Preservation of Velocity Pulses in Response Spectral Matching

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SUMMARY:
Response spectral matching is a process in which a real recorded earthquake ground motion is modified such that its response spectrum matches a desired target spectrum across a range of periods. Spectral matching algorithms aim to minimise artificial adjustments introduced to the seed, such that original non-stationary characteristics, such as velocity pulses commonly observed in ground motions recorded in the near-fault region, of are preserved. In this study, spectral matching of pulse-like records is carried out using two programs used in industry (*RspMatch2005* and *Oasys Sigraph*), with target spectra that account for the presence of pulses, and for two different pulse periods. The performance of the programs is compared, and typical problems encountered in matching pulse-like ground motions are summarised.

Keywords: Response spectral matching, near-fault ground motions, velocity pulses

1. INTRODUCTION

Response spectral matching is a process in which a real recorded earthquake ground motion is modified in some manner such that its response spectrum matches a desired target spectrum across a range of periods and possibly multiple damping values. Spectral matching algorithms aim to minimize the artificial adjustments introduced to the seed, such that the original non-stationary characteristics of the ground motion are preserved as much as possible. Velocity pulses, often observed in ground motions recorded in the near fault region, are an example of a non-stationary characteristic of seed ground motions that should ideally be preserved, since pulse-like ground motions are known to produce large nonlinear response on structural models. Spectral matching cannot be expected to add velocity pulses to seeds that did not originally contain them, and therefore we rely upon the selection of ground motions containing a velocity pulse with the desired characteristics (amplitude and period), and then check that the pulses are preserved in the matching process.

There is little guidance available to users of spectrum matching software as to what constitutes an acceptable modification to an initial seed ground motion, and how to assess if a ground motion may be considered “realistic” for use in response history analysis. Given the objective of response history analysis is to obtain unbiased, precise estimates of peak structural response quantities, matched motions should be considered acceptable on the basis of their effect on nonlinear structural response, and not based on whether every cycle of the original motion has been preserved intact. On the other hand, in lieu of specific studies on the effect of matching on nonlinear response, the engineering seismologist or analyst can only draw conclusions about acceptability based on visual observations of how much the record has changed in the time domain. In typical applications, this is done by a qualitative visual check on one or more of the acceleration, velocity or displacement ground motion histories, and the Husid plot (Husid, 1973), which shows the build-up of Arias Intensity (Arias, 1970) over time (e.g. see recommendations in Hancock et al. (2006)).

As part of the development of the ATC-82 document (NEHRP Consultants Joint Venture, 2011), a problem-focused study was carried out on the effect of spectral matching on structural analysis results, for seed motions not containing velocity pulses. The aim was to identify numerical limits to the amount of modification that should be considered acceptable to engineers making use of spectrally matched records for assessment of designs or existing buildings. A number of quantitative measures of change were studied, including absolute changes to peak values of ground acceleration, velocity and displacement, changes to cumulative measures, and parameters based on energy input into single degree of freedom systems. No reliable, statistically significant limits could be identified – even the most extreme modifications to original seed motions were no more likely to be associated with biased structural analysis results than records that were barely modified.

Ground motions containing pulses exhibit higher elastic spectral demand at structural periods in the vicinity of the period of the pulse (Shahi and Baker, 2011), and to the extent that elastic spectral demand is a good estimator of peak inelastic structural response, this effect can be taken into account with an appropriate target spectrum for matching. Records containing velocity pulses, however, are known to lead to disproportionately large nonlinear response (e.g. Akkar et al., 2005; Alavi and Krawinkler, 2001; Mavroeidis et al., 2004). It would be reasonable to conclude that a record matched to an appropriate target spectrum and containing a velocity pulse with the appropriate characteristics would impose an appropriate level of demand on inelastic systems.

The effect of spectral matching on seed motions containing velocity pulses has not previously been studied. If the seed record is selected on the basis of the presence of a velocity pulse with an appropriate pulse period, then it is reasonable to check that the pulse is still present in the record after the matching is carried out. A second part of the problem-focused study in the ATC-82 effort, described above, related to systematically checking the effect of spectral matching on velocity pulses in seed records. This paper summarises that work, and expands upon it with results for an additional spectral matching program not originally considered in that study.

