SELECTION OF TIME SERIES FOR SEISMIC ANALYSES

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ABSTRACT

To obtain design time series, it is common practice to select empirical recordings of ground motion and modify them by scaling or by making them spectrum compatible. Even after making time series spectrum compatible, the computed nonlinear response of a system can vary greatly depending on the recordings selected. A method for generating a time series selection procedure based on properties of the structure and ground motion, not simply magnitude and distance is presented. The procedure is for use in nonlinear analyses that are intended to result in an average response of the nonlinear system.

The structure specific properties are considered using a proxy of the nonlinear system. Using a suite of recorded and scaled ground motions as inputs, a regression analysis is performed to develop a model for the proxy response based on the properties of the record and the proxy. Candidate scaled time series are evaluated to find those that yield a response of the proxy that is near the expected response for an event. Those scaled time series with responses near the expected value are selected as the optimum time series for defining average response even if the scale factors are larger than commonly accepted.

Results for applications to structural response and slope stability are discussed. The resulting time series selection methods allow for wider magnitude and distance bins for candidate time series, and reduce variability in the response of the system.

Keywords: Time series, dynamic, nonlinear

INTRODUCTION

Most structures will experience inelastic deformations when subjected to severe earthquake ground motions. Many simplified techniques have been developed to estimate inelastic structural response for design purposes (e.g. Newmark and Hall, 1982; Makdisi and Seed, 1978). These procedures produce relatively small errors in the mean global displacement values, but the variability of the results can be substantial, particularly for large levels of inelastic behavior (Miranda and Ruiz-Garcia, 2002; Rathje and Bary, 2000).

For design under high inelastic demands, the uncertainty with these design procedures increases to a point that requires a high level of conservatism to avoid failure. More accurate analysis methods are needed to assess the performance of the structure. Nonlinear dynamic seismic analysis is increasingly common as a means to validate the simplified estimates of inelastic response used in the design process, and to assess the impact of higher mode effects on the structure. Due to the small number of time series used and the high variability of structural response, there are a number of potential
problems that must be surmounted. The response of the structure is sensitive to the time series selected and the method of modification employed. Thus, the estimates of structural response are dependent on the suite of time series used in the analysis. Additionally, with such large variability, the standard error of the estimates of response is large and it is difficult to make statistically significant conclusions.

If we limit ourselves to a few time series, the goals of the analysis must be more narrowly focused. We can achieve this by identifying a nonlinear engineering demand parameter on which the other response parameters are conditioned. If we choose time series that lead to a median value of the primary engineering demand parameter, then we reduce the variability in the estimates of the other response parameters.

Watson-Lamprey and Abrahamson (2006a) proposed a method for selecting time series such that after scaling, they lead to a near median response of a nonlinear parameter. The main concept is that using a simple nonlinear model we can evaluate a large number of candidate time series and from this large set identify those that lead to average response. First, we find a simple nonlinear model that can serve as a proxy for the more complicated nonlinear model for which we want a median response. Using the simple nonlinear proxy, we calculate response using as many time series as are available with differing degrees of nonlinearity. We then model the response of the proxy based on the record properties of the input time series. This tells us which record properties significantly influence nonlinear response.

We assume that the properties that lead to median response of the proxy will lead to median response of the more complicated system. We then develop predictive equations for the record properties that are important using the parameters of the design event (M, R, Sa). Using the predicted record properties, time series can then be selected based on their record properties, such that their record properties lead to a median nonlinear response of the proxy given the design event.

An engineering demand parameter must be identified that is sufficiently correlated to the secondary response parameters to reduce the variability to manageable levels. Additionally, it must be appropriate to check a median value of the response parameter selected. This engineering demand parameter will likely be a nonlinear response value of global system response (ie roof displacement).

