Generation of Improved Artificial Earthquakes For Seismic Qualification Testing

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SUMMARY:
Most international codes for seismic qualification testing of equipment specify that an artificial earthquake is used as an input motion. These time histories are typically generated iteratively starting with pseudo random number sequences, however the resulting shakes often place significant acceleration, velocity and displacement demands on the shaking table. Where this demand is beyond the performance of the table, most codes propose high pass filtering of the time histories to reduce the low frequency demand. This results in table motions that can be achieved, but the shakes will now not put the required energy into the specimen across the full range of frequencies defined by the code. Potentially this could result in an under-test of the specimen. Therefore some methods of modifying the time history generation process are suggested to reduce the performance demands made on the table without replying so heavily on high pass filtering of the earthquake motions.

Keywords: seismic qualification, equipment, shaking table, artificial time histories

1. INTRODUCTION

The majority of international codes used to define the requirements for seismic qualification testing of equipment for installation in seismic zones specify that an artificial earthquake is used for the shaking table testing. The codes specify that this artificial earthquake should be generated such that it matches a defined response spectra at a particular level of damping. A variety of other parameters such as strong motion duration, ramp times, number of strong motion peaks etc. for the time history are also defined by the various codes. Appropriate time histories meeting these requirements can be generated iteratively starting with pseudo random number sequences or starting with actual earthquake records. However these methods can create a range of earthquakes where there is a significant difference in the demand placed on the shaking table in terms of maximum acceleration, velocity and displacement required to reproduce the motions. Where this demand is beyond the performance of the shaking table to be used, most codes adopt some form of high pass filtering of the time histories to reduce the low frequency demand on the table. This results in table motions that can be achieved but it does mean that the resulting motion will not put the required energy into the specimen across the full range of frequencies defined by the code.

This paper compares the characteristics of artificial earthquakes produced to meet three of the main seismic qualification codes and considers the response of an idealised specimen subjected to these various motions. The adverse effect of high pass filtering of these time histories on the specimen response is also considered. In some cases it is possible that this modification of the time history will result in an under-test of the specimen which may mean that the equipment is not in fact fit for purpose when installed on site. Finally some methods are suggested whereby the time history generation process can be modified so that the performance demand made on the shaking table can be reduced without having to reply so heavily on high pass filtering of the earthquake motions.

2. SEISMIC QUALIFICATION CODES

A number of different codes are used for the seismic qualification of equipment but in this paper three of the most widely used codes are considered. For these codes the main requirements for the generation of the artificial earthquakes used for qualification testing are summarised below:

2.1 IEEE344 (2004) - Seismic qualification of equipment for nuclear power generating stations

IEEE344 (2004) is probably the most widely used test specification. The key requirements specified by this code for the derivation of the input motion are:

a) The TRS (Test Response Spectra) must envelope the RRS (Required Response Spectra) over the frequency range for which the particular test is designed (typically DC to 50Hz) to provide a conservative (but not overly so) test-table motion. A 5% damping value is normally assumed.
b) For comparison of the TRS and the RRS, the TRS must be computed with a damping value equal to or greater than that of the RRS and the analysis should be done at 1/6 octave points (or at a narrower bandwidth resolution).
c) The shaking table maximum peak acceleration must be at least equal to the ZPA (Zero Period Acceleration) of the RRS.
d) The time history should be stationary, i.e. the frequency/amplitude content of the waveform is statistically constant with time and does not vary significantly during the test. The code suggests a time interval TRS can be used to show this.
e) To properly account for vibration build-up and low-cycle fatigue effects, the duration of the strong motion portion of each test should at least be equal to the strong motion portion of the original time history used to obtain the RRS, with a minimum duration of 15 s. For tests using artificial earthquakes the stationary part of the test defines the strong motion length.

The IEEE344 code also notes that an input motion that fully envelopes the RRS occasionally requires high acceleration levels at the lowest frequencies which requires very high shaking table displacement capability. The code therefore proposes that the general requirement for enveloping the RRS by the TRS can be modified in the following way:

a) In those cases where it can be shown by a resonance search that no resonance response phenomena exist below 5 Hz, it is required to envelop the RRS only down to 3.5 Hz. However excitation must continue to be maintained in the 1 Hz to 3.5 Hz range to the capability of the test facility.
b) When resonance phenomena exist below 5 Hz, it is required to envelop the RRS only down to 70% of the lowest frequency of resonance.

This modification can be made either by high pass filtering the table motions generated to match the complete RRS or by reducing the RRS at the lower frequencies so that the matching algorithm simply generates a motion without the lower frequency contents.

