



ADAPTATION OF REAL EARTHQUAKE RECORDS TO PROVIDE RESPONSE SPECTRUM COMPATIBLE TIME HISTORIES FOR THE DESIGN OF STRUCTURES

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1.0 ABSTRACT

Analysis of the performance of structures under dynamic seismic loading has long been a requirement for any design team seeking to provide a safe and robust nuclear structure. The challenge facing engineers is to provide safe and robust designs, without resorting to overly simplified methods that result in unrealistic and expensive solutions. One technique recently questioned is the qualification of structures using earthquake time history records that are artificially generated in order to match a design response spectrum.

This paper presents a method for producing spectrum compatible records that are based on the manipulation of real earthquake records, rather than records created artificially. A description is given as to how appropriate real earthquake records may be selected from a database and then modified mathematically in order to ensure a close match with the target response spectrum. To arrive at high quality spectrum compatible records preparatory processing steps involving scaling of the original earthquake history must be made. This is followed by adding wavelets to the acceleration time history record to adjust the accelerogram such that it will more closely match a target response spectrum.

It will be demonstrated that the modifications proposed in this method do not alter significant characteristics of the real record. This paper therefore provides nuclear plant & equipment designers with a technique for establishing spectrum compatible time histories based on real earthquake records and yielding superior results to those traditionally obtained when using SIMQKE (Gasparini 1976) or similar codes which do not retain the characteristics of real earthquakes.

2.0 INTRODUCTION

In the design of earthquake resistant structures it is usual to represent the expected level of seismic ground motion by means of response spectra, either in displacement or acceleration format. The design response spectrum used in the design of nuclear facilities encompasses the seismic hazard for the area in question.

Ground motion prediction equations and Probabilistic Seismic Hazard Assessment (PSHA) are used by specialist geotechnical engineers and scientists in order to make provision for the uncertainty involved in ground motion predictions for some future postulated event. The design spectrum for the Sellafield nuclear facility in the UK is shown in Figure 1 and equates to an annual probability of exceedance of 10^{-4} (return period of 10,000 years), on which seismic design of nuclear facilities in the UK is based.

The aim of this paper is however, not to become submerged in the technicalities of how design response spectra are developed since this is generally outside the remit of the practising structural engineer who, presented with a design spectrum, simply wishes to design a structure to withstand it.

While the use of a design response spectrum may generally enable the analysis of a structure to be completed, there are occasions when this may not be the most appropriate method. For instance, structures that are extensive in plan or cannot be characterised by linear modal analysis due to material or geometric property variations, or when the conservatism of the response spectrum method gives too great an economic penalty. Sometimes a structure is so important to safety that full dynamic modelling is

required in which non-linear response characteristics can be included. In cases such as these a full time history analysis is required rather than analysis by the elastic design spectrum method. The question for the structural engineer therefore arises as to what time history data is to be used since the design code that is being followed will invariably expect conformity with an elastic response spectrum.

Historically, artificial earthquake time history records compatible with design response spectra have been generated using codes such as SIMQKE and these used for structural design purposes. Some of the reasons for the popularity of SIMQKE was that it produced time history data that was considered sufficiently compatible with the target design spectrum and it was readily available. However, such artificially generated records can have significant drawbacks and seldom represent all the characteristics of real earthquakes. For example, Figure 2 (Bommer 2004) illustrates SIMQKE generated accelerograms generated to match the S1 soil category elastic response spectrum from the French seismic design code. While these artificial records match the target spectrum very well, it is evident, even through cursory examination, that they do not resemble the characteristics normally seen in accelerograms from real earthquake records. Most noteworthy is that the acceleration does not noticeably reduce with time as in a real record. This may lead to an excessive number of acceleration cycles being applied to the structure. For these and other reasons, the use of artificially generated records is now viewed to be largely unjustifiable –it generally being recognized in the literature (Beyer 2007 & others) that a more suitable approach is required.