**BUILDINGS**

Nonlinear static procedures are popular with practicing structural engineers (FEMA 440). Two options are used predominantly: 1 – equivalent linearization techniques based on the assumption that the maximum total displacement of a SDOF oscillator can be estimated by the elastic response of an oscillator with a longer period and higher damping than the original, and 2 – displacement modification procedures that estimate the total maximum displacement of the oscillator by multiplying the elastic response by one or more coefficients. These procedures estimate the median ratio between nonlinear response and linear response. They are often adequate for estimating global nonlinear displacement, but not story shear and overturning moment (FEMA 440). If the procedure is adequate for estimating global displacement, then it is appropriate to examine a median response in the seismic analysis.

If time series are selected and modified to produce median nonlinear global displacement, then the seismic analysis will provide information on the variability in higher mode response parameters given the global displacement value. These higher mode response parameters will have a smaller variability due to the reduction in variability in global displacement. The predictions of engineering demand parameters within the structural model using the small number of time series that are generally employed will then be more statistically significant.

For predominantly first mode structures the nonlinear global displacement is proportional to the first mode inelastic response. Thus, if we use an elastic perfectly plastic oscillator with an initial period equal to that of the first mode of the structure as our proxy, we can develop a time series selection
algorithm that will yield time series that produce the median nonlinear first mode response of our structure given the design event.

Watson-Lamprey and Abrahamson (2006b) developed a time series selection method based on the response of an elastic perfectly plastic oscillator with an initial period of 1 second. Their evaluation of the bilinear oscillator response showed that response can be modeled with a relatively small variability if four properties of the time series are known: 1 – the ratio of pseudo-spectral acceleration at two times the fundamental period of the structure and the period of the structure \((S_{a2T_1}/S_{aT_1})\), 2 – the root mean square of acceleration \((A_{\text{RMS}})\), 3 – the peak ground velocity (PGV) and 4 – uniform duration calculated above the yield acceleration at the fundamental period of the structure \((\text{Dur}_{\text{UNI}})\). This allows for selection of time series such that after scaling, the time series parameters lead to a median bilinear oscillator response similar to that expected for the design event.

**BUILDING EXAMPLE APPLICATION**

As an example consider a building with a fundamental period of one second and the design event listed below:

PGA: 0.72 g
SAT=1s: 1.2g
SAT=2s: 0.61g
M: 7

The response spectrum is shown in Figure 1.

![Figure 1. Design response spectrum for example application.](image)

For this structure, assume that the R-value is 5.

Using the time series selection method developed by Watson-Lamprey and Abrahamson (2006b). Time series can be chosen that lead to a median nonlinear first mode response value using the following steps:

1. Compute the median \(A_{\text{RMS}}, \text{Dur}_{\text{UNI}}\) and PGV given the design event parameters using the models given below in eqs. 1, 2 and 3. Using the design event parameters, the \(A_{\text{RMS}}, \text{Dur}_{\text{UNI}}\) and PGV are: \(A_{\text{RMS}} = 0.225 \text{ g}, \text{Dur}_{\text{UNI}} = 8.4 \text{ sec} \) and \(\text{PGV} = 90 \text{ cm/s}\).

\[
\ln(A_{\text{RMS}}(g)) = -1.167 + 1.02 \ln(\text{PGA}) + \epsilon(\sigma = 0.20) \tag{1}
\]

\[
\ln(\text{Dur}_{\text{UNI}}(\text{sec})) = 4.581 - 0.364 \ln(S_{aT_1}) + 0.183 \ln(S_{a2T_1}) - \frac{6.126}{\ln(R) + 1.065} + \epsilon(\sigma = 0.47) \tag{2}
\]

\[
\ln(\text{PGV}(\text{cm/} \text{ sec})) = 4.767 + 0.217 \ln(S_{a2T_1}) + 0.696 \ln(S_{aT_1}) - 0.0402 M + \epsilon(\sigma = 0.43) \tag{3}
\]
2. Compute the median gamma value for the design event given the $S_{T=1s}$, $S_{T=2s}$, R, $A_{RMS}$, $D_{un}$ and PGV using the model in eq. (3) and coefficients in Table 1. Using the parameters from step 1 the median gamma is: $\gamma = 1.00$.

\[
(Sd_{Bl}(T_i)/Sd_{EL}(T_i))^{0.4} = \left( a_1 + a_2 \ln(A_{RMS}) + a_3 \ln(S_{T=2-T},/S_{T=T_i}) + a_4 \ln(D_{uni}) - a_5 \ln(PGV) \right) \ln(R) + 1 + \varepsilon
\]  

(4)

\[
\sigma = 0.145 \ln("R") - 0.040 \ln("R")^2
\]  

(5)

3. Select candidate ground motion recordings for scaling. This can be based on the traditional magnitude and distance bins approach (but the bins can be wider). Here we select records from the PEER (2004) dataset where 6.0<M, and R<50.