2.2 IEEE693 (2005) - Seismic design of substations

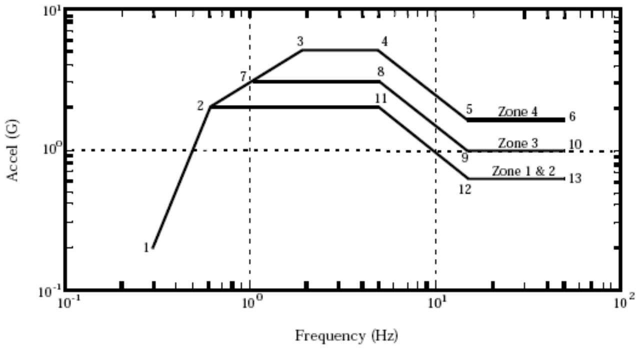
The second code to be considered is IEEE693 (2005). Although this code deals more specifically with the seismic design of substations and electrical switchgear it makes an interesting comparison with IEE344. This code was developed in collaboration with academics (Takhirov et al. (2005)) and the key extensions and differences between this code and IEEE344 are that:

a) The spectrum matching procedure should be conducted at 1/24 octave points or higher and result in a theoretical response spectrum that is within ±10% of the RRS at 2% damping.
b) For comparison of the TRS and the RRS, the TRS shall envelop the RRS within a –10% / +50% tolerance and the analysis should be done at 1/12 octave points (or at a narrower bandwidth resolution).
c) In lieu of developing a set of input motions for a time history test empirically based input motions are available.

IEEE693 also makes reference to the fact that there is a need to balance the concern that the equipment be tested should be adequately excited while at the same time avoiding over-testing equipment during its qualification. In particular this is the only code, that the author is aware of, that seeks to limit the number of cycles at excitation frequencies between 0.78Hz and 11.78Hz by specifying that the table motion shall include at least 2 and a maximum of about 25 high amplitude cycles of an SDOF oscillator response at 2% damping. A “high amplitude cycle” is defined as a cycle which consists of two positive or negative peaks of the same range with a peak of opposite sign between them, having an amplitude greater than or equal to 70% of the maximum response of the SDOF oscillator.

2.3 GR-63-CORE - Network Equipment-Building System (NEBS) requirements

The third code considered is GR-63-CORE (2002). Although this code does specify a RRS at 2% damping, as shown in Fig. 2.1, the code actually states that testing should by done using a prescribed waveform, VERTEQII, shown in Fig. 2.2. Nevertheless as an alternative many clients will accept a response spectrum compatible artificial earthquake that matches the spectra defined in this code. Using spectrum compatible motions also allows the generation of triaxial shakes rather than three identical single axis motions which helps to reduce the amount of shaking the specimen is subjected to and helps to minimise the effects of fatigue on the specimen.



Coordinate Point	Frequency (Hz)	Values for Upper Floor Acceleration (g)	Coordinate Point	Frequency (Hz)	Values for Upper Floor Acceleration (g)
Zones 1 and 2			Zone 4		
1	0.3	0.2	1	0.3	0.2
2	0.6	2.0	2	0.6	2.0
11	5.0	2.0	3	2.0	5.0
12	15.0	0.6	4	5.0	5.0
13	50.0	0.6	5	15.0	1.6
Zone 3			6	50.0	1.6
1	0.3	0.2			
2	0.6	2.0			
7	1.0	3.0			
8	5.0	3.0			
9	15.0	1.0			
10	50.0	1.0			

Figure 2.1. GR-63-CORE Required Response Spectra (From GR-63-CORE)

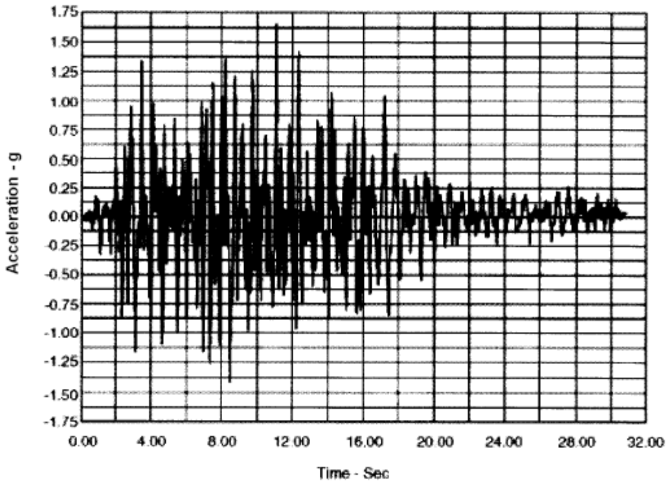


Figure 2.2. VERTEQII Zone 4 Earthquake Waveform (From GR-63-CORE)

In order to cope with the high displacement demands needed to recreate this waveform the GR-63-CORE code notes that the waveform can be filtered to reduce the low frequency components. Again the key differences between this and the codes already discussed are that:

a) The cut-off of the high pass filter on the drive signal shall not exceed 0.20 Hz and the cut-off of the low pass filter on the drive signal shall not be below 50 Hz.
b) The reproduction of the VERTEQII waveforms shall be verified by analyzing the TRS at 1/6 octave points from 0.5 to 50Hz. The sampling frequency of the time history also must be >200 Hz.