A generation ago only a very small database of measured earthquake records existed. The paucity of real records made the task of utilizing such records in dynamic analysis virtually impossible. In 2013 it can no longer be said that there is a paucity of real earthquake records. Indeed there is an abundance of good quality data now available. This paper reports how response spectrum compatible time histories suitable for structural design can be developed that are based on the manipulation of real earthquake records, rather than records created artificially. A method is described by which a practicing structural engineer may select, and manipulate a real earthquake acceleration record to obtain a close match to a target design response spectrum, and yet maintain the record's characteristics.

3.0 RECORD SELECTION

Record selection described in this paper has been applied specifically to develop time histories compatible with a UK design basis earthquake, although the method can readily be extended to apply to other geographical regions. Irrespective of the region concerned, record selection is based on two important considerations. The first relates to the target elastic response spectrum, the second to the structure of interest itself. The design response spectra have remained unchanged in the UK since the results of studies were first published (Principia Mechanica 1981). These are used in this paper and the investigation is limited to the 'medium' soil category, although the method applies equally to other site conditions.

Consideration of a specific structure enables information about site characteristics, and the period range of interest to be known. In this way any dominating magnitude-distance scenario can be considered. However, as this paper focuses on the methodology underpinning record selection and manipulation, no specific structure with its associated site characteristics is being considered. Hence a generic approach applicable to UK earthquakes based on an annual probability of exceedance of 1 in 10,000 has been used, based on information from Musson (2004). Therefore, selection has been based on the following criteria applicable to the UK:

- Magnitude Mw 5.8 < Mw < 6.6
- Epicentral Distance ED 0 < ED < 60km
- Focal Depth FD 0 < FD < 30km
- Site Characteristic Medium soil stiffness

In the above selection criteria the magnitude has the most significant effect on spectral shape and is therefore an important factor in record selection. Epicentral distance has only a limited influence on spectral shape. In order to ensure that records from subduction earthquakes are not included, the maximum focal depth parameter is also used.

3.1 Sources of Real Earthquake Records

In terms of locating an appropriate real earthquake record, there are now available many databases containing thousands of records from around the world. For instance the Pacific Earthquake Engineering Research Center (PEER) has a ground motion database containing in excess of 3000 earthquake records from diverse global locations. The PEER database can be accessed online at http://peer.berkeley.edu/peer_ground_motion_database.

Similarly, the Consortium of Organisations for Strong Motion Observation Systems (COSMOS) also has an extensive database of more than 4000 freely available earthquake records from around the world. These may be accessed via <http://db.cosmos-eq.org>.

The European Strong-Motion Database (ESMD) was compiled as part of the 5th Framework Programme of the European Union (Ambraseys 2004). The work was released in CD form in March 2004 and contains corrected acceleration, velocity and displacement time-histories of 462 triaxial strong-motion records from 110 earthquakes and 261 stations in Europe and the Middle East.

Other databases containing earthquake strong motion records are readily available.

3.2 Results of ESMD Search

The search of earthquake records for this paper was limited to the ESMD database which, using the above selection criteria and discarding records from non free-field stations, yielded 23 records for medium soil type. With the initial search based on geophysical criteria alone now completed, the degree of spectral match of each record with the target spectrum needs to be calculated. The appropriate method for spectral matching has been the subject of much debate.

4.0 SPECTRAL MATCHING

Ambraseys et al (2004) proposed a formula (equation 1) to evaluate the spectral compatibility, based on the average root-mean-square deviation of a selected spectrum from the target spectrum:

$$D_{rms} = \frac{1}{N} \sqrt{\sum_{i=1}^N \left(\frac{SA_o(T_i)}{PGA_o} - \frac{SA_s(T_i)}{PGA_s} \right)^2} \quad (1)$$

where

- N is the number of periods at which the spectral shape is specified
- $SA_o(T_i)$ is the spectral acceleration of the record at period T_i
- $SA_s(T_i)$ is the target spectral acceleration at the same spectral period
- PGA_o is the peak ground acceleration of the record
- PGA_s is the zero-period anchor point of the target spectrum respectively.