4. Scale all acceleration time series to the design event ground motion. This may be done by scaling to the $S_{T=1s}$, PGV or $S_a$ over some period range. Here we scale to $S_{T=1s}$.

5. Reject records where PGV, $A_{RMS}$ and $D_{un}$ are not within one standard deviation of their median values (from step 1). Additionally, reject records where $S_{T=2s}$ is not within 0.6 natural log units of the design value.

6. Calculate the difference between the estimated gamma value to the power of $-0.4$ for the design event (from step 2) and the gamma value to the power of $-0.4$ expected for each scaled ground motion (from step 4) and square.

7. Repeat steps 1 – 6 for R values of 1.5R, 1.2R, and R/1.2. This will generate four lists of scaled candidate records.

8. For records that appear on all lists, calculate the root mean square of the differences for the four gamma values. If both components of a record appear on the list then the component with the lower ranking is rejected.

9. The 7 records with the smallest difference from step 8 are chosen. The magnitudes of the earthquakes range from 6.24 to 7.51 and the distances range from 4 to 49 km. This is a wider range than is typically considered. The scale factors range from 2 to 67 indicating that some time series requiring large scale factors may still provide accurate estimates of the average response. A common feature of the time histories is that after scaling, they have similar $S_{a2}/S_{a1}$ ratios. A table of record properties after scaling is provided in Table 2.

<table>
<thead>
<tr>
<th>Record</th>
<th>M</th>
<th>Rrup (km)</th>
<th>Scale Factor</th>
<th>$A_{RMS}$ (g)</th>
<th>$D_{un}$ (sec)</th>
<th>PGV (cm/s)</th>
<th>$S_{a1s}$ (g)</th>
<th>$S_{a2s}$ (g)</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Event</td>
<td>7</td>
<td>5</td>
<td>0.225</td>
<td>8.4</td>
<td>90</td>
<td>1.2</td>
<td>0.61</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>6.24</td>
<td>4</td>
<td>3.82</td>
<td>0.206</td>
<td>9.81</td>
<td>82</td>
<td>1.2</td>
<td>0.67</td>
<td>1.01</td>
</tr>
<tr>
<td>2</td>
<td>6.69</td>
<td>31</td>
<td>10.9</td>
<td>0.184</td>
<td>10.5</td>
<td>105</td>
<td>1.2</td>
<td>0.41</td>
<td>0.99</td>
</tr>
<tr>
<td>3</td>
<td>6.5</td>
<td>49</td>
<td>66.7</td>
<td>0.227</td>
<td>9.68</td>
<td>89</td>
<td>1.2</td>
<td>0.57</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>6.69</td>
<td>24</td>
<td>4.62</td>
<td>0.190</td>
<td>12.5</td>
<td>98</td>
<td>1.2</td>
<td>0.42</td>
<td>0.99</td>
</tr>
<tr>
<td>5</td>
<td>6.6</td>
<td>16</td>
<td>5.50</td>
<td>0.253</td>
<td>5.06</td>
<td>119</td>
<td>1.2</td>
<td>0.55</td>
<td>1.03</td>
</tr>
<tr>
<td>6</td>
<td>6.69</td>
<td>24</td>
<td>6.24</td>
<td>0.206</td>
<td>7.46</td>
<td>115</td>
<td>1.2</td>
<td>0.41</td>
<td>0.98</td>
</tr>
<tr>
<td>7</td>
<td>7.51</td>
<td>15</td>
<td>1.97</td>
<td>0.223</td>
<td>6.41</td>
<td>91</td>
<td>1.2</td>
<td>0.75</td>
<td>1.03</td>
</tr>
</tbody>
</table>
EARTH STRUCTURES

