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SEED RECORD SELECTION FOR SPECTRAL MATCHING WITH RSPMATCH2005

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ABSTRACT :

The use of spectral-matching software, such as *RSPMatch2005*, allows the engineer to alter seed ground motions in the time domain to provide a very close match of a target response spectrum. Compared to the use of real recorded ground motions, a smaller number of spectrally-matched records can reliably be used, as the variability is less. A set of criteria for selecting seed motions for *RSPMatch2005* is presented, in which initial spectral shape is considered to be of primary importance, and other ground motion characteristics are used to filter the initial database. Rather than using earthquake magnitude bounds as a proxy for ground motion duration, as recommended by other authors, we suggest filtering explicitly on duration. For structures with a long fundamental period, the frequency content of the input motion is also very important, to avoid excessive noise at periods of interest in the original seed record, and excessive manipulation of the record in the spectral matching. A Matlab program which automates the selection criteria and provides a front-end for *RSPMatch2005* is also presented.

KEYWORDS: *RSPMatch2005*, ground motion selection, spectral matching, ground motion duration

1. INTRODUCTION

Numerous design codes and research publications provide guidance for the selection of seismic ground motions for use in time history analysis (see Bommer and Acevedo, 2004, and Beyer and Bommer, 2007, for recent reviews). Generally, these documents are based on the use of a number of real recorded ground motions, scaled by a constant factor over the full duration to be approximately consistent with the seismic hazard at the site. Seismological characteristics of the records, such as earthquake magnitude and epicentral distance, are usually considered in the selection of real records, as they influence the shape of the response spectrum, the energy content and duration of strong ground shaking, and therefore the expected demand on structures.

Spectral matching software, such as *RSPMatch2005* (Abrahamson, 1992, Hancock et al., 2006), makes adjustments to real recorded ground motions to provide a good match to a target response spectrum, which may be a code spectrum or a scenario spectrum consistent with a disaggregation of the hazard at a site. Using spectrally-matched records as input to time history analysis helps to minimise the variation in the spectral demand, and therefore allows fewer records to be used to obtain reliable estimates of the expected response (Hancock et al., 2008). Generally, *RSPMatch2005* is able to provide an excellent match of the target spectrum across a wide range of periods (and, if required, multiple damping levels), with relatively small adjustment to the seed accelerogram.

The purpose of this paper is to provide some initial guidelines for selecting seed records for use in spectral matching software such as *RSPMatch2005*, based on the authors' experience in generating suites of records for geotechnical and structural earthquake engineering analyses. While the suggestions presented herein are intended to be applicable to a wide range of earthquake engineering projects, we place particular emphasis on the requirements for performance-based seismic design of tall buildings, and other long period structures. This application is of special interest, for several reasons: (1) multiple modes of vibration contribute significantly to tall building response, and recommendations for selecting real recorded ground motions based on a single spectral ordinate are not appropriate; (2) as a result of hardware limitations and filtering characteristics, a large proportion of records are unreliable at long periods; (3) a large number of tall building projects are being carried out around the world based on performance-based approaches, with time history analysis as a basis.

As stated above, several existing references provide guidance on selecting real records for time history analysis, and much of the advice given is directly applicable to selecting seed records for *RSPMatch2005*. We do not aim to tread the same ground here, focussing instead on new approaches to the issues related to the selection of seeds for spectral matching.

Our philosophy for selecting records for *RSPMatch2005* may be summarised as follows:

- Structural response is strongly related to the response spectral ordinates; for best convergence and output quality from *RSPMatch2005*, records with a good initial fit to the target spectrum should be selected.
- Aside from their implicit contribution to spectral shape, magnitude and distance are considered to be primarily important for their effect on ground motion duration. Instead of selecting based on these seismological parameters, we instead select explicitly on duration.
- Only records with a usable period range which includes all structural vibration periods of interest should be used.
- With the availability of powerful desktop computers and online databases, more computationally demanding selection routines (for example, calculating spectral ordinates for multiple orientations of records) can be used.

