Development of empirical relationship between the observed and the estimated ground acceleration values of small to moderate earthquakes in northwest (Gujarat) and northeast (NE) regions of India

Pallabee Choudhury, Ketan Singha Roy, Charu Kamra and Sumer Chopra
Institute of Seismological Research, Gandhinagar, Gujarat, India

ABSTRACT
We developed empirical relationships between the ground accelerations directly obtained from the strong motion acceleration (SMA) data and the accelerations obtained by differentiating the velocity data from the broadband seismic records of the co-located sites, in the northwest (Gujarat) and northeast (NE) regions of India. In Gujarat, there are 215 earthquakes in the magnitude range of Mw 2.3–5.3, that occurred during 2006–2020, recorded by 18 co-located broadband seismograph and strong motion accelerograph stations. 94 events of magnitude range Mw 4.0–6.9, occurred during 2012–2017 are utilized from the 18 sites in the NE India. Using the developed relationships, we prepared ground motion distribution maps of few earthquakes that occurred in Gujarat and NE India. This is the first study of its kind for either or both the regions of India that assume great importance as priority areas of earthquake studies. The outcome of this study will help in predicting ground motion in the regions where SMA data is not available. Moreover, using the developed regression equation, a ground-shaking map can be generated instantly after an earthquake that will be of immediate use to the scientists, emergency response agencies, media, and general public.

1. Introduction
A ground motion prediction equation (GMPE) describes the attenuation of amplitudes of ground motion (acceleration, velocities) as a function of distance as well as magnitude and is important in accessing the seismic hazard of a site of interest. A GMPE depends on number of factors like, magnitude, distance from the source, local site conditions, type of faulting and most importantly the tectonic regime. These relations normally give peak ground acceleration (PGA) or the spectral acceleration (SA) in terms of the earthquake magnitude, source to site distance and local site condition.
The prediction based on such an empirical relation depends essentially on how best it can represent the regional and local geology (Douglas 2003).

However, the amount of data required to develop such an empirical relation based on recorded data is not available from any part of the world and thus majority of the GMPEs are developed using the synthetic data. In Gujarat, which is one of the most active intraplate regions of the world, few GMPEs are available (Mandal et al. 2009; Chopra and Choudhury 2011; NDMA 2011; Joshi et al. 2013) that are generated using various methodologies, incorporating local ground motion models (Choudhury et al. 2018). It has been observed that all the GMPEs provide disparate values of ground motion as some used recorded data (Mandal et al. 2009; Chopra and Choudhury 2011) whereas others used either a combination of recorded and synthetic data (Joshi et al. 2013) or only synthetic data (NDMA 2011). Many GMPEs are available for northeast (NE) India (Aman et al. 1995; Singh et al. 1996; Sharma 1998; Nath et al. 2005; Baruah et al. 2009; Sharma et al. 2009; Gupta 2010; NDMA 2011; Ramkrishnan et al. 2020). In NE India too, GMPEs are mostly developed using synthetic data obtained using simulations. Keeping that in mind, it becomes important to use the observed ground motion while developing a GMPE. Though the strong motion accelerograph (SMA) data are scanty, broadband seismograph (BBS) data are available in plenty. As the SMA data in India are sparse, the broadband waveforms can be used to obtain the acceleration time histories to fill data gaps (Choudhury et al. 2018).

Following an earthquake, the epicentral and magnitude information are not enough to assess the hazard, as these two cannot provide the damage pattern. In light of this fact, United States Geological Survey (USGS) developed ShakeMap, which is a depiction of actual ground shaking produced by an earthquake (US Geological Survey (USGS) 2017). For a given magnitude and hypocentral distance, ground shaking level at different sites can be different as it depends on site conditions and also variations in the propagation of seismic waves from the source to the site. In view of this, following an earthquake, generation of a ShakeMap is important for a reliable presentation of the ground shaking for diverse audience like scientists, emergency response agencies, media, and the general public.

The instrumentation Seismology in India has taken a step ahead with the deployment of the national seismological network operated by India Meteorological Department/National Centre for Seismology (Dattatrayam et al. 2014; Bansal et al. 2021) and Gujarat Seismic Network (Chopra et al. 2008) operated by the Institute of Seismological Research (ISR). Both the networks deployed a dense network of BBS and SMA. The seismological networks are generally deployed with the purpose of near real-time monitoring of the earthquake activity and the dissemination of the earthquake epicentral parameters to the authorities and agencies involved in relief and rescue operations. In view of this, most of the broadband stations are being operated in continuous mode, enabling real-time data receiving. The SMAs are kept in the trigger mode and the data reception is not real-time. The broadband stations, because of its wide frequency range, are able to record weak motions even from distant stations, unlike SMAs. Therefore, even with the advent of digital telemetry
network since 1995, strong motion database in India is sparse in comparison to the broadband records.