Newmark (1965) type deformation analyses constitute the basis for design of many earth structures. Simplified techniques such as Makdisi and Seed (1978) are available to evaluate displacements that occur due to sliding along a distinct, rigid perfectly-plastic slip surface. An important limitation of this procedure is that the seismic response of the potential sliding mass is computed separately from the computation of the displacement of the sliding mass (Rathje and Bray 2000). For systems that have low levels of nonlinear displacement the decoupled analysis provides a good estimate of the median coupled sliding displacement (Rathje and Bray 2000); however, for highly nonlinear displacements the decoupled displacement estimates are conservative and highly variable (Rathje and Bray 2000).

Design of earth structures is further complicated by the use of a very small number of time series, often only one. This severely limits the conclusions that can be drawn from the analysis. The high nonlinearity of many design cases means that there will be large conservatism (i.e., overestimation) of the nonlinear earth structure response. We are primarily concerned with the ability of the simplified technique to accurately predict median permanent displacement of the earth structure given the design event.

For stiff earth structures Newmark (1965) modeled the permanent global displacement as that of a rigid block that displaces when the input acceleration time series exceeds the yield acceleration of the system. We use Newmark displacement as our proxy to develop a time series selection algorithm that will yield time series that produce a median Newmark displacement of the sliding mass given the design event.

Watson-Lamprey and Abrahamson (2006a) developed a time series selection method based on the Newmark displacement. Their evaluation of the Newmark displacement showed that response can be modeled with a relatively small variability if four properties of the time series are known: 1 – the pseudo-spectral acceleration at a period of one second ($S_{aT=1s}$), 2 – the root mean square of acceleration ($A_{RMS}$), 3 – peak ground acceleration (PGA) and 4 – uniform duration of oscillator acceleration calculated above the yield acceleration with a period of 0 seconds ($Dur_{UNI}$). This allows for selection of time series such that after scaling, the time series parameters lead to a median Newmark displacement similar to that expected for the design event.

Makdisi and Seed (1978) modified the Newmark displacement procedure to account for the deformable response of the earth structure. They assumed that failure occurs on a well-defined slip surface and that the material behaves elastically at stress levels below failure, but develops a perfectly plastic behavior above yield. The analysis is performed in three steps: 1 – Yield acceleration is calculated. 2 – Earthquake induced accelerations in the embankment are determined using dynamic response properties and time histories of average acceleration for the potential sliding mass are determined. 3 – Displacement is calculated using the average acceleration time history. We use the decoupled sliding block analysis as our proxy to develop a time series selection algorithm that will yield time series that produce a median decoupled displacement of a sliding mass given the design event.

EARTH STRUCTURE EXAMPLE APPLICATION

As an example we will consider a stiff earth structure with a yield acceleration of 0.1g. Watson-Lamprey and Abrahamson (2006a) developed a time series selection method using Newmark displacement as a proxy for a stiff earth structure. This method is presented below.

We consider the design event listed below:

PGA: 0.6 g
The response spectrum is shown in Figure 2.

For this earth structure, assume that the yield acceleration is 0.1g.

1. Compute the median $A_{RMS}$ and $Dur_{ky}$ given the design event parameters using the models given below in eqs. (6) and (7). Using the design event parameters, the $A_{RMS}$ and $Dur_{ky}$ are: $A_{RMS} = 0.185 \text{ g}$ and $Dur_{ky} = 2.411 \text{ sec}$.

   $$\ln(A_{RMS} (\text{g})) = -1.167 + 1.02 \ln(\text{PGA}) + \varepsilon(\sigma = 0.20)$$  

   $$\ln(Dur_{ky} (\text{sec})) = \frac{-2.775 + 0.956(\ln(\text{PGA} / k_y)) - 0.597(\ln(\text{PGA})) + 0.381(\ln(Sa_{T=1s})) + 0.334M + \varepsilon(\sigma = 0.52)}{1.554}$$