2. GROUND MOTION SELECTION AND SCALING

2.1. Linear Scaling of Ground Motions

A number of studies have demonstrated that ground motion records can be multiplied by a constant scaling factor, within certain bounds, without biasing the results of non-linear analysis using these records (Shome et al., 1998; Iervolino and Cornell, 2005). This observation is convenient for earthquake engineering analysis, as a relatively limited number of ground motions have been recorded at the high amplitude levels required by modern seismic design codes, and therefore scaled-up ground motions from lower intensity recordings can be used. Luco and Bazzurro (2005) and Baker (2007a), however, have suggested that scaling records does bias non-linear results, if the parameter ε (a measure of the "peakiness" of a response spectrum) is not taken into account in the initial selection of ground motions. Baker explained the conflict with earlier studies by the fact that they considered records scaled both up and down, and therefore that the bias in using only scaled-up or scaled-down records was obscured. According to these authors, in practical situations in which scale factors greater than unity will generally be required, the results will be biased, albeit conservatively.

Recently, Hancock et al. (2008) carried out a comprehensive study on an 8-storey building model, with ground motions linearly scaled by factors up to 10.0, and concluded that no bias could be identified from the study. The baseline for their study was a number of regression analyses carried out on the results of 1656 non-linear time history analyses, using ground motions from the PEER NGA database (http://peer.berkeley.edu/nga/). For response quantities of interest, predictive equations in terms of moment magnitude, Joyner-Boore distance, soil type and style of faulting were developed. With these regression relationships as a basis, results from analyses with records scaled to match a target spectrum were assessed, and no bias was observed.

While noting that the results of Hancock et al. (2008) are based only on a single building model, they suggest that linear scaling of records, in combination with selection based on response spectral shape, can be used to generate a suite of records for unbiased non-linear analysis.

2.2 Rotation of Ground Motions

T he required output of the spectral-matching process is usually one or two components of ground motion which match a target spectrum. For two output components, this ignores the fact that, if calculated at intermediate angles, the response spectrum from the record will be smaller or greater than the target spectrum at certain periods. Since *RSPMatch2005* works on one component of ground motion at a time, it is not possible to consider the response for both components simultaneously, and to spectrally match them such that the motion is independent of direction. For this reason, the first author developed an extension to *RSPMatch2005*, named *RSPMatch2005bi*, which takes two components of ground motion as input, and produces records for which the maximum and minimum spectra are equal to a single target spectrum or two different spectra. The characterisation of bidirectional ground motion, and the program *RSPMatch2005bi*, are discussed in detail in (Grant, 2008).

Even using the original *RSPMatch2005*, however, it may be desirable to rotate the record into a new orientation prior to carrying out spectral matching. When only a single component of ground motion is required, we could either treat the two components of ground motion independently, and select either one or both of them for further processing, or we could use the two components to produce a number of possible seeds by rotating through all possible orientations. Using the latter option, the rotated record that is selected can be at an optimum rotation angle in terms of spectral fit, and is not governed by arbitrary considerations such as the angle at which the accelerometer happened to be orientated in the field.

The idea of rotating components before spectral matching can be extended to cases where two components of ground motion are required. Components can be rotated into a number of orientations, and the orientation which provides the two rotated components with the best initial fit to the target spectrum may be selected. This procedure may not be applicable when near-fault motions are required, as the original configuration of the components should be preserved for *RSPMatch2005*. In any case, the use of *RSPMatch2005* for near-fault ground motions requires further study, although it is likely that *RSPMatch2005bi*, which better preserves the original polarisation of the motion, may be especially useful in near-fault applications (Grant, 2008).

Note that the procedures discussed above are more computationally intensive than evaluating components only in the original form provided in the database. However, with the increasing power of personal computers, this becomes less of an issue, and from the authors' experience, time spent during initial selection of seed motions can improve the convergence of *RSPMatch2005*, reducing computation time and improving the quality of output.

2.3 Spectral Shape

In selecting records for time history analysis, whether linear or nonlinear, the linear response spectrum provides a reasonably direct measure of structural demand. While the overall amplitude of the spectrum can be adjusted with linear scaling (as discussed in Section 2.1), the shape of the spectrum, which is a measure of the relative frequency content of the record, generally requires spectral matching programs such as *RSPMatch2005* to modify. In order to minimise the amount of artificial manipulation in *RSPMatch2005*, and to improve the chances of quick convergence, it is important to use seed records with a good initial match of the target spectral shape, prior to spectral matching. We take the approach of using the goodness of spectral fit as the main method for ranking records; we use other parameters, discussed in subsequent sections, to filter the initial pool of records to ensure that the ground motions are appropriate.