2.4 Important differences between the three test specifications

All the codes outlined above define the frequencies at which comparisons between TRS and the RRS should be made, with these frequencies defined as either 1/6 or 1/12 octave points. However, only one of the codes defines the frequencies at which the artificial earthquakes should be matched. This omission has the potential to result in the creation of test motions that significantly under-test some specimens. For example, if the earthquake generation process only ensures that frequencies at the 1/6 octave points contain the correct energy to match the RRS there is the potential for frequencies between these points to have significantly higher, or more importantly, lower energy content. An example of this problem can be seen in Fig 2.3. The thick line shows the spectra for an earthquake only matched at 1/6 octave intervals and this spectra is close to the RRS at these 1/6 octave points. The spectra is also well within the ±4% tolerance limits shown. However when the spectra for this time history is calculated at every FFT frequency (the thin line) it is clear that there is a significant variation from the RRS at some frequencies. If a specimen being tested with this time history had a natural frequency of 2.4 Hz it would experience a spectral acceleration of 3.9g rather than the 5.4g RRS value, whereas if the specimen frequency was 3.3 Hz it would experience 6.7 g spectral acceleration. It is therefore important that the matching process always includes a sufficient number of frequency points even if the code being used does not specifically define this number.

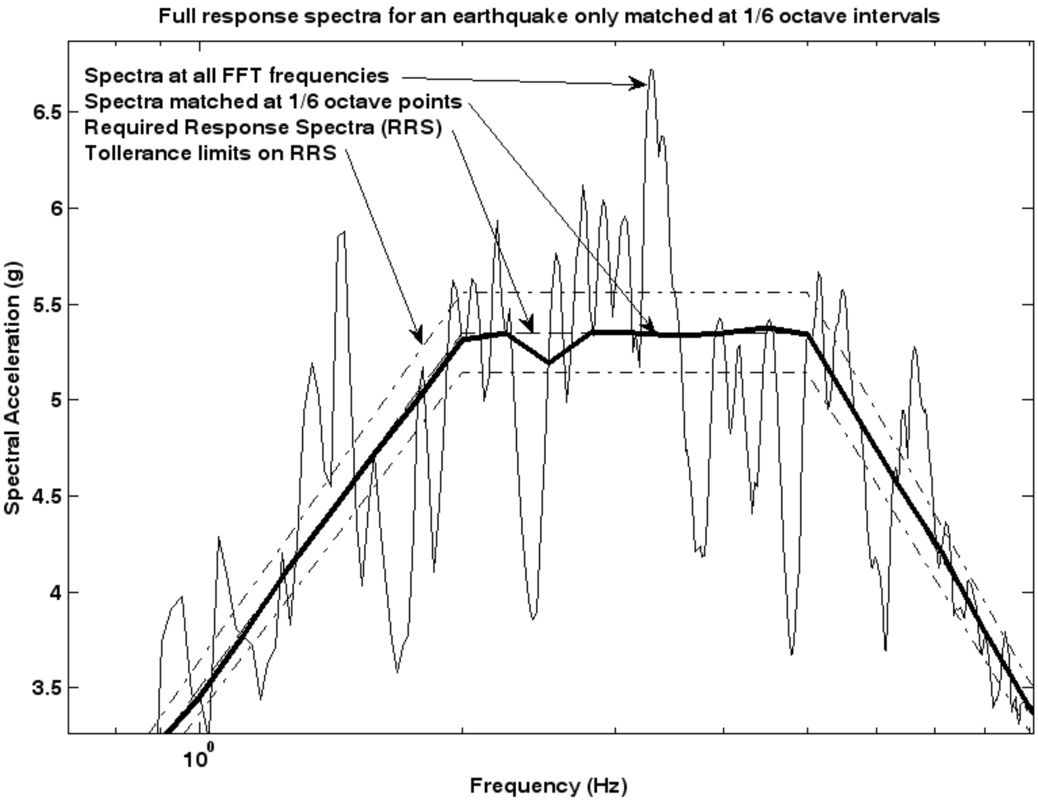


Figure 2.3. Full response spectra for an earthquake matched at 1/6 octave points

The other main difference between the codes is the level of high pass filtering of the table motion that is allowed, with the codes recommending that the motion should match the RRS above 0.5Hz, above 70% of the lowest frequency of resonance, or above 3.5 Hz depending on circumstances. In general the underlying assumption is that the input motion must match the RRS down to 70% of the lowest natural frequency of the specimen under test. Fig. 2.4 shows the standard response of a SDOF oscillator with different damping levels subjected to sinusoidal excitation. It can be seen that at 70% of the natural frequency of the oscillator the amplification ratio for the SDOF system is only about 2 and this value is almost independent of the specimen damping. This suggests that only requiring matching of the TRS down to 70% of the specimen natural frequency is reasonable.