Looking into the seismic networks in Gujarat and NE India, it is found that there are some sites where both BBS and SMA are co-located. The deployment of the BBS and SMA in the same geological conditions enabled us to use the broadband data of significant events on different networks recorded at various distances to obtain the acceleration time histories. It is also possible to validate the results with the recorded co-located acceleration values. Moreover, the comparison will make it possible to develop an empirical relation between the accelerations obtained from SMA records ($A_{SMA}$) and accelerations derived from BBS velocities records ($A_{BBS}$) for earthquakes of Indian region, using the available records. It will help us to fill the gap where acceleration data are scanty and also to present a near real-time map of ground shaking following significant earthquakes. This will also help in studying attenuation characteristics, directivity and characterizing sites for estimating seismic hazard.

In the present work, we make use of the recorded acceleration and velocity data from two different tectonic settings of India, which are seismically very active, NW India (Gujarat) and NE India and derived acceleration using the velocity records. We developed empirical relationships between $A_{SMA}$ and $A_{BBS}$ for soil and rock conditions for different components. The ground motions (velocity) are differentiated to estimate the acceleration and then the converted accelerations are plotted against the recorded accelerations to achieve a suitable scaling relationship between these two. We see that it is possible to use the velocity records to deduce the strong ground motion parameters from weak motion recordings. This is the first study of its kind in India for either or both Gujarat (intraplate) and NE region of India, which is of utmost importance as significant areas for seismic studies. India lacks strong motion data and instead of looking for the installation of new strong motion instruments and waiting for earthquakes to be recorded, we can start with what we have and this will help in filling the gaps.

2. Tectonic setting of Gujarat and NE India

Gujarat region has wide spectrum of rocks varying in ages from 2500 million years to a few thousand years only (Merh 1995). All types of rocks, igneous, sedimentary and metamorphic, occur within the state. Gujarat is the westernmost state of India and is a tri-junction of three failed rifts. These are Kachchh, Cambay and Narmada. Several active faults are present in Gujarat, most of which are located in the Kachchh region (Biswas 1987, 2005). Major faults in Kachchh are Nagar Parkar Fault (NPF), Allah Bund Fault (ABF), Island Belt Fault (IBF), South Wagad Fault (SWF), Kachchh Mainland Fault (KMF) and Katrol Hill Fault (KHF). No major fault system is present in Saurashtra, which is a horst. It mostly comprises fractures and lineaments. In mainland Gujarat region, two major rifts, Cambay and Narmada are located. Cambay rift is bounded by NNW-SSE oriented East and West marginal faults and Narmada rift is bounded by ENE-WSW oriented North and South Narmada faults (Figure 1(a)).
Figure 1. Earthquakes and stations used in this study of (a) Gujarat and (b) NE India shown with local geological settings (shown in the legend) and major faults. NPF: Nagar Parkar Fault, ABF: Allah Bund Fault, IBF: Island Belt Fault, SWF: South Wagad Fault, KMF: Kachchh Mainland Fault, KHF: Katrol Hill Fault, MCT: Main Central Thrust, MBT: Main Boundary Thrust, DF: Dauki Fault, KF: Kapili Fault, NDT: Naga Disang Thrust.
The NE India is one of the most seismically active regions and complex tectonic provinces of the world. It is a part between two major arcs, the E-W trending Himalayan arc in the north and N–S trending Indo-Burmese arc in the east. The major tectonic domains are the Eastern Himalayas (subduction boundary between Indian and Eurasian plate) comprising the Main Boundary Thrust (MBT) and Main Central Thrust (MCT) to the north, the Indo-Burma subduction zone to the east, the Shillong Plateau, the Mikir Hills and the Assam Valley (Figure 1(b)). In addition, some major tectonic features are the E-W trending Dauki fault, which separates the Shillong Plateau to the north and the Bengal basin to the south and the NW-SE trending Kopili fault that separates the Shillong Plateau and the Mikir Hills (Curray et al. 1982; Nandy 2001; Baruah 2008; Kumar et al. 2020).

3. Data and methodology

The Gujarat State Seismic Network (GSNet) being maintained by the ISR, Gandhinagar since July 2006, functioned well with 60 BBS spread throughout the state and neighbouring areas. Out of these 60, 45 are connected via very small aperture terminal (VSAT) to ISR. A total of 54 SMA are also deployed (Choudhury et al. 2014). While the online broadband seismic stations are equipped with Guralp CMG-3T broadband sensors (50 Hz–120s) and 24-bit Guralp CMG-DM24 and 130-01 digitizer (Reftek) data loggers, most of the strong motion stations are equipped with GeoSig made triaxial forced balance accelerometer (Chopra et al. 2008; Choudhury et al. 2014). The sites are located on varied geology, from Proterozoic to Quaternary (Figure 1(a)). The epicentral parameters are estimated using SEISAN software (Havskov and Ottemoller 1999), considering the region specific velocity models developed utilizing a total of around 900 earthquakes recorded by GSNet (Joshi et al. 2017). The derived region-specific velocity models made it possible to precisely locate the earthquakes occurring in these regions, enabling reliable estimation of earthquake locations.