With current desktop computing power, it is relatively simple to automate ground motion selection based on the goodness of fit of the initial spectral shape. Typically, the goodness of fit of the record response spectrum to the target spectrum can be measured with a scalar error function, and minimised over a range of periods of interest. The scaling factor for each record which minimises the error can also be evaluated. In the authors' experience, the error function used can make a large difference to the specific records that are recovered from a database, and it can be argued that different methods to calculate the error are appropriate for different applications. Two issues are important to consider:

1. An error function may be relative or absolute. For selection of records based on a relative error, the

error is calculated with ratios of spectral ordinates, and therefore whether pseudo-spectral acceleration (PSA), pseudo-spectral velocity (PSV) or spectral displacement (SD) is used to select records is irrelevant. For absolute error calculation, the absolute differences between record and target spectral ordinates are calculated, and the response quantity used becomes important. For example, an absolute error calculation based on SD may be the most appropriate for structures with long fundamental periods. A "least squares" approach is generally based on the absolute error.

2. The values at which the spectral ordinates are measured are also important. Often spectral ordinates provided in databases (such as the PEER NGA database) contain a much greater resolution of values at short periods than at long periods, and therefore these ordinates are implicitly weighted in the selection process. Although we have not explored this issue exhaustively, we would tentatively recommend using equally spaced periods over the range of interest, at least for tall building applications in which we do not want to implicitly weight short period spectral ordinates. Alternatively, equal spacing can be simulated by weighting the error at each period by the spacing of ordinates to either side. This gives equal weighting to each range of periods, which may be especially appropriate for tall buildings or other structural forms controlled by more than one mode of vibration.

For three-dimensional analyses, at least two ground motion components, measured in orthogonal horizontal directions, are required. If the target spectrum is representative of a geometric mean of the two components, or similar average measure, then the obvious recommendation is to select records for which the geometric mean of the two components' spectra are close to the target. This, however, does not distinguish between ground motion pairs with two similar amplitude components and pairs that are highly-polarised. Rather than taking the approach of adjusting the two components by different scaling factors to give a good initial match (as discussed by Beyer and Bommer, 2007), we prefer to select records for which the sum of the errors of the two horizontal components is minimised (i.e. total misfit = 50% component 1 misfit + 50% component 2 misfit). As discussed in Section 2.2, optimisation of the orientation angle of the components can be used to reduce the misfit further. If the vertical component is also required, this could also be given a small weighting (e.g. total misfit = 45% horizontal component 1 misfit + 45% horizontal component 2 misfit + 10% vertical misfit). Note that the target vertical spectrum should be different from the horizontal one.

If the target spectrum is representative of the maximum component (either maximum of two as-recorded components, or maximum rotated through 360°), a similar approach can be used. In this case, a minimum spectrum should also be defined, based on expected ratios of minimum to maximum response, and the selection can be carried out with respect to the two targets. Measures of bidirectional demand and spectral matching of two components of ground motion are discussed further in (Grant, 2008).

2.4 Magnitude, Distance and Duration

The two parameters most commonly used for ground motion selection are magnitude and distance – not surprisingly given their role in Ground Motion Prediction Equations (GMPEs). However, when the amplitude of the ground motion is adjusted by linear scaling and spectral shape is considered explicitly in the selection procedure and is modified using spectral matching, the effect of these two parameters on the linear response spectrum becomes less important. The main ground motion characteristic (from a structural point of view) not captured by the response spectrum and not altered by *RSPMatch2005* is the strong motion duration, which is strongly dependent on magnitude, and less strongly dependent on distance. For this reason, some authors (e.g. Bommer and Acevedo, 2004) recommend that ground motions should be selected based on a reasonably strict range of magnitudes (say ±0.2 magnitude units from the scenario magnitude), but with a more relaxed range of distances.