Clearly, the smaller the value of D_{rms} , the closer the match between the record and the target. Although this method of evaluating spectral compatibility limits the maximum deviation on the spectrum from the target, it also normalises both real and target record by their respective PGA values. PGA is a second order consideration compared with the spectral values over a period range of interest to the structure. Hence although equation (1) provides for identical spectral values over the range of periods of

interest in terms of the structure in question, the fact that the PGA differs can adversely affect the D_{rms} value and result in the record not being selected. Therefore, use of equation (1) is not considered to be ideal for engineering applications.

Various refinements on the calculation of D_{rms} have been proposed for example Beyer (2007) and Iervolino (2008). Each of these suffer various shortcomings as discussed in the literature whether these be biased towards the requirement of a specific design code or biased towards target spectrum accelerations that have the highest amplitudes. Hence the method of D_{rms} calculation favoured by NNL is given by equation (2) which makes use of the fact that spectral accelerations are lognormally distributed and that the target spectrum normally corresponds to the median (logarithmic mean) level for a scenario. Equation (2) is similar to that published by Kottke and Rathje (2008).

$$D_{rms} = \sqrt{\frac{1}{k-j+1} \sum_{i=j}^k (\ln[\alpha S_{a,R}(T_i)] - \ln[S_{a,T}(T_i)])^2} \quad (2)$$

In equation (2) spectral matching is limited to the period range $[T_j, T_k]$ where T_j and T_k are the j^{th} and k^{th} entries of the period vector for which the spectral accelerations are defined and for which spectral matching is desired. A scale factor α is calculated based on minimising the D_{rms} between the scaled target spectrum and that of the real record. $S_{a,R}$ and $S_{a,T}$ are the real record and the target accelerations respectively.

4.1 Initial Record Manipulation

For the 23 records noted in section 3.2 above, the initial manipulation of the horizontal components of the earthquake records determines the scale factor α of equation 2. The proprietary code MathCad (reference 9) proved to be a suitable tool for determining the scale factor α . A Mathcad routine was written in which the target and record spectra were read (the record has a spectrum for each horizontal direction), and then the α value giving the minimum D_{rms} calculated for each. Figure 3 illustrates the variation in D_{rms} with varying α and shows a clear minimum indicating that the record with this α value applied is a good candidate for further processing. For each earthquake the horizontal record yielding the lower value of α out of the two records was deemed to give the best D_{rms} fit and was then scaled by the calculated value of α . The data for the other horizontal direction was discarded.

4.2 Adjustment of the Record to Match the Target Spectrum

In making further adjustments to the records, this paper follows the method used by the authors of the program RspMatch2005 (Hancock et al 2006). This program incorporates adjustments using wavelets in the time domain. It thereby prevents the introduction of additional energy into the earthquake motion and preserves the non-stationary characteristics. For the RSPMatch2005 runs, a target PGA of 0.25g was set in order to match the target spectrum. The program was set to make two passes, matching within the target spectrum frequency range of 1.0-100.0 Hz and 0.5-100.0 Hz respectively. These ranges were determined more by trial and error, program convergence and observing the results, rather than good judgement based on technical reasoning.

Once wavelet adjustment of the record in RSPMatch2005 was complete the response spectrum of the adjusted record was determined and compared with the target. The Arias Intensity was also calculated in order to check that the energy content of the modified record had not been changed in an unacceptable way during manipulation. The result of this checking process left 6 records from the original 23 that

could be useable in dynamic analysis of structures at the UK Sellafield site. The record details and the calculated D_{rms} and scaling factor α of the six records are summarised in Table 1.

5.0 RESULTS

Figure 4 shows the response spectra of the 6 selected records following linear scaling but before wavelet adjustment, and compares these with the target spectrum. Figure 5 shows the response spectra of the 6 selected records following linear scaling and wavelet adjustment, and again compares these with the target spectrum. Good agreement between modified record spectra and the target spectrum is noted across the period range in Figure 5.