The National Seismological Network run by National Centre for Seismology (NCS), New Delhi deployed 115 digital BBS and SMA, both at same location, throughout the country (Bansal et al. 2021). NCS/India Meteorological Department (IMD) has deployed a seismic telemetry network in the NE India region in 2011 with an objective to improve detection capability and better estimation of the earthquake source parameters (Shukla et al. 2011; Bansal et al. 2021). The state-of-the-art network consists of 21 seismic stations (both BBS and SMA) with a central receiving station at NCS, New Delhi (Shukla et al. 2018; Bansal et al. 2021). All the stations are equipped with Reftek triaxial digital broadband seismometer (120 s) and Reftek strong motion accelerometer (Shukla et al. 2018) and positioned on different geological setup (Figure 1(b)). The data is received in near real-time through VSAT and the epicentral parameters are estimated using SEISAN software (Havskov and Ottemoller 1999), considering appropriate crustal velocity models. The waveform data are re-analysed to get the refined epicentral parameters. The magnitude of completeness of NCS network is M3.0 (Bansal et al. 2021). However, in our study, we have used earthquakes of M ≥ 4.0, the epicentral parameters are also validated with that given by the USGS.
We selected 215 earthquakes of magnitude range Mw 2.3–5.3 and depth range 3–36 km that have occurred in the Gujarat region during 2006 to 2020. All these earthquakes were recorded by 18 co-located BBS and SMA installed and operated by ISR. In total, there are 278 records. The earthquake epicentres and recording stations indicating source to station ray paths are shown in Figure 1(a). Out of these 18 stations, only one station is on soil (Figure 1(a)). We excluded the soil data from our analysis, as there is only one record. In case of NE India, data of 94 earthquakes in the magnitude range Mw 4.0–6.9, depth range 10–141 km is available for the analysis. In total, there are 200 time histories, recorded by 18 stations, of which 11 on rock and 7 on soil are available from NE Indian region (Figure 1(b)).

We wrote a python script (Python Core Team 2015) to do further analysis. Given epicentral distance, source depth and a velocity model, theoretical seismic wave travel time can be calculated based on the method of Buland and Chapman (1983). The TauP Toolkit (Crotwell et al. 1999), which utilizes this method and is a module of Obspy package (Beyreuther et al. 2010) has been used to calculate theoretical S-wave travel time. For a given event station pairs and an earth model IASP91 (1D reference model, Kennett and Engdahl 1991), theoretical S-wave travel time can be calculated using tau-p (delay time-ray parameter) algorithm. By adding origin time to S-wave travel time, we get S-wave arrival time. The S-wave arrival time facilitates us to cut waveform automatically (programmatically) around the theoretical S-phase. Since we have large dataset, this method saves enough time. We cut waveform 5 s before and 10 s after the theoretical S-wave onset so that maximum ground motion is contained in this time window. The seismic records close to the epicentre are more prone to be clipped. In the Gujarat region, majority of earthquake epicentres are very near to the recording stations, so there is a possibility of clipped records. We manually checked each record to ensure that the record under consideration is not clipped. The corrections for the instrument response and also for the baseline are carried out. Next, to filter high-frequency and/or low-frequency content from the time series a Butterworth filter is used to band-pass each velocity record between 1 and 20 Hz, keeping in view the frequency range of engineering significance. We kept the filtering range same for each record of both the regions to maintain uniformity. Each record is then differentiated to acceleration. Fourier transformation is applied to velocity data (time domain) to obtain velocity spectra (frequency domain). The velocity spectra is then multiplied with $-2\pi f f (\pi = 3.1415, f = \text{frequency})$, to obtain the acceleration spectra. Finally, inverse Fourier transformation is applied to the acceleration spectra to obtain the acceleration time series. The PGAs from each accelerograms are also noted for all the three components after carrying out the baseline corrections and band pass filtering in the same frequency range of the broadband record. An acceleration waveform and differentiated velocity waveform for an event of M4.0 of Gujarat and M5.6 in NE India are shown in Figure 2(a) and Figure 2(b), respectively. A good agreement of the two traces is evident. Nevertheless, a good match between the Fourier spectra of the observed and converted waveforms is indication of a fair conversion (Figure 2a, b, lower panel). The geometric mean of the PGAs obtained from NS and EW components is estimated, which we denote as the horizontal PGA. Several empirical relations have been obtained through log-log fit between the PGA obtained from acceleration and velocity records for the horizontal (HPGA) and
vertical (VPGA) components. The correlation coefficient ($r$) and standard deviation ($\sigma$) of the fit are also determined. The empirical relationships were developed for both the regions.

4. Results and discussion

The regional seismic networks in Gujarat and NE Indian regions have many sites where BBS and SMA are co-located and have recorded many moderate earthquakes.
It has been observed that most of the data in Gujarat is in the magnitude range 3.0–4.0 whereas in NE Indian region, majority of the data is in the range 4.0–6.0 (Figure 3(a)). The hypocentral distribution shows that in the Gujarat region, majority of earthquakes are in the range 10–100 km whereas in NE Indian region, majority are in the range 50–500 km (Figure 3(a)). We observe that the HPGA:VPGA ratio is more than 1 for NE region and less than 1 for Gujarat region (Figure 3(b)). However, it is interesting to note that about 50% of the records are having larger VPGA (Figure 3(b)) for Gujarat. This may be because of the fact that the commonly used ratio of HPGA and VPGA, that is, 2/3 in engineering applications is exceeded in the near-field and decreases below that value in the far-field (Niazi and Bozorgnia...
We note that for Gujarat the hypocentral distance of most of the earthquakes (Figure 3(a)) fall in the range 10–50 km (near-field), while for NE India, the same is > 100 km (far-field). Because of the difference in HPGA and VPGA values, we develop relations for horizontal and vertical components separately. Because of the difference in tectonic regime, the analysis for Gujarat and NE India is done separately as region specific parameters such as stress drop, kappa and inelastic attenuation that influence the ground motion are different for both the regions. We have made use of