2. Compute the median Newmark displacement value for the design event given the $Sa_{T=1s}$, $k_y$, $A_{RMS}$, $Dur_{ky}$ and $PGA$ using the model in eq. (8) and coefficients in Table 3. Using the parameters from step 1 the median displacement is: Newmark displacement = 57 cm.

   $$\ln(\text{NewmarkDisp(cm)}) = \begin{pmatrix}
   a_1 + b_1(\ln(Sa_{T=1s})) + 0.45 \\
   +b_2(\ln(Sa_{T=1s})) + 0.45^2 + c_1(\ln(A_{RMS}) - 1.0) \\
   +d_1(\ln(Sa_{T=1s} / PGA)) + d_2(\ln(Sa_{T=1s} / PGA))^2 \\
   +e_1(\ln(Dur_{ky}) - 0.74) + e_2(\ln(Dur_{ky}) - 0.74)^2 \\
   +\frac{1}{f_1(\ln(PGA / k_y) - f_2)} + \varepsilon
   \end{pmatrix}$$

Table 3. Newmark Displacement Model
3. Select candidate ground motion recordings for scaling. This can be based on the traditional magnitude and distance bins approach (but the bins can be wider). Here we select records from the PEER (2004) dataset where 6.0<M, and R<50.
4. Scale all acceleration time series to the design event ground motion. This may be done by scaling to the PGA, $S_{T=1s}$ or PGV. Here we scale to $S_{T=1s}$.
5. Reject records where $A_{RMS}$ and $Dur_{ky}$ are not within one standard deviation of their median values (from step 1).
6. Calculate the difference in the logarithm of the expected displacement and the logarithm of the expected median displacement for the design event is computed and then square.
7. Repeat steps 1 – 6 for $k_y$ values of $1.5k_y$, $k_y/1.5$, and $k_y/2$. This will generate four lists of scaled candidate records.
8. For records that appear on all lists, calculate the root mean square of the differences for the four yield acceleration values. If both components of a record appear on the list then the component with the lower ranking is rejected.
9. The records with the smallest difference from step 8 are chosen. The magnitudes of the earthquakes range from 6.19 to 6.93 and the distances range from 31 to 62 km. This is a wider range than is typically considered. The scale factors range from 3.5 to 12.6 indicating that some time series requiring large scale factors may still provide accurate estimates of the average response. A table of record properties after scaling is provided in Table 4 for the 10 records selected.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Std Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>5.463</td>
<td>0.0237</td>
</tr>
<tr>
<td>$b_1$</td>
<td>0.451</td>
<td>0.00933</td>
</tr>
<tr>
<td>$b_2$</td>
<td>0.0191</td>
<td>0.00107</td>
</tr>
<tr>
<td>$c_1$</td>
<td>0.591</td>
<td>0.00853</td>
</tr>
<tr>
<td>$d_1$</td>
<td>0.205</td>
<td>0.00923</td>
</tr>
<tr>
<td>$d_2$</td>
<td>0.0892</td>
<td>0.00229</td>
</tr>
<tr>
<td>$e_1$</td>
<td>1.039</td>
<td>0.00275</td>
</tr>
<tr>
<td>$e_2$</td>
<td>0.0427</td>
<td>0.000844</td>
</tr>
<tr>
<td>$f_1$</td>
<td>-1.409</td>
<td>0.0140</td>
</tr>
<tr>
<td>$f_2$</td>
<td>-0.100</td>
<td>0.000986</td>
</tr>
</tbody>
</table>

CONCLUSIONS

When we limit a nonlinear dynamic seismic analysis to only a few time series, we also limit the utility of the analysis. As long as this limitation exists, we must narrowly focus the goal of the seismic analysis to make statistically significant conclusions. We have presented a number of options for ways to focus a seismic analysis to fewer parameters. We have also developed a method for generating a time series selection procedure that reduces variability. Integral to this procedure is the recognition that the time series selection method must consider the nonlinear behavior of the structure. It is not enough to select based on distance and magnitude, this leads to too much variability. We present an example of one such procedure. This procedure is based on the record properties of the time series, leads to median nonlinear response of a nonlinear engineering demand parameter and allows for wider magnitude and distance bins for selection.
Table 4. Time series properties for selected records from earth structure example application.