2. STUDY METHODOLOGY

In this study, spectral matching of pulse-like records is carried out using two programs used in industry (*RspMatch2005* and *Oasys Sigraph*), and with three target spectra. The target spectra represent a magnitude 7.5 earthquake at 10 km from the source, conditioned on containing a pulse with a period of 3.1 sec and 5.5 sec, with different adjustments for the pulse: (1) a narrow-band adjustment, centred on the period of the pulse; (2) a broadband adjustment, affecting a wide range of frequencies; (3) no adjustment for the presence of a pulse. In the third case, the pulse is extracted and spectral matching is carried out on the residual ground motion; the pulse is then added back to the record following matching. Seed ground motions are selected from the PEER NGA database, containing a pulse with period within 10% of the two target values mentioned above. The study methodology is further described in this section.

2.1. Identification and Classification of Pulse-like Ground Motions

The algorithm of Baker (2007) is used in this study to identify ground motions that contain prominent velocity pulses. The algorithm is based on a wavelet decomposition of the velocity history of the ground motion. The highest energy wavelet is removed, along with the next nine highest energy wavelets with time and period close to the highest. The energy of the "pulse" component (the sum of these ten wavelets) is compared with the energy of the original ground motion, and if a significant portion of the energy of the motion is contained in the pulse component, then the ground motion is classified as "pulse-like". The algorithm returns a pulse indicator score, from zero to unity, and Baker (2007) showed that values of the pulse indicator greater than 0.85 indicated a significant velocity pulse was present (other criteria, such as a peak ground velocity of at least 30 cm/s, and a pulse that arrives early in the wave train, were used to attempt to identify significant records for engineering applications). The algorithm also identifies a pulse period, based on the pseudo-period of the wavelets contained in the pulse.

Baker (2007) classified all the ground motions contained in the PEER NGA database (Chiou et al., 2008), and the results are available on his website (http://www.stanford.edu/~bakerjw/), along with the MATLAB code used. This code was also used in the present study to classify the ground motions – both in terms of the pulse indicator score and pulse period – following spectral matching.

The algorithm does not distinguish between pulses produced by near-fault effects, and those that result from site effects or other characteristics of the fault rupture process. As far as structural analysts are concerned, the point of selecting ground motions exhibiting velocity pulses is to ensure that the extra demand produced by velocity pulses (e.g. Akkar et al., 2005; Alavi and Krawinkler, 2001; Mavroeidis et al., 2004) is taken into account in linear or nonlinear response history analysis. Unless it can be shown that those pulses generated by near-fault effects have substantially different characteristics from others, it seems reasonable to consider them all together for structural analysis applications. Other classifications of pulse-like ground motions available in the literature do attempt to list only near-fault pulse-like motions. Most notably, Hayden et al. (2012) recently catalogued pulse-like records in the PEER NGA database, as part of the ATC-82 effort (NEHRP Consultants Joint Venture, 2011, sec., 4.4), based on directivity considerations and observations on ground motion velocity histories.

2.2. Spectral Matching Software and Options Selected

A number of spectrum matching algorithms are available in the literature. Many of the computer programs in which these algorithms are coded are available in the public domain, and are used routinely in practice by both structural and geotechnical engineers. The algorithms may be divided into three main categories:

1. Those based on modifications in the frequency domain. *WES RASCAL* (Silva and Lee, 1987) and *Oasys Sigraph* (formerly *Synth*; Oasys Ltd, 2010) are examples of programs in this category.
2. Those based on modifications in the time domain. A commonly used program in this category is *RspMatch* (Abrahamson, 1992) and its successors *RspMatch2005* (Hancock et al., 2006), *RSPMatch2010* (Al Atik and Abrahamson, 2010), and *RspMatchBi* (for matching two-component ground motions (Grant, 2011)).
3. Those based on a wavelet decomposition, modification of wavelet coefficients, and subsequent re-composition. Mukherjee and Gupta (2002) and Suarez and Montejo (2005) presented programs in this category. (Note that *RspMatch* uses wavelet functions, but does not use the wavelet transform).