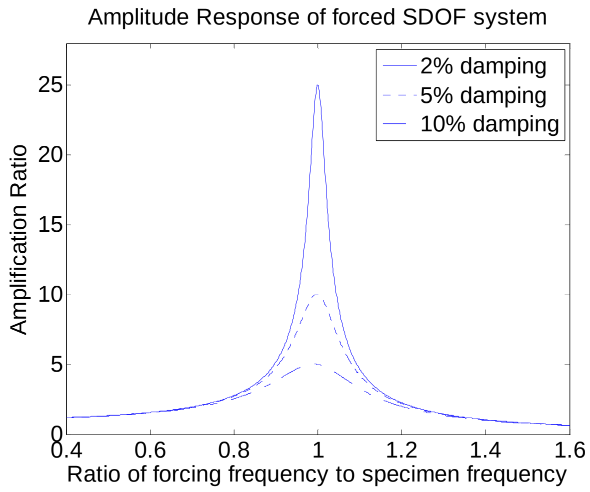


Figure 2.4. Response of s SDOF system to forced excitation at different damping levels.

Therefore if the specimen to be tested is known to have a low natural frequency this frequency can be used to determine the frequency above which the TRS must match the RRS. However prior knowledge of the specimen response is often not available before testing and then this high pass filtering of the input motion becomes more important and, thereore, should be kept to an absolute minimum. Ideally, if the specimen's natural frequency is unknown, to ensure the specimen will be subjected to input down to at least 70% of its natural frequency, the RRS should be matched across the full frequency range defined in the relevant code. However, this can result in motions that are unobtainable on most tables. For example to reproduce the GR-63-CORE Zone 4 spectra down to 0.3Hz a peak table displacement of around ±300mm is needed which is beyond the capacities of most tables around the world, a list of which can be found at Crewe (2008). Therefore the TRS motions are often high pass filtered so that they are achievable on the shaking table being used for the testing. While this will reduce the displacement capacity needed to reproduce the motion it is unlikely that the filtered motion is now optimal considering the performance limits of the shaking table. Therefore rather than filtering the input motion an alternative matching process is proposed whereby a large number of potential motions are compared to find the ones that accurately match the RRS down to the lowest possible frequency while minimizing the displacement, velocity and acceleration demands placed on the table.

3. GENERATION OF ARTIFICIAL EARTHQUAKES MATCHING A DEFINED RRS

The basic process for generating an artificial earthquake that matches a defined RRS, starting with a white noise or a pseudo random number sequence, is shown in Fig. 3.1. For all the data presented below the same repeatable seed number sequence was used as a starting point for all the matches. In this way any differences between results given are due to changes made to details in the matching process rather than as a result of a different initial starting position.

The process shown in Fig 3.1 is iterative and will quickly produce a time history that has a TRS that matches the RRS over the defined frequency range with reasonable accuracy. However, if the iteration process is continued beyond this first convergence it is often possible to find a better match for the TRS. This is particularly true if the damping level for the RRS is lower than 5% because there tends to be some oscillation of the calculated TRS around the RRS. This oscillation can be reduced, although it cannot be eliminated, by adjusting the FFT amplitudes using only a proportion of the inverse of the ratios of required spectral value to calculated spectral value at each frequency (rather than the 100% adjustment shown in Fig 3.1). Fig 3.2 shows the errors between the TRS and the RRS for 3000 matching iterations with 100% adjustment (left) and 80% adjustment (right) to the FFT amplitudes. The use of an 80% error adjustment clearly improves the stability of the matching process.

