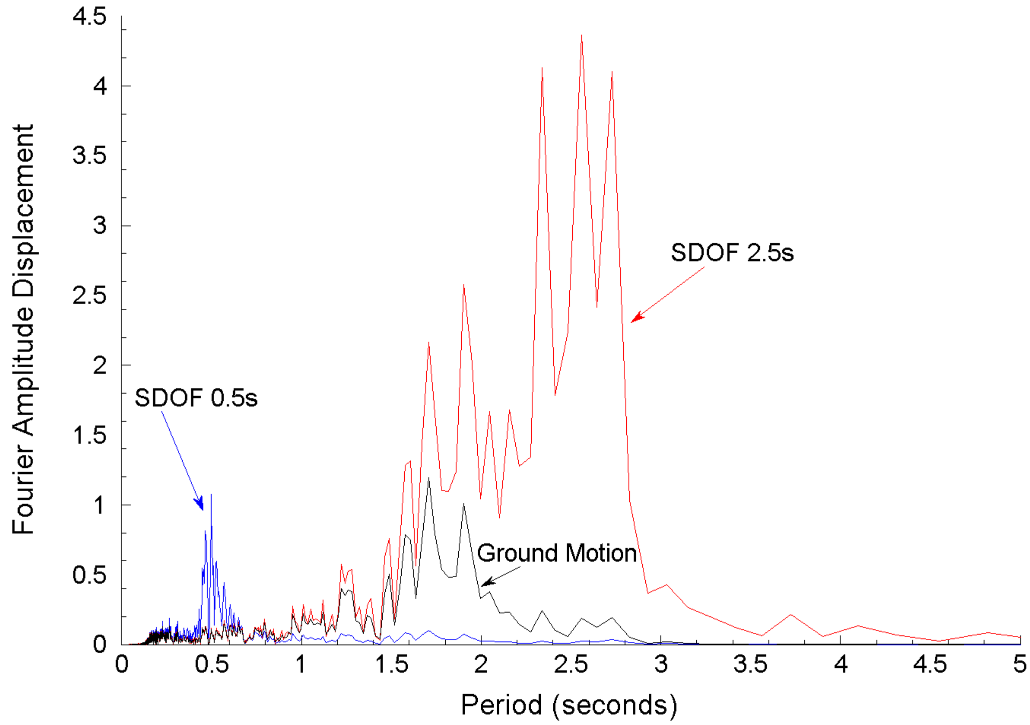

Figure 8: Fourier amplitude spectra of the time histories shown in Figure 7.

The Influence of Earthquake Magnitude

The influence of magnitude on the number of effective cycles is investigated using 28 strong-motion accelerograms from crustal earthquakes, with magnitudes ranging from 3.9M_w to 7.8M_w. All accelerograms were recorded at sites classified as rock, at distances between 5 and 20km from the surface projection of the fault. The accelerograms have been selected from the dataset used by Bommer *et al.* 2004 [54].

The number of effective acceleration cycles (Equation 7) is calculated for each record using rainflow range counting, peak counting including and excluding non-zero crossings (Figure 9). The number of cycles and bandwidth of the ground motion is intrinsically linked to the size of the rupture and earthquake magnitude. As would be expected larger magnitude earthquakes generally produce ground motions with greater numbers of effective cycles. Different functional forms relating the number of cycles to earthquake magnitude are investigated. Although the scatter in the results is significant, exponential magnitude dependence gives the greatest coefficient of determination, R^2 (Figure 9). Part of the scatter may be caused by rupture directivity, one of the accelerograms with remarkably large number of cycles is that of the 1994 6.7M_w Northridge earthquake recorded at Monte Nido Fire Station. This record has backward directivity and is discussed in the following section.

Small magnitude earthquakes rupture over a small area and produce high frequency ground motions, which are typically narrow-banded. These motions contain few non-zero crossing peaks so both peak counting definitions converge for small magnitude events (Figure 9). For the records used in this example, the rainflow counting definition gives consistently higher numbers of effective cycles than peak counting definitions. However, this is not always the case but depends on the amplitude of the non-zero crossing peaks and troughs in the time history.

