ANALYSIS OF DATA FROM STRUCTURAL RESPONSE RECORDERS IN NORTH AND NORTH EAST INDIAN EARTHQUAKES

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ABSTRACT

Himalayan region is one of the most seismically active regions of the world. Shillong plateau in North East India has been identified as one of the six most tectonically active regions of the world. Only limited strong motion records are available for earthquakes in India. India has a number of network consisting strong motion accelerographs in the high seismic zone, but these cannot be termed as sufficient. In addition, about 350 structural response recorders (SRR) has been installed in different parts of the country in the recent past.

The scope of this paper is to analyse the data recorded by SRR instrument with specific objectives of: (a) assessing the degree of uniformity between the SRR data, (b) examining the similarity between information from SMA and SRR data, and (c) developing a methodology for the computation of peak ground acceleration (PGA) from SRR data.

INTRODUCTION

India has a number of Strong Motion Accelerographs (SMA) networks in high seismic regions [1]. In addition, about 350 Structural Response Recorders (SRR) has been installed [2], [3] different parts the country under the Indian National Strong Motion Network (INSMIN) Program. SRRs are relatively inexpensive instruments consisting of six seismoscopes (natural periods: 0.40, 0.75, and 1.25sec; damping: 5% and 10% of critical) to measure the horizontal motion, fig. 1. The six seismoscopes together provide three points on the 5% response spectrum and three points on the 10% response spectrum. Since maximum motion in any direction is recorded, the SRR gives ordinates of the resultant response spectra. The scope of this paper is to analyse the data recorded in SRR and examine these with reference to the data recorded by SMA with the specific objectives of: (a) to assess the degree of uniformity between the SRR data, (b) to examine the similarity between information from SMA and SRR data, and (c) to develop a methodology for the computation of Peak Ground Acceleration (PGA) from SRR data.

Figure 1: Photograph of a SRR [4].
STRONG MOTION DATA

Table 1 lists four earthquake events, having magnitude range 5.5 to 7.3, SMA and SRR records of which are considered. Three of these events are on thrust fault while one is a subduction zone earthquake. In all, there are 65 SMA and 307 SRR records with epicentral distance ranging from 3 to 300 km for SMAs and 4 to 772 km for SRRs.

The epicentral distance is considered in the present study as the control distance to the fault. There is considerable variation in the epicenter location for these events as per United States Geological Survey (USGS) [5], India Meteorological Department (IMD) [6], and DEQ [7] and sometimes the difference between these epicentral locations reported in these documents are upto 100 km. For all four events, the correlation coefficient between the average PGA in the two horizontal directions from SMA records and the epicentral distance was calculated. The epicentral location that gave the best correlation coefficient has been considered in the present study.

The SRR produces records in a two-dimensional reference frame, i.e., any point on the SRR record results from the two-dimensional input in the horizontal plane. On the other hand the SMA records are unidirectional ones; the input motion is recorded along mutually perpendicular directions. Thus, prior to comparing the records from SMA and SRR the SMA records have to be processed to represent the two-dimensional input. The time history record of ground acceleration along one horizontal direction was used as an input to calculate the response acceleration of a single degree of freedom (SDOF) oscillator with a given natural period \( T \) and damping \( \zeta \% \) of critical. The ground acceleration along the other horizontal direction was determined following same approach. The resultant of these response accelerations acting along mutually perpendicular directions was calculated by taking the vector sum of response accelerations at each time instant. This procedure is repeated covering the complete time history. The maximum value of resultant response acceleration history is taken as the resultant spectral acceleration (RSA) for the given natural period \( T \) and damping \( \zeta \% \) of critical.