Since it is desirable to ensure that manipulation of the record does not adversely affect its characteristics a check of Arias Intensity build up is carried out. For record 001715xa, the build up of Arias Intensity for the original and unmodified record is shown Figure 6(a). Once more good agreement between the original and modified response spectrum compatible records is noted showing in this case that the modification of the original record has not adversely altered the energy characteristics. For the same record, Figures 6(b) and 6(c) show the velocity and displacement histories of the original record and as modified. After application of the scaling factor the difference between the original and adjusted records is minimal giving confidence in the results produced by the linear scaling and wavelet adjustment method presented.

6.0 CONCLUSION

A method for deriving design response spectrum compatible time history records based on the selection and manipulation of real earthquake records has been presented. It has been demonstrated that the method for linear scaling and wavelet manipulation of the real earthquake record produces a high quality record that is compatible with the target spectrum. It has also been demonstrated that the method does not compromise the integrity of the original record through manipulation, and characteristics such as energy build up, velocity history, and displacement history remain largely unchanged.

Records based on recordings of real earthquakes are becoming widely available giving a wide range of choice. As the real records database is clearly very large, and the methods for manipulation of such records to give accelerograms which closely match target response spectra have been demonstrated, resort to artificially generated records is no longer justified. This is especially true in light of the significant drawbacks in using such artificially generated records. As noted by Bommer (2004) the legitimate use of artificial records particularly for non-linear analysis is questionable since such records generally have an excessive number of strong cycles of strong motion and as a consequence when simulating the behaviour of a structure under seismic load too much energy will be input into the system.

While the quality of manipulated real earthquake records can be readily demonstrated, the practicing structural engineer should exercise caution in establishing how many of such records should be used in a structural analysis. Recommendations given in various design codes vary, however, a number of statements are encountered relatively frequently, (including the suggested use of seven or more records and the design based on the average response obtained from the seven records, or the use of three records and design based on the maximum structural response). Hancock et al. (2008) found that when records with an appropriate spectral shape are chosen and modified using a wavelet-based approach, then as few as one or two records can be used for the estimation of peak measures of response, such as peak drift, to within 10%. Hence while this paper equips the structural engineer with a method for record selection and manipulation to give realistic accelerograms matching a design response spectrum, good judgment must still be exercised in using sufficient records to demonstrate the integrity of the structure.

7.0 REFERENCES

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TABLES

Table 1 – Summary of ESMD Earthquake Records Selected

Date	Time	Country	Station	M_w	ED (km)	Record	D_{RMS}	Scale Factor
1999-09-07	11:56:51	Greece	Athens- Sepolia (Garage)	6.04	14	001715	0.261	1.181
1978-04-15	23:33:48	Italy	Naso	6.10	18	000171	0.360	3.349
1976-09-15	03:15:19	Italy	Forgaria- Cornio	6.04	14	000134	0.493	1.994
1990-05-05	07:21:17	Italy	Brienza	5.84	28	000947	0.263	4.194
1991-06-15	00:59:20	Georgia	Oni	6.10	50	000532	0.263	5.846
1997-09-26	09:40:30	Italy	Matelica	6.04	27	000602	0.255	3.695