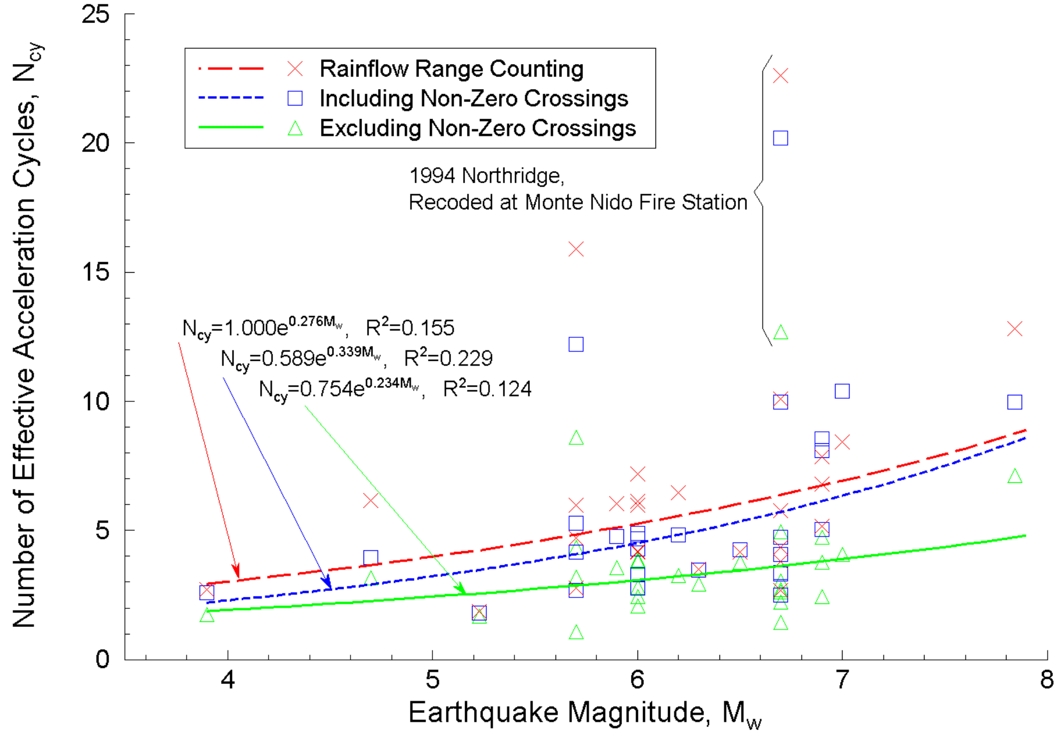

Figure 9: Relationship between number of effective cycles and earthquake magnitude, exponential trend lines shown by dashed and solid lines.

Source-to-Site Distance

The number of effective cycles in 78 accelerograms from the 1994 6.7M_w Northridge earthquake is calculated to investigate the influence of site-to-source distance (Figure 10). Distances are defined as the closest distance from the surface projection of the fault to the site (R_{jb}), as proposed by Joyner and Boore [55]. The Rainflow range counting, non-zero crossing and zero crossing peak counting methods are used. Trend lines indicate that the number of effective cycles increase with distance. However, the increase is small, approximately one cycle in 30km, and the scatter in the data leads the coefficients of determination, R^2, to be less than 0.04 for all forms of trend line.

The scatter in the prediction is investigated further by plotting two of the accelerograms recorded on rock at approximately 20km from the fault (Figure 11). The difference appears to be caused by rupture directivity (Sommerville *et al.* [56]). The accelerogram recorded at Castic (Old Ridge Route) has forward directivity, causing fewer acceleration peaks with longer period and larger amplitude. The accelerogram recorded at Monte Nido Fire Station has backward directivity, which results in a greater number of acceleration peaks, although these have lower amplitude. It is interesting to note that the record with forward directivity has a damage parameter (equation 1) approximately twice that of the record with reverse directivity, although it only contains a quarter of the number of effective cycles. This illustrates that damage is caused by a combination of cycle amplitude and the number of cycles.