<table>
<thead>
<tr>
<th>Events</th>
<th>Date</th>
<th>Type Of EO</th>
<th>Mag</th>
<th>Epicentral Location</th>
<th>SMA Number Rack</th>
<th>Distance R (km)</th>
<th>SRR Number Rack</th>
<th>Distance R (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 Aug 1988 (Shillong)</td>
<td>Subduction</td>
<td>7.3 (Ms)</td>
<td>25.562°N, 92.187°E</td>
<td>33</td>
<td>99</td>
<td>323</td>
<td>122</td>
</tr>
<tr>
<td>2</td>
<td>20 Oct 1991 (Uttarkashi)</td>
<td>Thrust</td>
<td>7.0 (Ms)</td>
<td>30.738°N, 78.792°E</td>
<td>13</td>
<td>19</td>
<td>152</td>
<td>111</td>
</tr>
<tr>
<td>3</td>
<td>29 Mar 1999 (Chamoli)</td>
<td>Thrust</td>
<td>6.6 (Ms)</td>
<td>30.410°N, 79.420°E</td>
<td>10</td>
<td>8</td>
<td>123</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>26 Apr 1986 (Kangra)</td>
<td>Thrust</td>
<td>5.5 (mb)</td>
<td>32.193°N, 76.290°E</td>
<td>9</td>
<td>3</td>
<td>28</td>
<td>17</td>
</tr>
</tbody>
</table>

COMPARISON OF SRR DATA AND SMA DATA

Nine different ratios of RSA obtained from SRR recordings (hereinafter termed as response ratio) are compared statistically with those derived from SMA records. The first six response ratios
of RSAs are for different periods but correspond to the same damping ratio. Response ratio $\gamma_1 \gamma_2$ corresponds to ratio of responses at two time periods $T_1$ and $T_2$ with the same damping ratio $\zeta$. The ratio of RSA having periods of 0.4sec and that at 0.75sec for 5% damping is denoted as $\gamma_{0.4/0.75}^{0.05}$. Remaining three ratios studied are the ratios between the RSAs for different damping values at a given period. The response ratio $\gamma_1 \gamma_2$ denotes the ratio of responses at different damping values $\zeta_1$ and $\zeta_2$ but corresponding to the same period $T$. The response ratio of RSA for 5% damping and for 10% damping at same period 0.4 sec is denoted as $\gamma_{0.4/1.25}^{0.05}$. Following observations are made from the data,

1. The scatter in the response ratios calculated from SRR data appears to be larger than that from SMA data. In case of SRR, different oscillators record the motion for different natural periods and damping values and there tends to be a large variation in the ratio of the two quantities. For SMA, same time history is used to compute the response for different natural periods and damping ratios and which most probably led to a limited variation in the two quantities. This may be the reason for higher scatter in the response ratios obtained from SRR records in comparison with that from SMA records.

2. The shape of the frequency distribution of the ratios determined from the data recorded in SRRs and SMA are similar in nature. The shape of the distribution functions are either symmetrical or somewhat skewed to the left. It can be assumed that these ratios follow either normal or lognormal distribution. Chi-square ($\chi^2$) test for goodness of fit [8] indicates that with 95% level of confidence, the assumption of distribution being normal is acceptable.

3. For both SRRs and SMAs, the peaks of the distribution lie almost near the same response ratio.

4. The distribution for response ratios $\gamma_{0.4/0.75}^{0.05}$ and $\gamma_{0.75/1.25}^{0.05}$ is regular than that for $\gamma_{0.4/1.25}^{0.05}$. This is expected since the response for oscillators having smaller difference in natural period will be better correlated.

5. For some SRR stations the ratio of response with 5% damping to that with 10% damping is less than 1.0. However, the response of a 5% damped system should be greater than that with 10% damping. Similarly, for some SRR stations this appears too high.

A parameter, Average Amplification Ratio for Damping indicating the average of $\gamma_{0.4/0.75}^{0.05}$, $\gamma_{0.75/1.25}^{0.05}$ and $\gamma_{0.4/1.25}^{0.05}$, for each recording station was calculated. The average of “mean plus one standard deviation” value of the above parameters for this event considered was found to be 1.83. Hence, an upper cut-off point, $U_{\text{cut}}$, was fixed at 1.85 i.e., any SRR record for which the Average Amplification Ratio for Damping exceeds 1.85 was removed from the data set for further calculations. Similarly, a lower cut-off, $L_{\text{cut}}$, was selected as 1.0. Based on this criteria, 18 observations were removed from the 1st event, 16 being above $U_{\text{cut}}$ and 2 below $L_{\text{cut}}$. From the 3rd event 8 observations (4 above $U_{\text{cut}}$ and 4 below $L_{\text{cut}}$) and from the 4th event 4 observations (4 above $U_{\text{cut}}$) were removed.