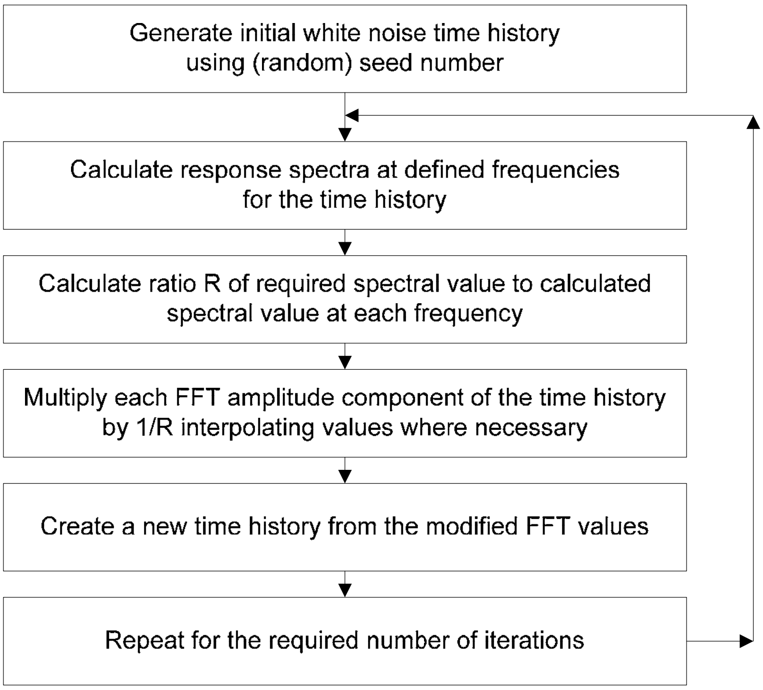


Figure 3.1. Flow diagram for iterative response spectra matching

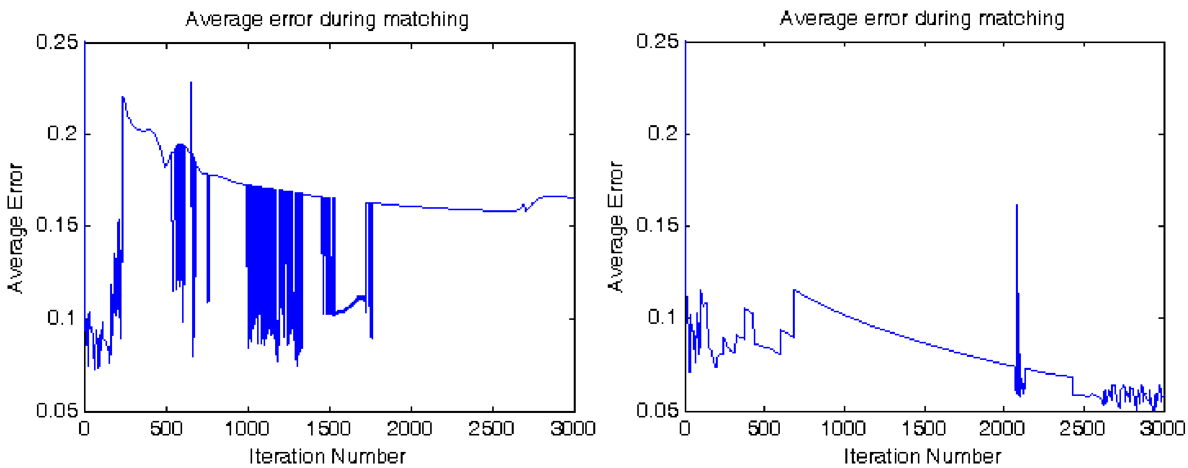


Figure 3.2. Error during matching with 100% (left) and 80% (right) adjustment of error at each iteration.

3.1 Number of iterations in matching process

Fig 3.2 (right) also shows the benefit of continuing the iteration process significantly beyond initial convergence. In this case the time histories matching the RRS most closely are only found after 2600 matching iterations. Therefore a significant number of iterations should always be performed to give the best chance of capturing a good match for the particular starting point used.

However it is worth noting that although a particular time history might have an overall excellent match to the RRS it is also important to look at the number of points in the TRS outside the tolerance limits. Therefore to decide which is the best time history that was generated using a particular seed number it is suggested that iterations with the fewest number of points above and below the defined tolerance limits on the required spectra are compared. Of these iterations either the one with the smallest peak displacement, velocity or acceleration or the one with the smallest average error can be picked depending whether accuracy of matching or minimization of demand is deemed most important.

3.2 Number of frequency points used when matching TRS and RRS

In section 2.4 the importance of getting a good match at all frequencies across the testing range was noted. IEEE693 states that matching of the TRS and RRS should be done at a minimum of 1/24 octave points. The effect of changing the number of frequencies being matched can be seen in Fig 3.3. In this case a GR-63-CORE spectra is being matched from 0.8Hz to 50Hz. The lowest lines show the original spectra which has been multiplied by 1.07 to get a target spectra 7% higher than the base spectra. This target then has tolerance bands of ±4% added, similar to those shown in Fig 2.3. In all four cases the TRS is almost indistinguishable from the RRS (except below 0.8Hz) where it falls well below the RRS values. However the spectral values calculated at all FFT points vary considerably. Fig 3.3 (c) shows that the full spectra for a time history matched at 1/24 octave points is generally within about 5% of the required value at all frequencies. This is significantly better than the spectra for time histories where only 1/12 or 1/6 octave points were matched where there were errors at some frequency points as high as 40%.