Figure 3. (a) Magnitude and hypocentral distance distribution of the earthquakes used in this study (b) Comparison of horizontal (HPGA) and vertical (VPGA) components of PGA.
Figure 4. Distribution of PGA (observed) and PGA (estimated) for rock sites of (a) Gujarat, (b) NE India and (c) soil sites of NE India. Left panel shows the geometric mean of the two horizontal components while right panel shows the vertical component.
those data and developed empirical relationships between the observed PGA recorded on SMA and converted PGA obtained from BBS as depicted in Figure 4 for both horizontal and vertical components. We took geometric mean of two horizontal components, north-south and east-west, to represent horizontal component.

One of the major factors that influence the amplitudes and characteristics of the strong ground motion is the subsurface geology (Borcherdt 1970; King and Tucker 1984; Aki 1988; Field et al. 1992). To account for that, records are separated into rock and soil based on the local site conditions (Table 1). We see that there is only one record on soil site (MUN) in the Gujarat region and we discard this record from the analysis. As for NE India, 49% of the records are on soil, so it becomes reasonable to prepare two different datasets based on the local geology. Accordingly, we

| Station name | Lat(°N) | Lon(°E) | Local site condition | No. of records | Magnitude Range |
|--------------|---------|---------|----------------------|----------------|-----------------|
| Badargadh (BDR) | 23.475 | 70.571 | Rock | 35 | 3.1–4.8 |
| Bela (BEL) | 23.874 | 70.802 | Rock | 7 | 3.3–4.4 |
| Bhimasar(BHI) | 23.194 | 70.165 | Rock | 8 | 3.0–4.1 |
| Bhavnagar(BHV) | 21.694 | 71.997 | Rock | 1 | 5.1 |
| Chobari (CHO) | 23.516 | 70.345 | Rock | 65 | 2.5–4.8 |
| Desalpar (DES) | 23.742 | 70.686 | Rock | 1 | 4.8 |
| Dharoi (DHR) | 24.007 | 72.847 | Rock | 1 | 3.4 |
| Dholavira (DOL) | 23.892 | 70.620 | Rock | 3 | 2.3–3.7 |
| Dudhai (DUD) | 23.320 | 70.126 | Rock | 28 | 3.0–4.5 |
| Junagarh (JUN) | 21.355 | 70.724 | Rock | 1 | 4.0 |
| Khavda (KAV) | 23.922 | 69.766 | Rock | 31 | 2.6–4.5 |
| Lodrani (LOD) | 23.892 | 70.620 | Rock | 2 | 3.0–3.7 |
| Morbi (MOR) | 22.839 | 70.893 | Rock | 12 | 3.9–5.3 |
| Mundra (MUN) | 22.775 | 69.683 | Soil | 1 | 4.4 |
| Nalinya (NKL) | 23.327 | 68.828 | Rock | 4 | 4.0–5.0 |
| Siu (SIP) | 24.386 | 72.294 | Rock | 2 | 2.7–5.3 |
| Surat (SUR) | 23.606 | 70.488 | Rock | 35 | 3.0–4.5 |
| Vamka (VAM) | 23.425 | 70.431 | Rock | 41 | 2.3–4.4 |

#Broadband stations with CMG-3T sensor (Guralp) and CMG-24 digitizer (Guralp)
/C3 Broadband stations with CMG-3T sensor and 130-01 digitizer (Reftek)
/C15 Stations with GSR-18 (GeoSIG) strong motion accelerographs
/H17039 Stations with Etna (Kinemetrics) strong motion accelerographs

All stations in NE India are equipped with Reftek triaxial digital broadband seismometer (120 s) and Reftek strong motion accelerometer.
were able to develop the relationships for both rock and soil sites in NE India as we have enough data to carry out the regression analysis whereas in Gujarat, we have data from only one soil site. In view of this, we were able to develop relationship for rock sites only, for Gujarat.