In this study, the first category is represented by *RspMatch2005* and the second by *Oasys Sigraph*. Other programs in these categories are based on different methods, and may be more or less effective in preserving velocity pulses. Algorithms in the third category offer the potential to generate ground motions that could be considered realistic in both the frequency and time domains, although they have not been widely adopted in practice as yet, and are not considered further.

Each of the programs selected has a number of options available to the user to modify the characteristics of the matching process. Default options recommended in the user manuals for the software were used where possible. Matching was carried out to the target spectrum described in Section 2.3 for 5% damping only, and for periods in the range 0.1 seconds to 8 seconds. Peak ground acceleration (PGA) was not matched in *RspMatch2005*; in *Oasys Sigraph*, a target PGA is required, and was taken as the zero-period ordinate of the target spectrum. In *RspMatch2005*, multiple sweeps can be carried out over widening period ranges, to improve the matching. Here, two sweeps were carried out, from 0.1 seconds to 0.4 seconds, then from 0.1 seconds to 8.0 seconds.

2.3. Development of Target Spectra and Pulse Periods

Several target spectra were considered, based on different methods for taking into account the effect of velocity pulses on the elastic spectral demand. Initially, a baseline spectrum was developed that did not take into account the effect of pulses, based on the median from the Campbell and Bozorgnia

(2008) ground motion prediction equation, with M_w = 7.5 and R_{jb} = 10 km.

Pulse periods of 5.45 s and 3.11 s were considered, corresponding to the median and median-minus-one-standard-deviation values from the Shahi and Baker (2011) prediction equation with M_w = 7.5. Note that the Shahi and Baker (2011) pulse period definition is based on the Baker (2007) pulse identification algorithm discussed in Section 2.1, and therefore the target spectra and ground motions selected (see Section 2.4) are consistent. For a given structural analysis application, these pulse periods may not be the most demanding, depending on the structural periods of interest. The goal here is to consider one longer period, for which the pulse period is relatively well-separated from the main energy content of the ground motion, and a shorter one, which may be more demanding for typical structural applications, and may overlap more with the energy content of the residual shaking. Even shorter pulse periods will produce a large demand on typical buildings, but these are much less likely to be produced by the scenario M_w = 7.5 earthquake.

Three different modifications to the baseline spectrum (or to the way in which spectral matching was carried out) were applied:

1. A narrow-band adjustment, centred approximately on one of the two pulse periods, based on the model proposed by Shahi and Baker (2011). The modification at periods much smaller or greater than the pulse period is small.
2. A broadband adjustment, based on the model of Somerville et al. (1997), later modified by Abrahamson (2000). This model increases all spectral ordinates for periods above 0.5 seconds, and is generally used to modify a uniform hazard spectrum when the pulse period is unknown.
3. The baseline (unamplified) spectrum is used, but, before matching, the “pulse” component of the ground motion identified by the algorithm of Baker (2007) is removed, and matching is carried out on the residual motion only. Following matching, the pulse component is added back to the record.

For the narrow-band adjustment, two target spectra were developed (one for each pulse period); for the broadband adjustment and unamplified target, the target spectrum was not dependent on pulse period. The target spectra are shown later in the discussion of the matched records (Figure 1).

2.4. Selection and Scaling of Seed Ground Motions

Ground motions were selected from the PEER NGA database (Chiou et al., 2008), from the fault-normal component of those identified by Baker (2007) as containing a pulse. Only records with a maximum usable period greater than 8 seconds were considered. For each target spectrum, all records with pulse period within ±10% of the scenario pulse period were used – a total of 8 and 5 records for the 5.45-second and 3.11-second pulse periods, respectively, were available satisfying these criteria. Information about each of the 13 ground motions is given in Table 1.