FIGURES

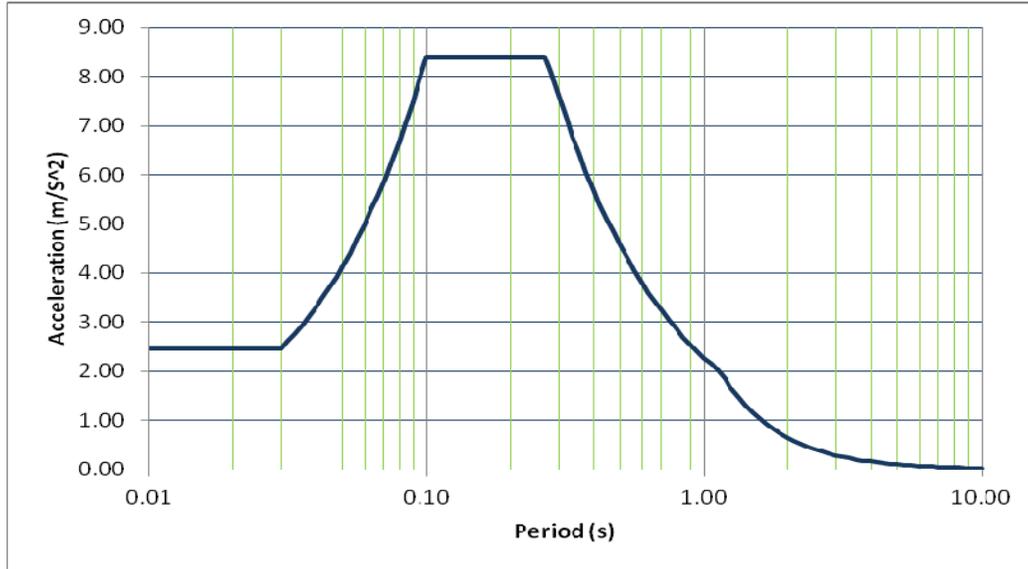


Figure 1 – Design Response Spectrum for Sellafield Nuclear Facility. 5% Damping. Medium Soil

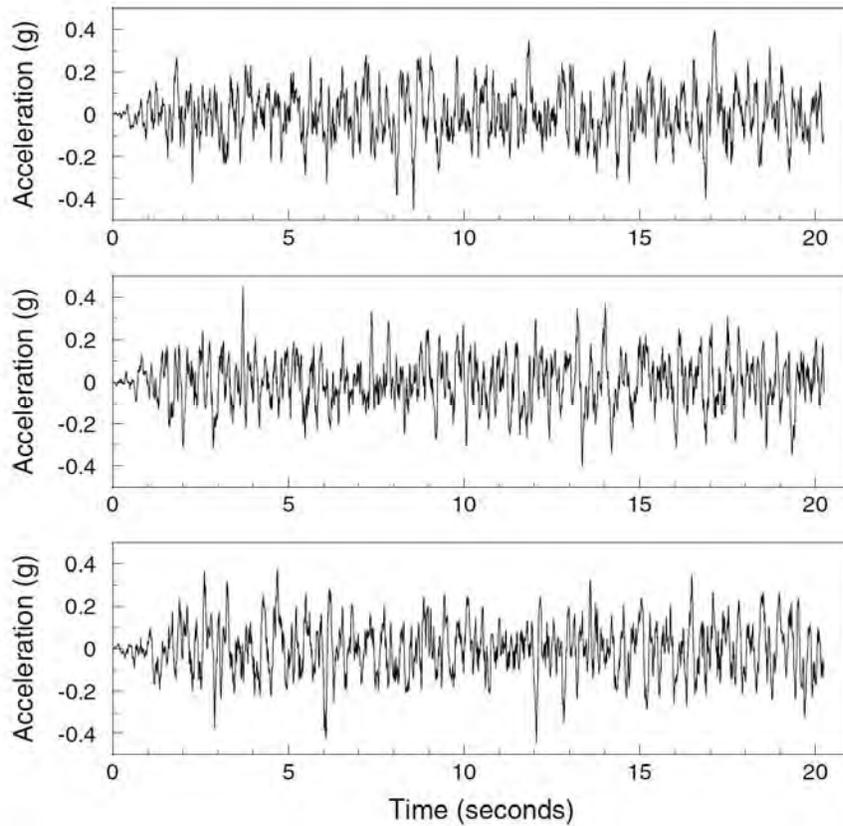


Figure 2 - Artificial accelerograms generated to match the S1 soil category elastic response spectrum from the French seismic design code