Correlation coefficient (CC) between the response values considered in the analysis were studied along with other statistical parameters for SRR as well as SMA data. Following observations are made from the statistical analysis results:

1. In general, the mean and median values of response ratios from SRR the data are fairly close to the corresponding ratio obtained from SMA data. Especially, the median values from two data sets compare better than the mean values. The difference between median values of all the ratios ranges from 1% to 68%, average difference being 16%; whereas the difference between mean values is in the range of 3% to 45% having average difference of 20%.

2. The mean values of response ratios of RSAs corresponding to a constant period obtained from SRRs for different damping $\gamma_{0.4/0.75}^{0.05}$ are generally higher (average difference of 19%) compared to the corresponding ratios obtained from SMA records.
3. The median values of the response ratios, $\frac{\gamma_{5\%/10\%}}{\gamma_{15\%/20\%}}$, determined from SRRs based data for different damping values show good agreement with that of SMAs (average difference of 5%). At the same time, the difference in the median values of response ratios at various natural periods with same damping $\frac{\gamma_{T_1/T_2}}{\gamma_{T_1/T_2}}$ shows considerable difference (average difference of 25%).

4. The standard deviation of response ratios for different natural periods but with same damping obtained from the SRR data compares well with that from the SMA data. However, standard deviation of response ratios for different damping values having same natural period is much higher when determined from the SRR data than that from the SMA data. In fact, the value obtained from SRR data may be four to five times that from the SMA data. This is perhaps an intrinsic nature of the data obtained from SRR records and can most probably be attributed to six different sensors that are used in SRR.

5. The correlation coefficient between the responses from SMAs as well as SRRs show good agreement with each other for all the earthquakes. However, for the 29 March Chamoli earthquake, the correlation coefficients corresponding to $\text{RSA}_{0.4}$ and $\text{RSA}_{1.25}$ and $\text{RSA}_{0.25}$ and $\text{RSA}_{1.25}$ for SRRs with 5% damping show large deviation from the corresponding values for SMA. This may be due to poor calibration of the instruments with period 1.25 sec and 5% damping.

From the above observations, it can be concluded that the characteristics shown by SMAs and SRRs are similar in nature. The similarity of characteristics of data from SRRs and SMAs were further verified. Since the data follow normal distribution, the following test statistic has been performed to examined whether the response ratio values obtained from the data of SRRs and SMAs have originated from the same population [9]:

$$Z = \left( \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{\sigma^2_1}{n_1} + \frac{\sigma^2_2}{n_2}}} \right)^{\frac{1}{2}}$$

where, $Z$ is the test statistic; $\bar{x}_1$, $\sigma_1$ are the mean and standard deviation of the samples obtained from SRRs and $\bar{x}_2$, $\sigma_2$ those from SMAs; and $n_1$, $n_2$ are corresponding number of observations. $\delta$ is the difference in the population means ($\mu_1$, $\mu_2$) which will be equal to zero if the population means are same. The assumption that the samples of SRRs and SMAs do not come from the same parent population can be considered acceptable if does not lie in the range +1.96 to -1.96 (corresponding significance level, $\alpha = 5\%$). It was observed that the recordings made by SRRs are similar to that of SMAs. However, one must avoid using SRR data for study of response ratio for different damping values.

**SPECTRUM AMPLIFICATION FACTOR**

The high frequency waves of the ground motions attenuate faster with distance than the low frequency waves. Hence, dependence of the spectrum amplification factors, which is the ratio of RSA and PGA (SAF=RSA/PGA), with epicentral distance needs to be explored. The correlation coefficient ranges from +0.53 to -0.50 for different events. No general conclusion could be drawn about the distance dependence of amplification factors for these events (Fig. 2). Therefore, it is reasonable to assume that $\text{(RSA/PGA)}_{T_1/T_2}$ independent of epicentral distance $D$ for the regions considered in the study.
Figure 2: Amplification factor of the resultant Spectral Acceleration versus epicentral distance for the August 6, 1988 Shillong earthquake

Table 2 contains the mean, median, and standard deviation for the SAFs calculated from the SMA data and also the correlation coefficient between RSA and PGA. It can be observed from Table 3 that the mean or median values of SAF can be used for estimation of PGAs using SRR data. Further, the correlation coefficients (CC) can be used as weighing functions for averaging the PGA values obtained from six RSA values.