Prior to matching, ground motions were linearly scaled; different scaling factors were applied to the records for each of the three matching scenarios. For the narrow-band and broadband adjusted target spectra, ground motions were linearly scaled to provide a close initial match of the target spectrum over a period range within 20% of the pulse period (“Scale 1” and “Scale 2” in Table 1, respectively). For the third scenario, in which an unamplified spectrum was used as a target for matching the residual motion, the target spectrum no longer represents an appropriate target for initial scaling, at least around the pulse period (as it does not take into account the presence of pulses). Therefore, in this case the ground motions were scaled to a constant peak ground velocity = 69 cm/s, from the Bray and Rodriguez-Marek (2004) predictive equation for pulse-like ground motions (scale factor “Scale3” in Table 1).

Table 1. Ground Motions Containing Velocity Pulses Selected for Spectral Matching Study

#	Event	Year	Station	Scale 1	Scale 2	Scale 3
1. Records selected and scaled for T_p = 5.45 seconds						
1	Imperial Valley-06	1979	El Centro Array #3	2.94	1.99	1.68
2	Imperial Valley-06	1979	El Centro Array #8	1.91	1.28	1.42
3	Imperial Valley-06	1979	El Centro Diff. Array	2.08	1.44	1.16
4	Landers	1992	Lucerne	1.04	0.70	0.49
5	Kocaeli, Turkey	1999	Gebze	2.03	1.36	1.33
6	Chi-Chi, Taiwan	1999	TCU036	1.28	0.88	1.11
7	Chi-Chi, Taiwan	1999	TCU065	0.62	0.41	0.54
8	Chi-Chi, Taiwan	1999	TCU075	1.10	0.74	0.78
2. Records selected and scaled for T_p = 3.11 seconds						
1	Imperial Valley-06	1979	EC Meloland Overpass FF	0.93	0.49	0.60
2	Cape Mendocino	1992	Petrolia	1.79	0.94	0.84
3	Northridge-01	1994	Sylmar - Olive View Med FF	0.89	0.47	0.56
4	Chi-Chi, Taiwan	1999	TAP003	2.23	1.16	2.09
5	Chi-Chi, Taiwan-03	1999	CHY024	1.93	1.02	2.09

3. RESULTS AND DISCUSSION

3.1. Summary of Effectiveness of Spectral Matching

Spectral matching was carried out on each of the seed records, to the three target spectra (and scaling methodologies) discussed in Section 2.3, and using the two programs discussed in Section 2.2. Generally, the programs converged to the specified tolerances over the full period range. The 5%-damped pseudo-acceleration spectra for the records after spectral matching with *RspMatch2005* are compared with the target spectra in Figure 1. In this figure, the unshaded period range is the range considered in the spectral matching. The results show a good match over the period range considered in the spectral matching – a finding that also held for the records matched using *Oasys Sigraph*.