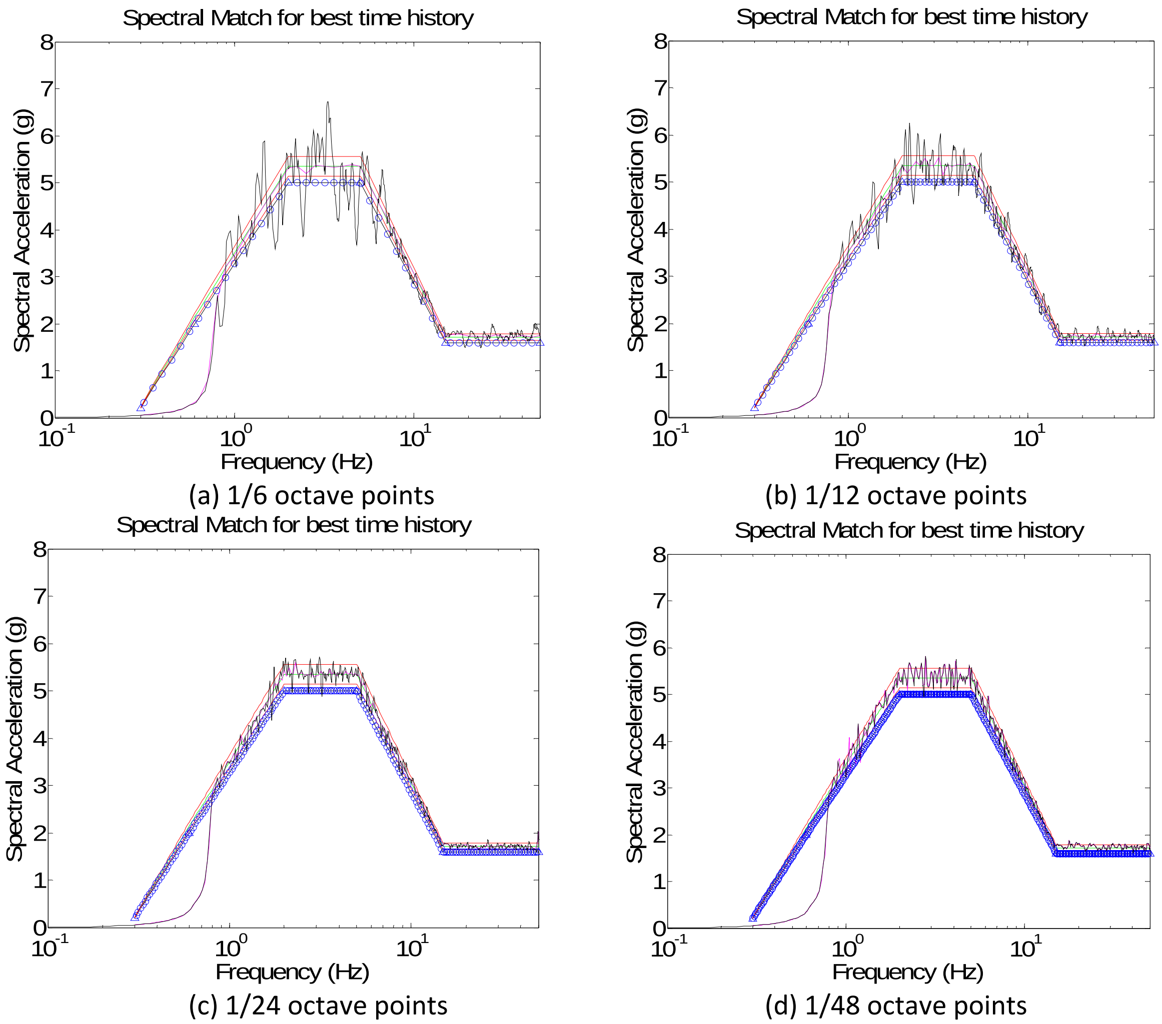


Figure 3.3. Matching of GR-63-CORE spectra from 0.8Hz to 50Hz a different frequency resolutions

It is also useful to compare the characteristics of the time histories associated with each of these matches. Table 3.1 shows the peak demands for each of these time histories. It is interesting to note that although matching at more frequency points does tend to increase the peak displacements the increase is not that significant considering the corresponding improvement in quality of the spectral match. The main disadvantage of matching at more frequencies is the time taken for the matching. In this case doubling the number of frequency points increased the iteration time by aprox 60%. Therefore matching at 1/48 octave points is not recommended because the improvement in matching is not significantly better than at 1/24 octave points.

Table 3.1. Characteristics of motions generated with same random seed, matched at a different frequency intervals

Frequency points being matched	1/6 octave	1/12 octave	1/24 octave	1/48 octave
Peak displacement	119.8 mm	125.5 mm	132.6 mm	133.4 mm
Peak velocity	1.09 m/s	0.99 m/s	0.99 m/s	0.99 m/s
Peak acceleration	1.42 g	1.31 g	1.36 g	1.44 g
Time taken for 200 iterations	4.2 s	6.4 s	11.3 s	18.2 s

3.3 Low frequency cut-off used in matching

In section 2.4 the use of high pass filtering of input motions was described as a way to reduce the demands made on the shaking table during testing. Unfortunately filtering a matched TRS motion also has an impact on the quality of the match between TRS and RRS over the full range of frequencies. This can be seen in Fig 3.4 where an 8^{th} order high pass filter has been applied to the TRS on the right. The filtering (from 0.6Hz) has reduced the peak displacement demand of the time history from 335mm to 222mm but quality of the matching has also deteriorated.