For Gujarat, we see that the regression equations fit the data with a good correlation

\[
\log_{10}(HPGAsma) = 0.86 \times \log_{10}(HPGAbbs) + (-0.27), \quad r = 0.91 \quad \text{and} \quad \sigma = 0.14 \quad (1)
\]

\[
\log_{10}(VPGAsma) = 0.78 \times \log_{10}(VPGAbbs) + (-0.39), \quad r = 0.83 \quad \text{and} \quad \sigma = 0.19 \quad (2)
\]

As for the NE India data, the following equations (3&4 for rock sites and 5&6 for the soil sites) are fitted for the data. The correlation coefficients (r) are standard deviations (\(\sigma\)) are written.

\[
\log_{10}(HPGAsma) = 0.94 \times \log_{10}(HPGAbbs) + (-0.03), \quad r = 0.95 \quad \text{and} \quad \sigma = 0.12 \quad (3)
\]

\[
\log_{10}(VPGAsma) = 0.95 \times \log_{10}(VPGAbbs) + 0.02), \quad r = 0.95 \quad \text{and} \quad \sigma = 0.13 \quad (4)
\]

\[
\log_{10}(HPGAsma) = 0.89 \times \log_{10}(HPGAbbs) + (-0.08), \quad r = 0.97 \quad \text{and} \quad \sigma = 0.09 \quad (5)
\]

\[
\log_{10}(VPGAsma) = 0.94 \times \log_{10}(VPGAbbs) + 0.06), \quad r = 0.97 \quad \text{and} \quad \sigma = 0.10 \quad (6)
\]

Corresponding plots are shown in Figure 4 and the coefficients of the developed equations are presented in Table 2. We see that in Gujarat, for the horizontal component, 90% records are within the statistical limit, with a correlation factor of 0.91 and 82% of records with a correlation factor of 0.83 are inside ±1\(\sigma\) limit for the vertical component. For NE India, 94% and 90% HPGA and VPGA records with correlation factors of 0.95 and 0.97 are within the statistical limit for rock and soil data, respectively. In statistics, the correlation factor measures the strength and direction of a linear relationship between two variables on a scatterplot. We see that the correlation factors lie in the range 0.83–0.97, which indicates a fairly strong positive relationship. A near perfect positive relationship is reflected in NE India as the correlation factors are 0.95 (rock) and 0.97 (soil). A comparatively high \(\sigma\) of 0.19 is found for Gujarat for vertical component (equation 2). However, for equation (1) and (3)-(6), very small standard deviation values 0.09–0.14 are indicative of the fact that the individual data values are very close to the mean value.

Apart from the local site conditions, magnitude and distance are also two main factors that affect the ground motion. In view of this, influences of magnitude and hypocentral distance (HD) are also studied for both the regions. Figure 5(a) plots the residual, that is, the difference between the observed and the estimated values of the PGAs as a function of distance and magnitude for Gujarat. It is evident from Figure 5(a) that the observed acceleration values are larger than the estimated ones. It is observed that for the horizontal component, the residuals are within 95% confidence limits (within ±2\(\sigma\)), except for few records. Often, large sharp PGA spikes are
observed for small non-damaging events at close-in distances (Wu et al. 2003). In addition, directivity in combination with local site-effect may also have played a part in increasing the accelerations at certain sites. For vertical component, it is seen that the residuals are beyond 95% confidence limit for 11 records. All are near distance events (HD < 50km) in the magnitude range M2.6–4.1 and the recording stations are BDR(5), DUD(1), CHO(1), KAV(3) and SUV(1). This may be because of the fact that the observed VPGA is large in the near-field (Niazi and Bozorgnia 1991) and that is also reflected in Figure 2(b).

For NE India, the residual plots are shown in Figures 5(b) and (c), for rock and soil sites, respectively. It is observed that for rock sites, six records comprising two at GTK site and four at TURA show high residuals whereas for soil site, little high (almost negligible) residual is seen in three records, all at GUWA. Remaining are within 95% confidence limits. The higher residuals are seen at a distance range 100–500 km and magnitude range 4.3–5.7 for rock sites and for soil, within 100 km and magnitude range 4.0–4.5. The residual plots do not show much difference within the horizontal and the vertical components and the observed PGA is found more than the predicted in all cases. Kumar et al. (2020) reported values of near surface attenuation parameter kappa at TURA and GTK as 0.0306 and 0.0288, which are low as compared to the average value of 0.0368 in NE India. This will result in comparatively high acceleration at these sites. As the kappa is the high frequency attenuation parameter, we speculate that it may have affected the observed acceleration values. A marginally high observed PGAs at GUWA might be due to the source radiation pattern and/or local site effect.

Figure 6 shows a combine graph where all the data for Gujarat and NE India are plotted along with the developed relationships. We see that a similar trend is observed in the soil and the rock sites of the NE India with a linear shift, as expected. It is interesting to note that despite of difference in tectonic regime and attenuation characteristics, a similar trend in the regression lines is depicted in the Gujarat and the NE India sites. Since Gujarat data is devoid of large magnitude samples, we may reasonably use the NE relationship for higher magnitude. Similarly, Gujarat relationship will provide reasonable estimate of PGA for lower magnitude earthquakes in the NE Indian region. In this context, it is also important to mention that the hazard level associated to these regions are different due to difference in the source, site, path characteristics and associated hazard parameters. Sharma et al. (2016) carried out a study on characteristics of ground motion response spectra from earthquakes recorded in NE India from stations installed in different geological formations. They also performed a comparative study to explore the similarities and differences in the spectra of similar rock formations in Gujarat and NE India. They found the peak of