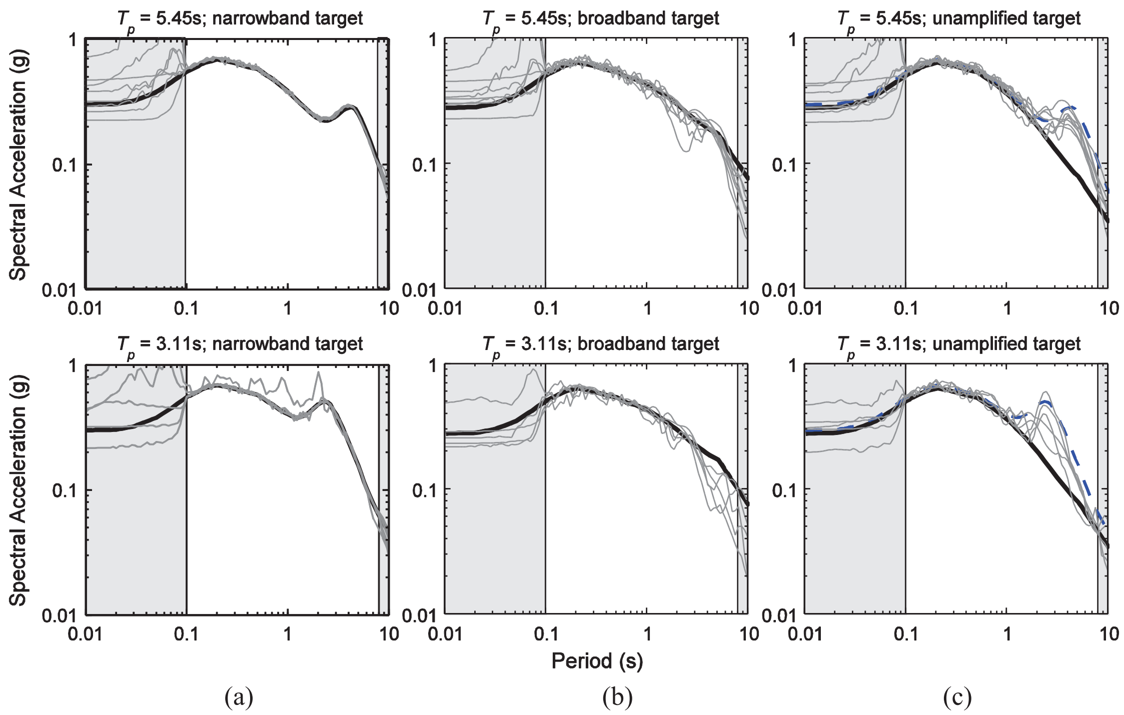

Figure 1. Response spectra of spectrally-matched records compared with target spectra. Records matched to (a) narrowband target, (b) broadband target, and (c) records with pulse extracted, matched to an unamplified target, and then the pulse added back.

A few other observations and clarifications should be made on Figure 1:

- Spectral accelerations outside the matched period range are largely unaffected. Some applications also consider short period spectral accelerations (and/or peak ground acceleration) to be important. Since pulses affect primarily the longer period spectral content, this is not expected to affect the results in this paper significantly.
- One record for the T_p = 3.11 second pulse period, matched to the narrowband target spectrum, did not converge, which is apparent from the relatively poor fit to the target spectrum.
- For the broadband target, initial work as part of the ATC-82 problem-focused study found that it was difficult to obtain convergence using the normal matching procedure. Therefore, for the *RspMatch2005* matching, a modified algorithm was carried out, wherein the pulse was removed using Baker's algorithm, spectral matching was performed to a modified target spectrum (accounting for the removal of the pulse) and then the pulse was re-added. This is explained further in ATC-82 (NEHRP Consultants Joint Venture, 2011), and accounts for the fact that the final match to the target spectrum is not perfect for these records. This was not done for the *Oasys Sigraph* records, which means that the comparison between the two programs is not completely fair.
- For the records matched using the third procedure from Section 2.3 (extract pulse, match the residual to an unamplified target, re-add the pulse), the records immediately following matching gave a very close fit to the target spectrum, shown as a black line in Figure 1. A better comparison, however, is between the spectra for the records with pulses added back in to a spectrum that appropriately takes into account the effect of the pulse and its period. Hence, the dashed blue line in Figure 1, the same as narrowband target spectrum used in the first method, is the best comparison for the final records. Again, the match is not perfect here, but the method appears to give records with a reasonable spectral content.

3.2. Classification of Significant Modifications Introduced by Spectral Matching

The key goal of this work is to check whether velocity pulses are preserved in spectral matching of records to various target spectra and using various algorithms. As discussed in the introduction, there are no quantitative criteria available for measuring whether a record has been modified too much to be considered acceptable for use in structural analysis. This is particularly true for records containing pulses. In typical applications (with or without pulses), ground velocity histories (and/or acceleration, displacement and Arias Intensity histories) are compared before and after matching, and judgement is used to determine whether modifications are too large.