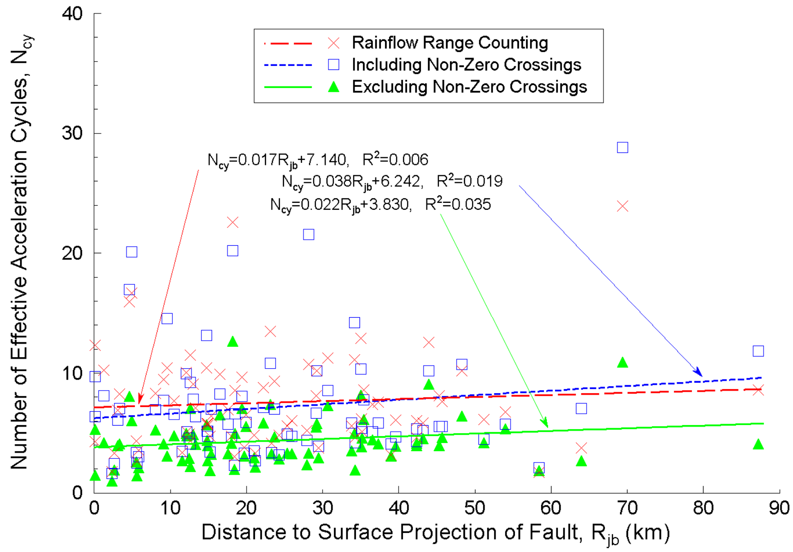

Figure 10: Relationship between number of effective cycles and source-to-site distance for 78 accelerograms from the 1994 6.7M_w Northridge earthquake; linear trend lines shown by dashed and solid lines.

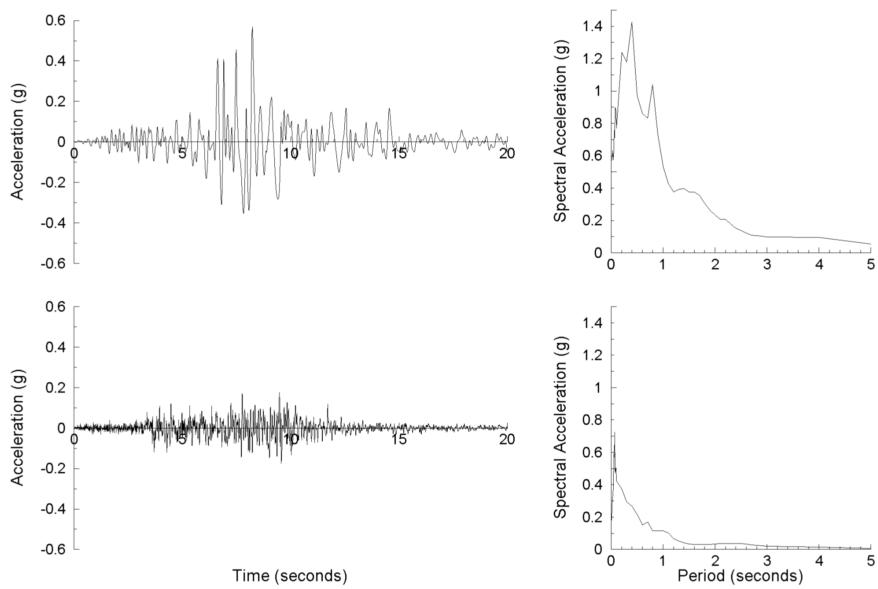

Figure 12: Accelerograms and response spectra from the 1994 6.7M_w Northridge earthquake, recorded at Castaic – Old Ridge Route (upper) and Monte Nido Fire Station (lower), both stations on rock approximately 20km from the fault.

CONCLUSIONS

Definitions of the number of cycles of earthquake-induced motion have been reviewed, classified and compared. Motions with broad-banded frequency content contain significant number of non-zero crossing peaks, which results in significant differences in the number of cycles counted using different definitions. The use of a SDOF system with period smaller than the dominant period of the ground motion filters out broad-banded response. However, the motion of structures with long natural period, such as tall buildings and bridges, is likely to be broad-banded so it is particularly important to use a cycle counting definition that can allow for this, such as Rainflow counting.

As would be expected, the motions from larger magnitude earthquakes are found to have a greater number of effective cycles. Ground motions from large magnitude earthquakes also have broad-banded frequency content so again the cycle counting definition used is important. The number of effective acceleration cycles is found to increase with distance from the fault. However, the increase is small, approximately one cycle in 30km, and the scatter in the data leads the coefficients of determination (R^2) to be very low. Rupture directivity is shown to have an important influence on the number of cycles in near-field ground motions. Finally, it is emphasized that engineers and researchers using cycle counting should state the definition used when reporting their work.

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