Table 2: Statistical parameters of the SAF for the different earthquakes.

<table>
<thead>
<tr>
<th>Event</th>
<th>RSA=</th>
<th>Mea n</th>
<th>Medi an</th>
<th>SD</th>
<th>CC*</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-Aug-1988 Shillong</td>
<td>0.4</td>
<td>2.26</td>
<td>2.17</td>
<td>1.00</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>1.43</td>
<td>1.23</td>
<td>1.02</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>0.77</td>
<td>0.54</td>
<td>0.73</td>
<td>0.43</td>
</tr>
<tr>
<td>20-Oct-1991</td>
<td>0.4</td>
<td>1.20</td>
<td>0.96</td>
<td>0.55</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0.76</td>
<td>0.58</td>
<td>0.53</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>0.69</td>
<td>0.57</td>
<td>0.48</td>
<td>0.97</td>
</tr>
<tr>
<td>29-Mar-1999</td>
<td>0.4</td>
<td>1.26</td>
<td>1.05</td>
<td>0.74</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0.96</td>
<td>0.64</td>
<td>0.47</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>0.60</td>
<td>0.49</td>
<td>0.41</td>
<td>0.81</td>
</tr>
<tr>
<td>26-Apr-1986 Kangra</td>
<td>0.4</td>
<td>2.44</td>
<td>2.43</td>
<td>1.03</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>2.14</td>
<td>2.27</td>
<td>0.78</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>0.99</td>
<td>1.01</td>
<td>0.29</td>
<td>0.85</td>
</tr>
</tbody>
</table>

*Note: Correlation between RSA and PGA.

ESTIMATION OF PEAK GROUND ACCELERATION FROM SRR DATA

Average magnification factors obtained from accelerograms at a SMA station have been used to arrive at the PGA from the spectral acceleration values of the SRR records for the Uttarkashi earthquake of 20th October 1991 [10]. In another study, the amplification factor to be used for calculation of PGA from SRR records has been calculated based on the amplification factor computed from the strong motion accelerographs of nearest stations [11]. In the present study, RSA values from SMA data are used to back-calculate PGAs and compared with the recorded PGA. The
error in PGA value prediction is defined as:

\[ \text{Error} = \frac{1}{n} \sqrt{\sum_{i=1}^{n} \left( \frac{\text{PGA}_{\text{predicted}} - \text{PGA}_{\text{observed}}}{\text{PGA}_{\text{observed}}} \right)^2} \]  

(2)

where, \( n \) is the number of points used to estimate the error.

Using six values of RSA at each recording station, one can obtain six values of PGA by using either mean, \( \mu_i \), or median, \( m_i \), SAFs. Further, these six values of PGA at a station can be simply averaged or averaged using the CCs between RSAs and PGA values. Following five possible methods emanate from this concept:

1. **Use of median values of SAF**

   \[ \text{PGA} = \frac{1}{n} \sum_{i=1}^{n} (\text{RSA}_i / m_i) \]  

(3)

2. **Use of median values of SAF and weight functions**

   \[ \text{PGA} = \left[ \frac{\sum_{i=1}^{n} (w_i \text{RSA}_i / m_i)}{\sum_{i=1}^{n} w_i} \right] \]  

(4)

Where \( w_i \) is the individual weight assigned to \( i^{\text{th}} \) observation. \( w_i \) is taken as the correlation coefficient between \( i^{\text{th}} \) RSA and PGA.