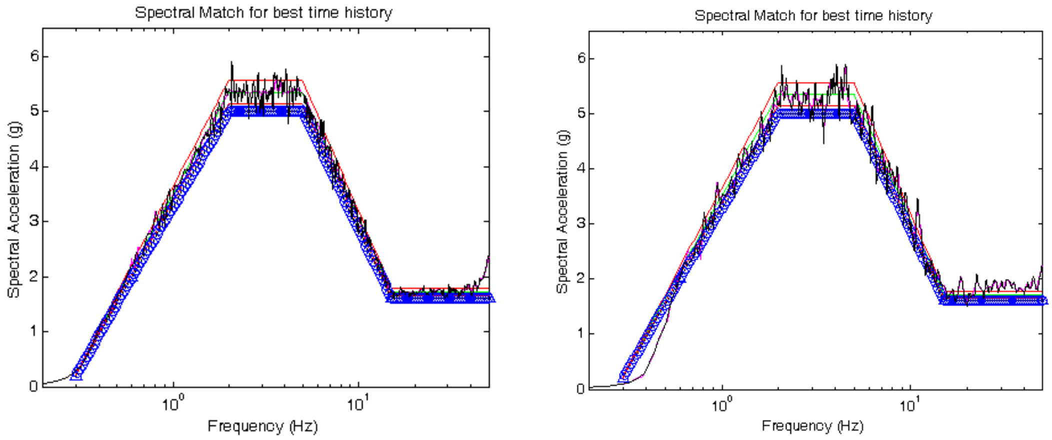


Figure 3.4. Effect of high pass filtering on quality of TRS/RRS match (left) unfiltered, (right) filtered

As an alternative to high pass filtering the matching process can be modified so that matching only occurs over the frequency range of interest. In this way the quality of the matching can be maintained down to the lowest frequency defined. Fig 3.5 (left) shows an equivalent match (i.e. from 0.6Hz) to that shown in Fig 3.4 (right) but the quality of the match over the whole frequency range is better. It is also worth noting that the peak displacement for this match (188mm) is significantly lower than that for the filtered time history (222mm). Indeed if it is accepted that a displacement limit of about 222mm is acceptable for use on the shaking table in question then, using this method, it is possible to match down to 0.5Hz, Fig 3.5 (right), and still have a peak displacement of only 228mm.

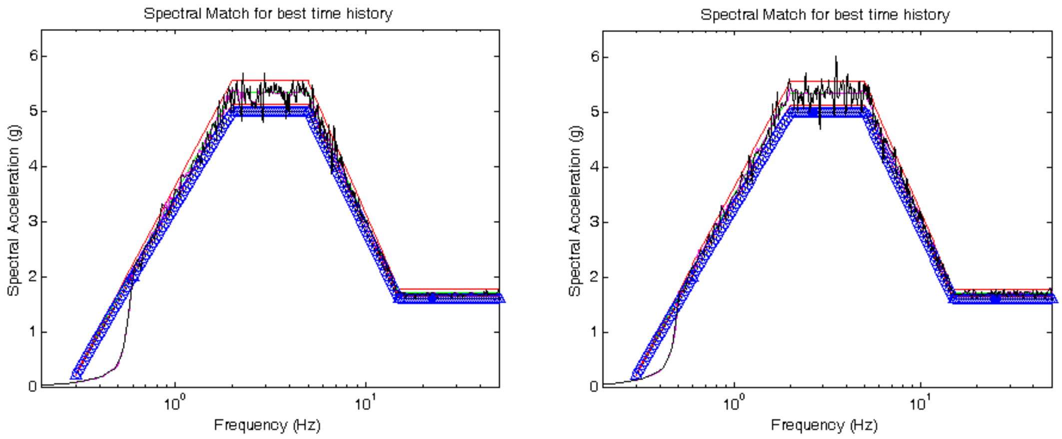


Figure 3.5. Matching over defined frequency ranges (left) >0.6Hz, (right) >0.5Hz instead of filtering

The impact of matching over reduced frequency ranges as a means to reduce the performance demands on a shaking table can be seen in Table 3.1 where a small change in frequency content can have a large impact on the resulting time history.

Table 3.2. Typical characteristics of 'best' iteration for different low frequency cut-offs

Cut-off frequency for matching	0.3 Hz	0.5 Hz	0.8 Hz	1.0 Hz	2.0 Hz
Peak displacement	326.2 mm	220.6 mm	140.2 mm	109.5. mm	36.3 mm
Peak velocity	1.70 m/s	1.40 m/s	1.16 m/s	1.15 m/s	0.61 m/s
Peak acceleration	1.70 g	1.76 g	1.67 g	1.63 g	1.44 g

4. OPTIMISATION OF TIME HISTORIES FOR TESTING

The methodology described above can be used to generate a single time history that accurately envelopes a specified RRS. However it is then desirable to repeat this whole process a number of times to search for a time history with the best characteristics for the shaking table being used for the qualification tests. This might involve hunting for a time history that minimises the peak displacement, velocity or acceleration. The characteristics being minimised will depend on the shaking table and the characteristics of the spectra being matched, but for most shaking tables it is likely that the low frequency performance (i.e. peak displacement) is the limiting factor. Therefore the following optimization processes have looked to minimize the peak displacements, although similar effects can be observed if searching for time histories with minimum velocities or accelerations.