<table>
<thead>
<tr>
<th>Event</th>
<th>Station Name</th>
<th>EQ ID#</th>
<th>Mag.</th>
<th>Rrup (km)</th>
<th>Vs30 (cm/s)</th>
<th>Scale Factor</th>
<th>Scaled PGA</th>
<th>Scaled SaT=1s</th>
<th>Scaled Durkυ</th>
<th>Scaled ArMS</th>
<th>Expected Newmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Event</td>
<td>–</td>
<td>–</td>
<td>7</td>
<td>5</td>
<td>400</td>
<td>–</td>
<td>0.6</td>
<td>2.41</td>
<td>0.19</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>Chalfant Valley – 02 1986</td>
<td>Benton</td>
<td>103</td>
<td>6.19</td>
<td>22</td>
<td>271</td>
<td>3.57</td>
<td>0.63</td>
<td>1.1</td>
<td>2.59</td>
<td>0.18</td>
<td>61</td>
</tr>
<tr>
<td>Loma Prieta 1989</td>
<td>APEEL 7 - Pulgas</td>
<td>118</td>
<td>6.93</td>
<td>42</td>
<td>415</td>
<td>3.87</td>
<td>0.61</td>
<td>1.1</td>
<td>2.81</td>
<td>0.17</td>
<td>64</td>
</tr>
<tr>
<td>North Ridge – 01 1994</td>
<td>Leona Valley #2</td>
<td>127</td>
<td>6.69</td>
<td>37</td>
<td>446</td>
<td>7.10</td>
<td>0.65</td>
<td>1.1</td>
<td>2.60</td>
<td>0.18</td>
<td>61</td>
</tr>
<tr>
<td>North Ridge – 01 1994</td>
<td>Leona Valley #3</td>
<td>127</td>
<td>6.69</td>
<td>37</td>
<td>685</td>
<td>6.15</td>
<td>0.52</td>
<td>1.1</td>
<td>2.34</td>
<td>0.18</td>
<td>55</td>
</tr>
<tr>
<td>North Ridge – 01 1994</td>
<td>Littlerock – Brainard Canyon</td>
<td>127</td>
<td>6.69</td>
<td>47</td>
<td>822</td>
<td>7.45</td>
<td>0.54</td>
<td>1.1</td>
<td>2.29</td>
<td>0.18</td>
<td>54</td>
</tr>
<tr>
<td>Coalinga – 01 1983</td>
<td>Parkfield – VC4W</td>
<td>76</td>
<td>6.36</td>
<td>35</td>
<td>376</td>
<td>10.91</td>
<td>0.50</td>
<td>1.1</td>
<td>2.68</td>
<td>0.17</td>
<td>62</td>
</tr>
<tr>
<td>Coalinga – 01 1983</td>
<td>Parkfield – FZ 16</td>
<td>76</td>
<td>6.36</td>
<td>28</td>
<td>339</td>
<td>3.53</td>
<td>0.69</td>
<td>1.1</td>
<td>2.67</td>
<td>0.19</td>
<td>64</td>
</tr>
<tr>
<td>Chi-Chi – 03 1999</td>
<td>TCU054</td>
<td>172</td>
<td>6.2</td>
<td>37</td>
<td>461</td>
<td>12.59</td>
<td>0.50</td>
<td>1.1</td>
<td>2.13</td>
<td>0.20</td>
<td>54</td>
</tr>
<tr>
<td>North Ridge – 01 1994</td>
<td>Wrightwood Jackson Flat</td>
<td>127</td>
<td>6.69</td>
<td>49</td>
<td>376</td>
<td>8.65</td>
<td>0.77</td>
<td>1.1</td>
<td>2.66</td>
<td>0.19</td>
<td>63</td>
</tr>
<tr>
<td>Chi-Chi – 04 1999</td>
<td>CHY02</td>
<td>173</td>
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<td>20</td>
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<td>0.53</td>
<td>1.1</td>
<td>2.83</td>
<td>0.17</td>
<td>66</td>
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REFERENCES