While this recommendation should produce, on the average, a suite of ground motions with durations appropriate for the scenario event, a more direct approach would be to select directly on duration. This is especially important for the relatively small suites of records that we can reliably use when spectrally-matching (Hancock et al., 2008), as selecting one or two outliers that have hazard-consistent magnitudes but that are longer or shorter than expected for the scenario event may bias the response. We therefore suggest using a GMPE to give an expected value of duration as a function of scenario magnitude, distance, and possibly fault mechanism (see Kempton & Stewart, 2006 and Alarcón, 2007 for some possible GMPEs for duration).

Upper and lower bounds of duration on which to filter may be selected depending on the application. For degrading structures and liquefaction modelling, for example, duration is particularly important, and relatively tight bounds should be considered. An appropriate method may be to consider one standard deviation ($\pm 1\sigma$) above and below the median in the GMPE for duration, or alternatively to use the scenario magnitude ±0.2 magnitude units in the GMPE, for consistency with Bommer and Acevedo's suggested range. For non-degrading structures, a wider range of ground motion durations may be permissible (say $\pm 2\sigma$).

There are many different measures of ground motion duration in the literature (see Bommer and Martinez-Pereira, 1999, for a comprehensive review), and the numerical values obtained by two different measures can easily vary by an order of magnitude. Clearly, a measure of duration consistent with the GMPE must be employed. Bommer and Martinez-Pereira differentiate between relative and absolute duration measures; a useful property of relative duration measures is that they are unaffected by linear scaling, and therefore may be stored in the ground motion database ahead of time. For example, the authors have calculated the significant duration – the time interval over which 5% to 95% of the total Arias intensity of the record is accumulated – for all the records in the PEER NGA database, for use in ground motion selection. Therefore, the records can be filtered on duration before the linear scaling and goodness-of-spectral-fit calculation is carried out.

2.5 Usable Frequency Content

An oft-ignored but fundamentally important characteristic of a ground motion record is the usable frequency content: specifically the minimum usable frequency (or, equivalently, maximum usable period), beyond which the noise-to-signal ratio of the record is excessively high. This frequency is a function of the accelerometer and filtering characteristics used to produce the acceleration time history and should, ideally, be provided in the ground motion database. While *RSPMatch2005* should generally be able to alter a seed record's spectrum beyond its maximum usable period to match a target spectrum, the resulting record will be adjusted noise at these periods, and will not be appropriate input for structural analysis.

The PEER NGA database provides the minimum usable frequency for 3518 of 3541 of its records in the meta-data flatfile, which provides a useful filter for ground motion selection. This number is reduced by approximately half when only records with a maximum usable period greater than or equal to 4 seconds are considered, and is halved again for a maximum usable period of 8 seconds or greater. Many tall buildings have elastic periods in the 4–6 second period range, or greater, and allowing for concrete cracking and other nonlinearity, the requirement for records with usable periods as high as 8 seconds can be appreciated. Considering that the PEER NGA records were prepared specifically for the purpose of deriving GMPEs for long period spectral response ordinates, the records from other databases which do not provide this information could be expected to be at least as limited. The problem is not that there are not enough records available, but that if records are selected without considering the usable frequency range, there is a good chance that they will not be appropriate for long period applications.

2.6 Other Considerations

As emphasised in the above discussion, our philosophy in ground motion selection is to not overly restrict the pool of available records by imposing geotechnical or seismological criteria that are not expected to affect structural response significantly (or whose effect is not captured by some more direct measure such as spectral shape or ground motion duration). A measure of ground motion energy content, such as total Arias intensity, may be useful for some applications, and could be treated in the same way as duration. As with the significant duration, we have calculated the total Arias intensity for all the records in the PEER NGA database for ground motion selection applications; note, however, that the Arias intensity is affected linearly by the scaling factor, and therefore the filtering must be carried out post-scaling. Arias intensity is also a useful post-processing check to ensure the final matched record has not deviated too greatly from the desired energy content and duration (Hancock et al., 2006).