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**Table 2. Coefficients of scaling relations developed in the present study and standard deviations.**

| Component | a  | b  | Std dev (r) | Correlation Coefficient (r) | Region and local geology |
|-----------|----|----|-------------|----------------------------|--------------------------|
| H         | 0.86 | -0.27 | 0.14 | 0.91 | Gujarat (rock) |
| Z         | 0.78 | -0.39 | 0.19 | 0.83 | |
| H         | 0.94 | -0.03 | 0.12 | 0.95 | NE India (rock) |
| Z         | 0.95 | 0.02  | 0.13 | 0.95 | |
| H         | 0.89 | -0.08 | 0.09 | 0.97 | NE India (soil) |
| Z         | 0.94 | 0.06  | 0.10 | 0.97 | |
Figure 5. The distributions of residuals, i.e. differences between logarithms of observed PGA and predicted/derived PGA, with respect to distance and magnitude. The mean $\mu$ and standard deviation $\sigma$ associated with the residuals are also indicated. The 68% and 95% confidence level are marked by dashed and solid lines.
the response spectra of similar formations at different periods in both the regions. Although the amplitude of the spectral amplification is almost same, the peak being on the higher side for similar formations for the NE India (Sharma et al. 2016). They concluded that for a structure on same geological formation with the same natural period, the design seismic forces would be higher in Gujarat region than in NE region. Even though their study does not involve analysis of the free field motion (PGA), still having regional differences in ground motions in different tectonic regions, particularly in their attenuation, is a fact that is believed worldwide. Because of this difference, PGA values will differ in both the regions. Characterizing the differences is not within the purpose or scope of this present study, but ought to be underscored.

Immediately after an earthquake, the shaking level is generally presented by a ShakeMap. A ShakeMap is simple but approximated, due to the simple formalism of the GMPEs. GMPEs predict a ground shaking that is more uniform than it would be expected for actual earthquake. One of the important limitations of the ShakeMap is that it fails to show the directivity and local site-effect. In view of this, many times, the ground motions are underestimated. This will be reflected in ground motion maps, which we have prepared using the relationships developed for the Gujarat and the NE India region. Using the developed relationship, we prepare a ground motion map, which is a representation the PGAs of a M5.2 earthquake that occurred in Kachchh on 19 June 2012 (Figure 7(a)). This was referred as the Dholavira earthquake, having a strike-slip mechanism (Choudhury et al. 2016). Though the event was well recorded at 15 SMA sites, we incorporated data of 16 BBS sites after converting their amplitudes to PGA using the developed empirical relationship. We used data from 31 stations spread widely all over Gujarat region (Figure 7(a)) and prepared a PGA map. From Figure 7(a), it is evident that the directivity effect is well-

![Figure 6. PGA (observed) vs PGA (estimated) for Gujarat and NE India regions. The lines show the scaling relation developed in the present study.](image-url)
captured as we can see that the lobes are elongated in the strike direction, both close and away from the fault. If we use simple GMPE for plotting, then circular concentric circles will be formed for each PGA and directivity and local site-effect will not be captured. To test another scenario, we prepared a ground motion distribution map of the 14 June 2020 Bhachau earthquake (M5.3) using data from 27 stations (Figure 7).
Along with data from 15 SMAs, we used data from 12 BBS stations, converted them into accelerations using the developed relationship. The earthquake occurred on a ESE-WNW reverse fault, dipping towards south. Here, in this case also, the

7(b)). Along with data from 15 SMAs, we used data from 12 BBS stations, converted them into accelerations using the developed relationship. The earthquake occurred on a ESE-WNW reverse fault, dipping towards south. Here, in this case also, the

Figure 8. The ground motion maps for the (a) 3 January 2017 (M 5.7), (b) 24 January 2015 (M 4.7), (c) 27 April 2013 (M 4.4) and (d) 13 September 2014 (M 4.1) NE India earthquakes generated using the acceleration values derived with the scaling relationship and the observed ones. The estimated focal mechanism of each of the earthquake is plotted.
directivity effect is clearly reflected. It is observed that at nearly the same distance, the sites on the hanging wall side experienced higher PGAs than those on footwall side. If we compare Figure 7(b) with Figure 7(a), we see that the ground motions generated by the M5.2 earthquake is less (max PGA ~ 0.1 g) than those generated by the M5.3 earthquake (max PGA~0.12g), though the magnitude difference is very minor. Also, the distribution of ground motions are entirely different. It is a well-
known fact that the strike-slip, thrust, or normal-faulting earthquakes differ systematically. The same size reverse earthquake at a same distance to the site and site condition generates 20–30% larger ground motion than a strike-slip earthquake (Somerville and Abrahamson 1995; Spudich et al. 1996; Bolt and Abrahamson 2004).