For a systematic investigation of the types of changes to watch out for in spectral matching of records containing pulses, it is useful to use quantitative measure of the extent to which the record may be considered "pulse-like", and, if relevant, pulse characteristics – particularly pulse period. In this study, the quantitative pulse classification method of (Baker, 2007) is used both before and after spectral matching to investigate changes that have been introduced. As noted in Section 2.1, in this method a potential pulse is extracted using a wavelet decomposition, and a pulse indicator score is assigned based on what portion of the overall energy of the record the extracted pulse represents. A pulse indicator greater than 0.85 is taken as being representative of a pulse-like record. A period is also assigned to the pulse, based on the pseudo-period of the extracted wavelets. As well as using these numerical measures assigned by Baker's method, the velocity history of the extracted pulse (and residual ground motion when the pulse is removed) are compared before and after matching.

Illustrative examples of total velocity history, extracted pulse and residual ground motion are shown in Figure 2. The velocity history is only shown around the time that the pulse occurs to make the changes clearer. The first example, Figure 2(a), is one in which the matching process was very successful at preserving the pulse amplitude, period and waveform. Other examples are provided to give examples of typical problems that were observed with some of the post-matched records:

1. *Pulse indicator < 0.85; pulse weakened*. Figure 2(b) shows an example of a pulse that has essentially been eliminated by the matching (in this case, pulse indicator decreased from 1.0 to 0.017). It seems reasonable to reject these records, on the basis that the record is no longer

"pulse-like".

2. *Pulse indicator < 0.85; rest of record strengthened.* A more difficult example is represented by Figure 2(c). In this case, the pulse indicator has decreased from 1.0 to 0.035, but the extracted pulse has not been significantly affected. The reason that such a low pulse indicator is assigned is that significant energy content has been added to the rest of the record, and the extracted pulse is no longer such a defining feature. Although this has not been verified numerically, one could hypothesise that records like this (that contain both a realistic, high amplitude velocity pulse, and moderate to high energy content over a longer duration of shaking) would be at least as demanding on nonlinear structural models as conventional pulse-like ground motions, and therefore could be reliable for structural analysis where velocity pulses are considered to be important.
3. *Pulse period modified (± 20%).* Figure 2(d) and (e) show a pair of examples where Baker's classification method indicates that the pulse period has been increased by more than 20% (from 5.9 sec to 7.3 sec, and from 5.1 sec to 7.5 sec, respectively). Although the problem is first identified numerically from the pulse period, this can partly be attributed to the way in which the pulse period is identified by Baker's method. In the first example, the waveform of the pulse has been changed – loosely speaking, from a pulse with three significant half cycles to one with one strong half cycle and two weaker ones. This is similar in the second example, although the waveform is not affected so significantly. As with the previous examples, without carrying out structural analysis with these ground motions it is difficult to understand the acceptability of these artificial changes. However, it does suggest that the pulse period calculated from the extracted wavelets perhaps more suitable as a proxy for identifying other potential problems, rather than being representative of actual changes in the frequency content of pulses. Other measures of pulse period (e.g. Jonathan D. Bray and Rodriguez-Marek, 2004) may be more related to the effect of pulses on structural response, and could be considered for checking pulses pre- and post-matching.
4. *Pulse time of occurrence or waveform significantly modified*. Figure 2(f) shows a rare example of a record where the pulse extraction methodology identifies a pulse both pre- and post-matching (pulse indicator from 1.0 to 0.98), with similar pulse periods (3.1 sec to 3.7 sec), but occurring at different times within the record. In this case, so much artificial manipulation has taken place that a new pulse has been generated by the *RspMatch2005* software, and the old pulse has been removed. Although there may be some value in developing algorithms to add pulses to records without pulses, this is not the goal of the present study, which focuses on preserving existing pulses in records. Furthermore, in this particular example, the record is particularly non-physical, in that the velocity ramps up from zero within a fraction of a second of the start of the record.