Another requirement that should be enforced after filtering, scaling and evaluation of goodness-of-spectral-fit is an upper bound on the number of records taken from a single earthquake event. We have not carried out a statistical analysis of this issue (although a comparison of intra- and inter-event components of variability in GMPEs should provide some insight), but it is intuitively obvious that the number of records from a single event should be limited to ensure that a peculiar seismological feature is not over-represented. This is particularly important with a smaller suite of records, as we may reliably use when the records are spectrally-matched (although note that Hancock et al., 2008, find that one spectrally-matched record is sufficient to predict most response quantities accurately, and a suite of only one record is taken 100% from a single event!).

Finally, to the authors' knowledge, spectral matching of records which include near-field characteristics has not been studied in sufficient detail to give recommendations here. The work of Baker (2007b), who presented a numerical measure of the presence of a near-field pulse in an accelerogram, could be useful for automated identification of appropriate ground motions. Since spectral matching adds wavelet function to existing peaks, it seems that careful selection of input records and a target spectrum, and the use of wavelet forms that preserve velocity pulses could generate ground motions with near-field characteristics. Since near-field motions tend to be more highly polarised than far-field ones, the use of *RSPMatch2005bi* (see Section 2.2) may also be worthwhile.

3. AUTOMATION OF SELECTION AND SCALING CRITERIA

Automation of the selection criteria discussed above allows efficient and consistent record preparation across a range of projects, even if every application has its own requirements determined by local design codes and local practice. Furthermore, automating the selection and scaling of seed motions means that records can be easily converted between different file formats, and output can be presented in a graphical form for ready assessment of the spectral matching process. For these reasons, a program that embodies much of the selection and scaling philosophy discussed above was developed by Arup, using the Matlab® Graphical User Interface (GUI) Editor (Mathworks, 2007). The program has been employed in a number of projects for which spectrally-matched ground motions were required (e.g. Ghosh and Bhattarcharya, 2008). The main screen in the GUI is illustrated and annotated in Figure 1.

r first selects a preliminary scaling and selection algorithm, initial criteria for filtering the database, and limits on linear scaling of the seed records. Following this, the target spectrum is read in from an input file. The program then automatically determines optimal linear scaling factors for all the records in the database, applies the filtering according to the user criteria, and sorts the remaining records in order of fit to the target spectrum. In the interests of speed, this preliminary sorting is based on the GMRotI50 (Boore et al., 2006) spectral ordinates provided with the PEER NGA flatfile, even for applications where only a single ground motion component is required, or for which the GMRotI50 spectral ordinates are not relevant (such as when the target spectrum is based on the maximum component). This allows the initial sorting to be carried out for the whole PEER NGA database in just a few seconds on a personal computer. Re-filtering of the database is carried out "on the fly" when input filters are edited by the user, and the number of records passing the filter is displayed.

Following the initial selection, the user may carry forward a number of records for further processing, based on a more computationally-demanding selection algorithm, selected by the user. For applications where only one ground motion is required, the "best single horizontal match" may be generated, based on the rotation approach discussed in Section 2.2. Clearly, the calculation of 180 response spectra (180° in 1° increments) for a range of periods is more computationally-demanding than the initial filter (based on spectral ordinates already provided