Figure 9. Comparison of PGA estimated in present study with the available region specific GMPEs for the (a) 19 June 2012 (M 5.2) and (b) 14 June 2020 (M 5.3) earthquakes. MEA: Mandal et al. (2009), NDM: NDMA (2011), CAC: Chopra and Choudhury (2011), JEA: Joshi et al. (2013).
Likewise, we prepared ground motion maps for four earthquakes that have occurred in NE India, on 3 January 2017 (M 5.7), 24 January 2015 (M 4.7), 27 April 2013 (M 4.4) and 13 September 2014 (M 4.1). The maps are shown in Figure 8(a–d). In all these cases, number of data values from SMA were only few. These were supplemented with BBS values using empirical relationship developed for NE India region. We used data from 14, 11, 14, 9 BBS stations along with 2, 1, 1, 5 SMA stations for M4.4, M4.1, M4.7 and M5.7, respectively. Of these, two earthquakes are reverse and two are of strike-slip mechanism. Here we don’t see much variation or effect of directivity as the stations are distant, unlike Gujarat. The PGAs are attenuating with increasing distances, which is absolutely anticipated. However, in all cases we see that the station TEZP show a relatively larger than expected ground motion, except for the M5.7 earthquake. Generally, PGA decreases with increasing distances. As TEZP (100 km) is the nearest station to the epicentre of the M4.4 than ZIRO (119 km) and ITAN (126 km), so larger PGA is reasonable. For M4.1, TEZP (125 km) is the farthest, the other two are ZIRO (104 km) and TAWA (119 km). The reason for higher PGA at TEZP in this case is the local site condition. TEZP site is on soil, whereas ZIRO and TAWA are on rock (Table 1), so the waves might have amplified in the sediments, thereby increasing the PGA. Here, it is observed that sites TEZP (319 km), JORH (217 km) and DIBR (273 km) located in Brahmaputra basin have larger than expected PGAs. Saikia et al. (2017) carried out detailed analysis of the shallow sedimentary structures in the Brahmaputra valley by inverting receiver functions from ten BBS stations and revealed a recent and thick sedimentation piled over the basement in the valley. The sedimentary layer thickness varies from 0.5 to 6.5 km across the valley. They reported the thickness of the topmost layer to be 1 km and 3.7 km beneath TEZP and JORH. We assume that the thick crustal sediment cover has amplified the ground motion even at location far away (200–300 km) from the epicentre. Zalachoros et al. (2019) developed a ground motion model (GMM) for small to moderate earthquakes (Mw 3.0–5.8) in Texas, Oklahoma, and Kansas using 4,528 ground motions recorded in that region. The GMM thus developed account for magnitude, distance, and $V_{S30}$ scaling and predicts less amplification at sites with $V_{S30} < 600$ m/s because of the thinner sediments beneath the stations, particularly at longer periods. TEZP has thinner sediments (Saikia et al. 2017) and is at a longer distance from epicentre, than JORH. The long period earthquake waves propagated through the sediments caused amplification at TEZP. In addition, the dominant frequency of the incoming seismic waves might have caused amplification that gives rise to comparatively high PGA values at TEZP. Thorough and precise study of the site characterization at these stations would possibly address to this enigma.

Moreover, for validations, we compared the acceleration values obtained using the relationships developed in the study, with the region specific GMPEs developed by various researchers (Mandal et al. 2009; Chopra and Choudhury 2011; NDMA 2011; Joshi et al. 2013). The comparison is shown in Figure 9(a,b). NDMA (2011) developed the GMPE for A-type rocks (shear wave velocity ≥1.5 km/s). While the GMPEs of Chopra and Choudhury (2011) and Joshi et al. (2013) are valid for rock sites of Gujarat region, Mandal et al. (2009) developed the relation for rock sites with a shear wave velocity of 760 m/s. We applied site correction factors to NDMA (2011) and
Mandal et al. (2009), following Choudhury et al. (2017), to get the ground acceleration values. Then we compared the acceleration values estimated using the relationship developed in the present study with the four Gujarat specific GMPEs. We see that NDMA (2011) reflects overestimation in both the cases. Also, for the earthquake of M5.2, the predicted acceleration values match well with the GMPEs of Mandal et al. (2009) and Joshi et al. (2013) at a distance $\leq 200$km beyond which the values fit with the GMPE of Joshi et al. (2013). For earthquake of M5.3, the predicted values match reasonably well with GMPEs of Joshi et al. (2013) and Chopra and Choudhury (2011). Hence, it appears that for Gujarat region, the developed relationship can reliably be used to fill the data gaps where observed acceleration data are not available.

The validation in the same way is carried out for NE India data too. Unlike Gujarat, many GMPEs are available for NE India (Aman et al. 1995; Singh et al. 1996; NDMA 2011, REA: Ramkrishnan et al. 2020). The grey solid lines mark the 68% confidence level corresponding to the GMPE of NDMA (2011).