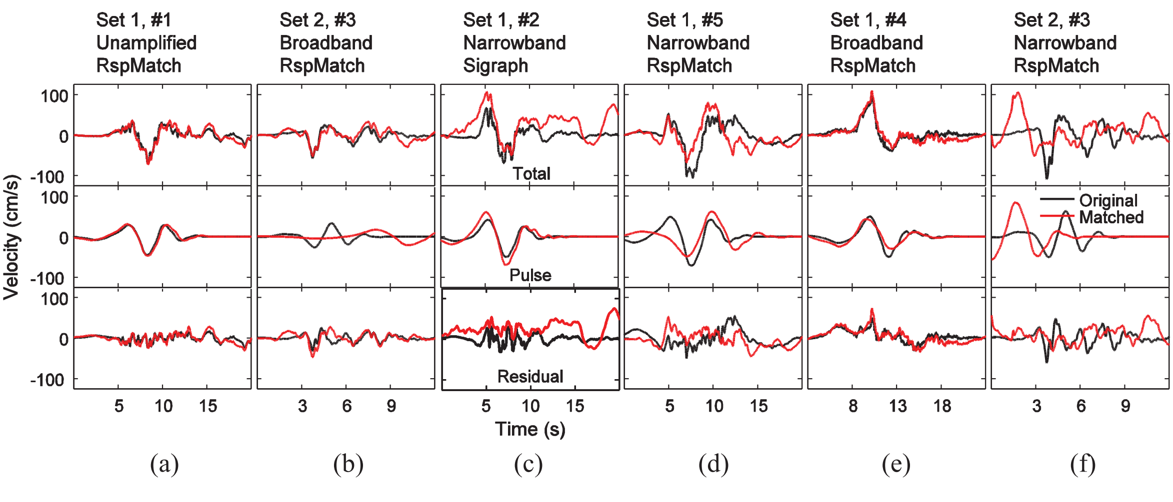

Figure 2. Examples of velocity histories of pre- and post-matched records. Only a limited portion of each record, including the complete velocity pulse, is shown. The seven examples are explained in the text.

Table 2. Summary of Classification of Spectrally-Matched Records

Program:	Matched with ***RspMatch2005***			Matched with ***Oasys Sigraph***		
Target:	**Narrowband**	**Broadband**	**Unamplified**	**Narrowband**	**Broadband**	**Unamplified**
1. Records selected and scaled for T_p = 5.45 seconds						
Record 1	✓	✓	✓	✓	✓	2
2	3	✓	✓	2	✓	2
3	✓	✓	✓	2	2	✓
4	2	3	3	✓	2	2
5	3	4	✓	✓	2	2
6	✓	3	3	✓	2	3
7	✓	2	✓	2	2	✓
8	✓	✓	✓	✓	✓	✓
2. Records selected and scaled for T_p = 3.11 seconds						
Record 1	1	3	✓	2	1	2
2	1	1	✓	✓	1	2
3	4	1	1	3	1	2
4	✓	1	✓	2	1	✓
5	✓	1	✓	1	1	✓

From the above classifications of potential problems with spectral matching of records containing pulses, it is difficult to draw definitive conclusions without carrying out structural analyses with these records, to see if they impose appropriate demand on nonlinear structural models. Nevertheless, a summary of the classifications for all the input records, target spectra, pulse periods and analysis software is given in Table 2**.** In the table, a green tick mark indicates that the pulse has been preserved, a red 1 or 4 refers to problems 1 and 4 above, and an orange 2 or 3 refers to problems 2 and 3. As discussed above, problems 1 and 4 should generally lead to rejection of the record, whereas 2 and 3 may be acceptable, but should prompt further investigation. This table is discussed more in subsequent sections.

3.3. Effect of Pulse Period on Results

Comparing records in sets 1 and 2 in Table 2 (pulse period of 5.45 sec and 3.11 sec, respectively), a general conclusion is that the matching process is generally more successful for the longer pulse period. This observation holds particularly for the records matched to a broadband spectrum, but is also true for the other targets. Records with longer pulse periods tend to be more obviously separated into long period spectral demand, dominated by the pulse, and shorter period demand, governed by the higher frequency content of the motion. For shorter pulse periods, the interaction between the demand caused by the pulse and that caused by the rest of the record is higher. This means that when the record is manipulated by the spectral matching software, modifications to the higher frequency part of the ground motion are more likely to also alter the wavelets that are extracted by the pulse identification process.