Three batches of runs with a different number of matched time histories were compared. Each batch used the same random seed sequence to generate the time histories so the smaller batches form part of the largest batch. In the smallest batch, which compared only 20 time histories, the 'best' motion had a peak displacement of 119.8mm whereas in the batch of 1000 time histories the 'best' motion had a peak displacement of 106.8mm. The characteristics of the earthquakes with the smallest peak displacement found in each batch are summarized in Table 4.1.

Table 4.1. Characteristics of 'best' time history found for different batch sizes

Number of Time histories compared	20	200	1000
Peak displacement	119.8 mm	111.9 mm	106.8 mm
Peak velocity	1.09 m/s	0.98 m/s	0.95 m/s
Peak acceleration	1.42 g	1.45 g	1.49 g

When the batch of 200 time histories were generated a total of 127 did not exceed a specified velocity limit of 1.5m/s and the peak displacements for these time histories are shown in Figure 4.1 (left). For the larger batch of 1000 time histories, 589 did not exceed the velocity limit and their peak displacements are shown in Fig. 4.1 (right).

The relatively linear distribution of peak displacements found in the 200 runs (Fig 4.1 (left)) shows that this number of runs is not able to pick up the extreme ends of the distribution. However when more time histories are compared (Fig 4.1 (right)) it is clear that some of the most optimial motions at the extremes of the distribution are now being found. However the improvement in peak displacement demand between these two runs (5.1mm or just under 5%) might not justify the additional fivefold computational effort except in extreme cases.

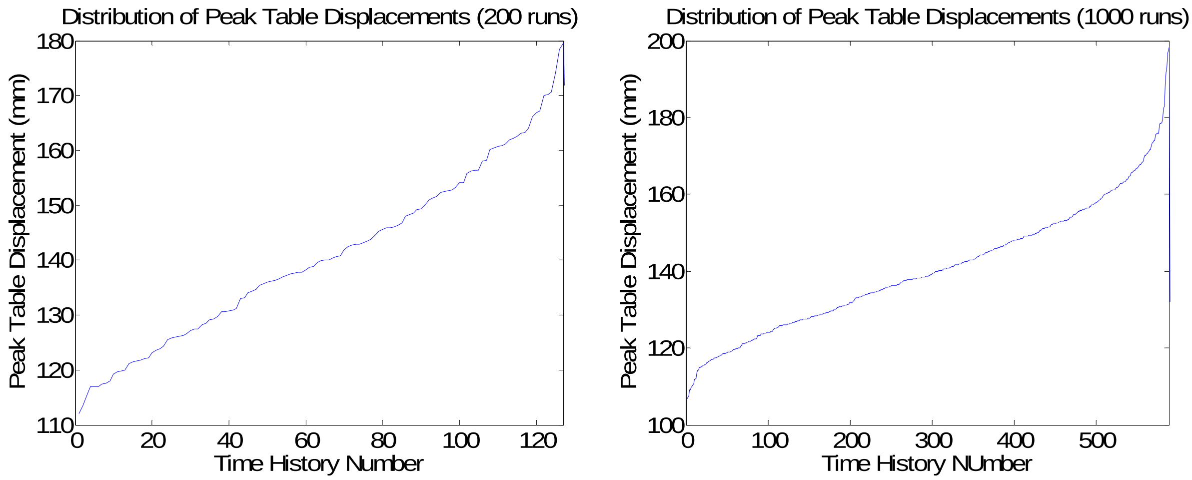


Figure 4.1. Sorted distribution of peak table displacements comparing 200 (left) and 1000 (right) time histories

5. CONCLUSIONS

The author does not believe that any of the three codes outlined in this paper fully address the issues arising from the generation of artificial earthquake for seismic qualification testing. However by using the best aspects of each of the codes it is possible to generate time histories that are an excellent match to any specified RRS. In order to achieve the best possible match of a RRS the following recommendations are made:

a) The iterative matching process for each time history should be continued beyond initial convergence to capture later iterations that may be a much closer match to the RRS.
b) The spectra matching procedure should be always conducted at a minimum of 1/24 octave points.
c) High pass filtering of input motions should not be used to limit the demands placed on the shaking table by the TRS. Matching over a reduced frequency range is more effective and results in a TRS that matches the RRS more closely.

Finally by repeatedly generating time histories using different initial starting conditions to create a reasonably large set of motions it is possible to find motions that place significantly lower demands on the shaking table which will enable matching of the RRS down to the lowest possible frequency.

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