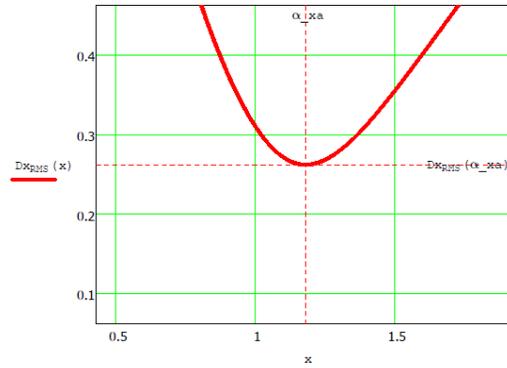


Figure 3 – Typical Variation in D_{RMS} for Varying Scale Factor α

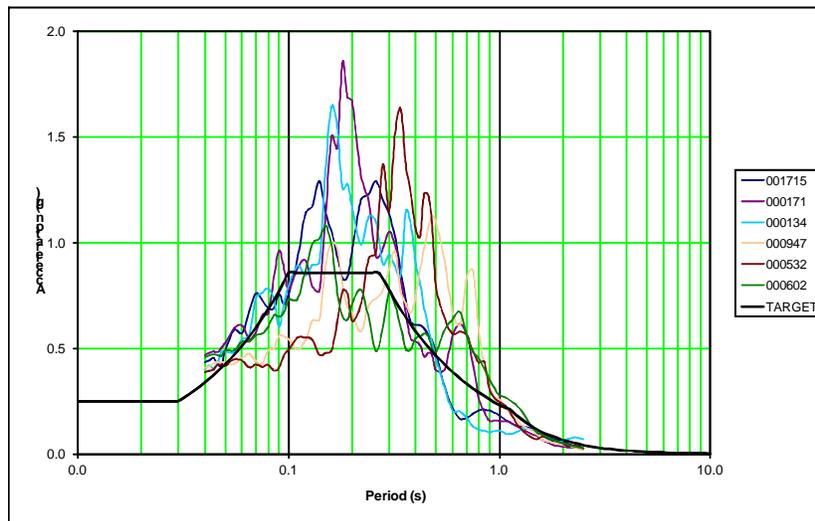


Figure 4 – Selected Set of Records Response With Spectra Linearly Scaled

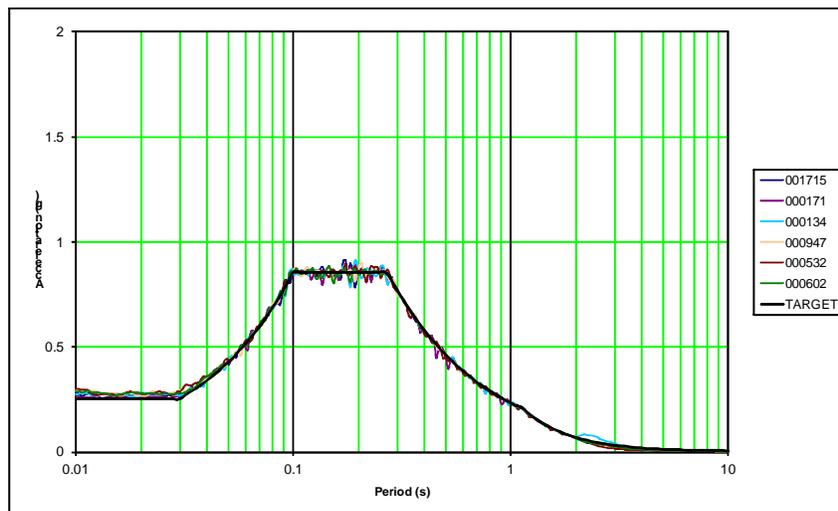


Figure 5 – Selected Set of Records Response Spectra Following Wavelet Adjustment in RSPMatch2005