3. **Use of mean values of SAF**

   \[ \text{PGA} = \frac{1}{6} \sum_{i=1}^{6} (\text{RSA}_i / \mu_i) \]  

(5)

4. **Use of mean values of SAF and weight functions**

   \[ \text{PGA} = \left[ \frac{\sum_{i=1}^{n} (w_i \text{RSA}_i / \mu_i)}{\sum_{i=1}^{n} w_i} \right] \]  

(6)

5. **Best fit curve**

Further, the least square analysis of the data was carried out by using two best fit curves which linearly relate RSA’s to PGA’s. The expressions for the curves are as follows:

**Model I**:

\[ \text{PGA} = b_1 \text{RSA}_{0.4,5\%} + b_2 \text{RSA}_{0.75,5\%} + b_3 \text{RSA}_{1.25,5\%} + b_4 \text{RSA}_{0.4,10\%} + b_5 \text{RSA}_{0.75,10\%} + b_6 \text{RSA}_{1.25,10\%} \]  

(7)

**Model II**:

\[ \text{PGA} = b_1 + b_2 \text{RSA}_{0.4,5\%} + b_3 \text{RSA}_{0.75,5\%} + b_4 \text{RSA}_{1.25,5\%} + b_5 \text{RSA}_{0.4,10\%} + b_6 \text{RSA}_{0.75,10\%} + b_7 \text{RSA}_{1.25,10\%} \]  

(8)

The method of using mean values of SAF with CCs between RSA and PGA as weight functions can be considered as rational approach for calculation of PGA from SRR data.

**SPREAD IN PREDICTED PGA**

The spread in the six values of PGA obtained from one SRR station have been compared with that from the SMA data. At each station, the coefficient of variation, \( \left( \sigma/\mu \right) \), of the six predicted PGAs have been calculated. This value, when averaged across all the stations considered in the earthquake, gives Average Coefficient of Variation (ACV). ACV can be considered to represent the average extent of spread that occurs among the six predicted PGAs. Since the
weighing functions will also be affecting the variation, the weight, \( w_i \), was assumed equal to 1.0 during this analysis. Table 3 gives the computed values of ACV both from SMA data and SRR data. It is observed from the results that the mean values can be used as conversion factors and CC as weighing functions for calculation of PGA from SRR recordings. The observed values of peak ground acceleration from SMAs for different events as well as the predicted values of acceleration from the SRRs for Shillong earthquake (August 6, 1988) are given in the Fig. 3. It can be observed that these two compares well.

Table 3 Coefficient of variation among the six PGA calculated from SA values of SMAs and SRRs (Weights equal to unity)

<table>
<thead>
<tr>
<th>Event</th>
<th>Amplification factor</th>
<th>SMA</th>
<th>SRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-August-1988 Shillong</td>
<td>Mean</td>
<td>0.314</td>
<td>0.388</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>0.253</td>
<td>0.371</td>
</tr>
<tr>
<td>20-Oct-1991 Uttarkashi</td>
<td>Mean</td>
<td>0.309</td>
<td>0.356</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>0.291</td>
<td>0.345</td>
</tr>
<tr>
<td>29-Mar-1999 Chamoli</td>
<td>Mean</td>
<td>0.289</td>
<td>0.364</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>0.275</td>
<td>0.351</td>
</tr>
<tr>
<td>26-Apr-1986 Kangra</td>
<td>Mean</td>
<td>0.231</td>
<td>0.486</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>0.201</td>
<td>0.444</td>
</tr>
</tbody>
</table>

Figure. 3 : Calculated PGAs from SRRs plotted along with the observed PGAs from SMAs for August 6,1988 Shillong earthquake

CONCLUSIONS

1. A large number of data are recorded by Structural Response Recorders during the recent earthquake in India. Even though SRRs are rather simple and seem to be crude instruments, the responses obtained from these are found to be quite reliable.
2. Based on the analysis and comparison of data from SMAs and SRRs, it can be concluded that the recordings made by SRRs are similar to that of SMAs. However, one must avoid using SRR data for study of response ratio for different damping values.
3. The correlation of Spectrum Amplification Factors with epicentral distance seems to be poor. No general conclusion could be drawn about the distance dependence of Spectrum Amplification Factors for the events considered
4. A methodology has been developed for estimation of horizontal peak ground acceleration from SRR data by using mean values of spectral amplification factors for calculation of PGAs and applying correlation coefficient between RSA and PGA as weighing functions. The predicted peak ground acceleration using the methodology compares very well with the recorded PGA from the Strong Motion Accelerographs. Hence the database of peak ground acceleration can be enhanced considerably.

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REFERENCES