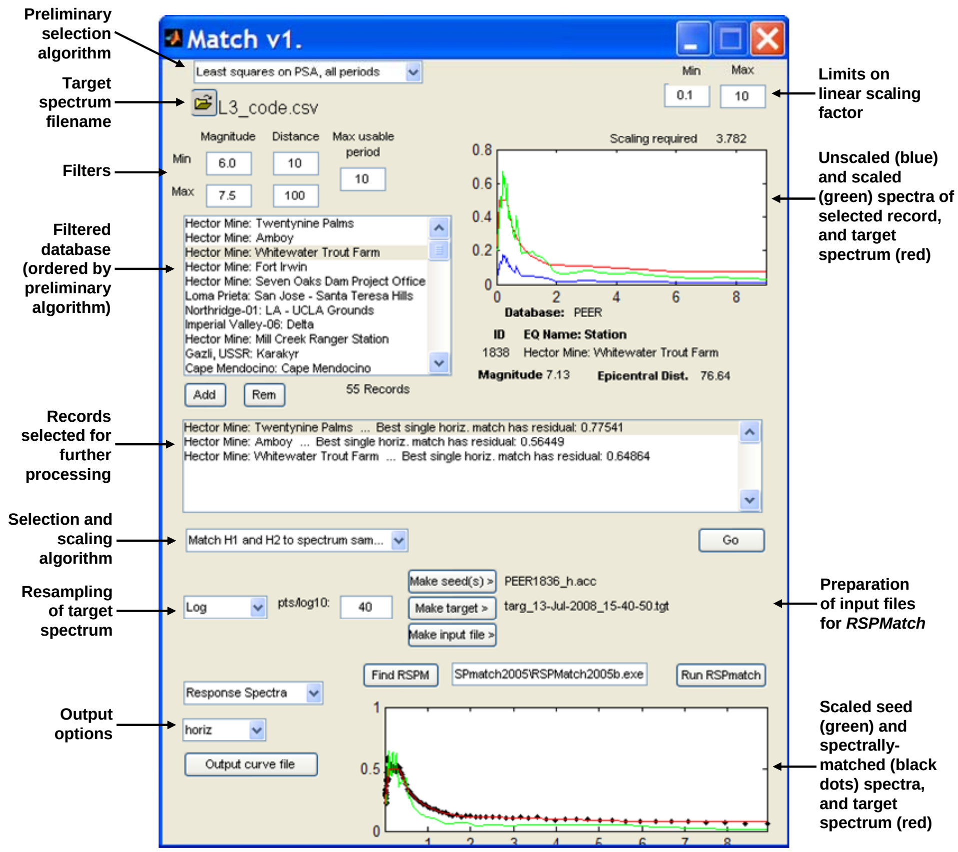

Figure 1 Screenshot of Arup in-house ground motion selection program with annotations of key features

in the PEER NGA flatfile), but this stage may be carried out on a much smaller number of records, based on the initial filtering, in a few seconds of computation time.

When more than one ground motion component is required, the program currently allows one of two options: either scale the two components individually by different scaling factors to optimise the individual fit to the target, or scale them both by the same factor to minimise the sum of the errors. In the current version of the program, no rotation of the components is carried out, although an algorithm analogous to the "best single horizontal match" is planned and could easily be implemented, as discussed in Section 2.2. Note that only one target spectrum is allowed by the program, although the next version of the program will allow different target spectra for maximum and minimum rotated components, for use with *RSPMatch2005bi*.

Once records have been selected for input to *RSPMatch2005*, the input files (*.inp, *.tgt and *.acc files) are prepared. The target spectrum is resampled with user-defined spacing (either linear or, as recommended by the *RSPMatch2005* manual, logarithmic spacing). The preparation of the *.inp file loads a separate interface which presents, by default, input parameters recommended in the *RSPMatch2005* manual. The *RSPMatch2005* executable is called from the GUI, and, when matching is complete, results are displayed on the screen, allowing rapid assessment of whether the spectral matching has been successful, and of the quality of the output.

Version 2.0 of the ground motion selection and *RSPMatch2005* pre- and post-processing program is in development. The new version allows more options for database management, filtering records, and algorithms for selecting records that meet a wider range of project-specific requirements and seismic design codes. The new program also allows an interface for *RSPMatch2005bi*, discussed in Section 2.2, including different inputs for the maximum and minimum target spectra.

4. CONCLUSIONS

Selecting seed records for spectral matching software such as *RSPMatch2005* is not significantly different from selecting real recorded ground motions to use unaltered in time history analysis. Rather than give a thorough literature review of guidelines for selecting records, we have attempted to highlight the unique features of selecting seeds for matching, as well as to provide some new insight into how the whole procedure can be rationalised and automated.

Spectral matching attempts to minimise the variability in the input to thereby minimise the variability in the output, and allow a smaller number of records to be reliably used. We carry through this objective to other characteristics of the ground motion such as duration and Arias intensity, by including them explicitly in the selection process rather than relying on a large suite of records to give the expected values in the average. We also insist that only records with usable frequencies which include all dominant frequencies of the structure should be used, as otherwise the noise-to-signal ratio is too high. As demonstrated in the example of the Arup selection software, the above guidelines can readily be automated, allowing a suite of spectrally-matched records to be generated and checked within a relatively short time.

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