Recall that the target pulse periods were selected based on a scenario $M_w = 7.5$ earthquake (the median and 16^{th} percentile values from a pulse period prediction equation). Smaller magnitudes are associated with shorter pulse periods, and the difficulties experienced could be exacerbated.

3.4. Effect of Target Spectrum on Results

The least successful results were obtained using the broadband target spectrum. This is not surprising, in that the broadband adjustment to the spectrum takes into account the presence of pulses only in an average sense, and does not account for the influence of pulse period on spectral demand. Real records containing pulses will generally have an increased demand at periods close to the pulse period, as in the adjustment model of (Shahi and Baker, 2011) used in the narrowband target spectrum. Artificially constraining an individual pulse-like ground motion to a target spectrum without this perioddependence tends to flatten out the effect of the pulse (leading to a "type 1 problem" from Section 3.1), or a general increase the energy content across a range of periods (leading to a "type 2 problem"). This broadly agrees with the observations from Table 2, particularly for the *Oasys Sigraph* program.

The records matched to the unamplified spectrum (with pulse extracted, and then re-added following matching) were the most successful, at least as far as the preservation of velocity pulses is concerned. The trade-off in this case is that the pulse is added back in after matching, and there is therefore less control over the final spectral shape. Ideally, adding the pulse will not affect the spectral content at periods away from the pulse period, and this seems to hold for the pulse periods used here (Figure 1c). Based on the discussion in the previous subsection, for shorter pulse periods, there may be more association between the residual spectral content and the effect of the pulse, and the final response spectrum may be excessively high when the pulse is re-added.

3.5. Effect of Spectral Matching Software on Results

The two spectral matching programs used in this study give comparable results. In Table 2**,** there are more green ticks associated with *RspMatch2005*, but fewer red 1s or 2s associated with *Oasys Sigraph.* In general, *Oasys Sigraph* gave more "type 2 problems", which were described in Section 3.1 as requiring further investigation before acceptance. Note that these programs were chosen to represent time-domain (*RspMatch2005*) and frequency-domain (*Oasys Sigraph*) spectral matching methods, but other programs in these categories (or in the third category described in Section 2.2: algorithms based on wavelet decomposition) may be more or less effective at preserving velocity pulses. Furthermore, reasons other the preservation of velocity pulses may dictate one program over another. For example, time domain methods have generally been preferred over recent years, based on studies such as (Naeim and Lew, 1995), although these issues could be reinvestigated with modern programs and taking into account recent developments in ground motion selection and modification (NEHRP Consultants Joint Venture, 2011).

4. CONCLUSIONS AND RECOMMENDATIONS

This paper has investigated the preservation of velocity pulses in ground motions that are modified using spectral matching software. Matching was carried out to three different types of target spectra, and for two different pulse periods. It is difficult to draw general conclusions from this relatively small scale study, but the following preliminary observations can be drawn:

- If velocity pulses are required in ground motions for structural analysis, seed records with the appropriate pulse period should be selected initially.
- The presence of the pulse following spectral matching can be checked using the method of Baker (2007). Note, however, that this method was calibrated based on unmodified pulse-like ground motions, and artificially modified ones may have unusual pulse waveforms or broadband energy content. These records may not be identified as "pulse-like" according to the algorithm, but may satisfy the requirement of higher nonlinear structural demand that real records with pulses are expected to produce.
- Shorter period pulses – of the order of the shorter period investigated here, 3.11 seconds, or less – may present more problems for spectral matching. In these records, there may be more interaction between the spectral demand caused by the pulse content and that produced by the general shaking of the ground motion over the rest of its duration.
- For applications where an appropriate pulse period can be identified – or when a pulse period based on the structural period is conservatively selected – it is recommended to use a target spectrum that takes into account the narrowband amplification at periods close to the pulse period. Alternatively, the third method investigated here (removing the pulse, matching to an unamplified spectrum, then re-adding the pulse) can be used if a slightly worse spectral fit is acceptable.

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