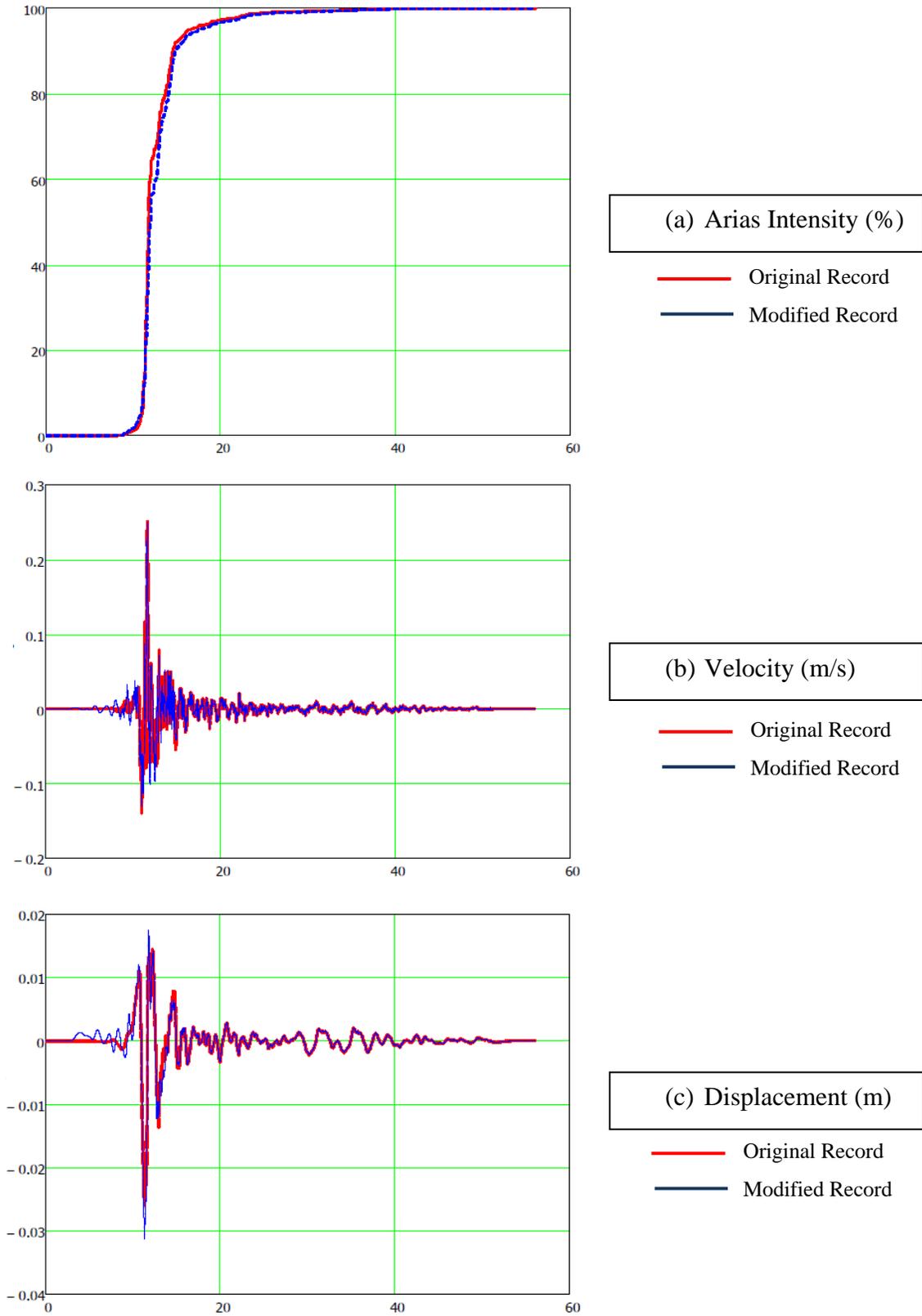


Figure 6 – Arias Intensity, Velocity, Displacement v Time (s) for Record 001715xa – Original & Modified