Figure 10. Comparison of PGA estimated in present study with the available region specific GMPEs for the (a) 3 January 2017 (M 5.7), (b) 24 January 2015 (M 4.7), (c) 27 April 2013 (M 4.4) and (d) 13 September 2014 (M 4.1) earthquakes. AEA: Aman et al. (1995), SEA: Singh et al. (1996), NDM: NDMA (2011), REA: Ramkrishnan et al. (2020). The grey solid lines mark the 68% confidence level corresponding to the GMPE of NDMA (2011).
However, most of the GMPEs are valid for $M \geq 5.0$, except for Nath et al. (2005), Baruah et al. (2009), NDMA (2011) and Ramkrishnan et al. (2020). While the maximum distance range used in Nath et al. (2005) and Baruah et al. (2009) are 100 and 145 km; NDMA (2011) and Ramkrishnan et al. (2020) GMPEs are applicable for a larger distance range of 500 and 640 km, respectively (Ramkrishnan et al. 2020). In view of this, we compared the acceleration values obtained for M5.7 earthquake with Aman et al. (1995), Singh et al. (1996), NDMA (2011) and Ramkrishnan et al. (2020). The derived acceleration values of M4.7, M4.4, M4.1 earthquakes are compared with NDMA (2011) and Ramkrishnan et al. (2020) GMPEs. We could not test our data with GMPEs of Aman et al. (1995) and Singh et al. (1996) as in both the equations, the maximum distance considered was 200 km. The comparison of individual earthquakes is shown in Figure 10(a–d). We see that the acceleration values (except a few) of the M4.1 and M4.7 earthquakes (reverse mechanism) somewhat fall within ±1sigma values of the GMPE of NDMA (2011), while M5.7 and M4.4 (strike-slip mechanism) are little off from the acceleration values as predicted by NDMA (2011). It may be noted that GMPEs for NE Indian region are mostly developed using synthetic data obtained using simulations. In these simulations, it is really a challenge to incorporate path and site effects. The present data is actual recordings at those sites and provides true picture of path and site effects. Though the relationships predicted values with fair accuracy for sites within 200 km, the GMPEs failed to model ground motions at sites far off distances (> 200 km). This shows the importance of actual recordings. However, for the M5.7 earthquake, the acceleration value at the near distant station (AGT~97km), exactly match with the predicted values of GMPEs of Aman et al. (1995), Singh et al. (1996) and NDMA (2011). The GMPE of Ramkrishnan et al. (2020) speculates overestimation in all the cases. Ramkrishnan et al. (2020) developed the GMPE utilizing 24 events of magnitude range 4.2–6.9 and hypocentral distance 42–640 km, which may not represent full spectrum of ground motion characteristics of the entire NE India region. For this reason, the predicted values may not be close to the observed ones. This also calls for developing a region specific GMPE with more observed data, that can account for fault mechanism, directivity and other complexities. The regression equation developed in this study may provide useful inputs towards doing so.

It is necessary to mention here that there might be uncertainties derived from observations as well as estimation that could give rise to bias to the results. We need to identify such error sources to achieve optimal quality control, data analysis, and interpretation. One such source could be clipped seismic waveforms. The seismic waveforms would be clipped when the amplitude exceeds the upper-limit dynamic range of the seismometer. Clipped waveforms are typically assumed not useful and need to be discarded as these will not present the actual amplitude. Either during quality check, we need to reject such waveforms, or the clipped seismic waveforms may be restored (Zhang et al. 2016). In addition, seismic signals are occasionally masked by seismic noise. One of the main issues in any study that involves seismic data is to ensure high signal-to-noise (SNR) ratio or to improve SNR by applying proper ways of data acquisition and processing (Bormann and Wielandt 2013). In
particular, more attention on data from stations established on soft soils is needed, as those stations tend to be noisier. One of the sources of uncertainties in the estimation of the accelerations could be underestimation. Accelerograms have been computed from the seismograms by derivation, using the Fourier transformation and it may filter out the high frequency of the corresponding seismogram. Nevertheless, the recorded accelerograms may have a greater abundance of high frequency energy than the derived one. This is what we observe at TURA and GTK stations in NE India.

5. Conclusions

The strong ground motion parameters at a site of interest have many engineering applications. Such parameters are difficult to get in the absence of strong motion recordings. Many earthquake recording sites in Gujarat and NE India have co-located strong motion and broadband instruments. This motivated us to develop scaling relationships between the PGAs from the strong motion recordings and that derived from weak motion recordings obtained from co-located broadband instruments, for these two seismically active regions of India. The empirical relationships thus obtained have high correlation coefficient, in excess of 0.9 in most of the cases. The Gujarat data is rich in low to moderate earthquakes, mostly within 100 km of the source zones whereas NE Indian data comprises moderate to large earthquakes mostly in the range 100–200 km of various sources. It is observed that the empirical relations of Gujarat and NE India do not have significant differences in trend and values of the coefficients of the regression equations. Therefore, for moderate to strong earthquakes in Gujarat, NE India equation can provide a fair estimate and for small to moderate earthquakes in NE India, Gujarat relationship can be used. Fair comparison of the acceleration values derived using the developed regression equations with the region specific GMPEs of both the regions validate the results of our analysis, especially for Gujarat region. However, NE India acceleration values were little far from the predicted values given by the GMPEs, as NE India is one of the most complex tectonic provinces of the world and traditional GMPEs fail to capture such complexities at regional distances. We conclude that a realistic ground motion map can be obtained as more stations can contribute in its preparation by using the scaling relationships developed in the present study. It can take care of either or both source and site complexities like directivity, fault type, sedimentary thickness, which are otherwise not accounted in traditional GMPEs. The outcome of the present study will help in filling the data gaps where strong motion recordings are not available. Moreover, the present findings will be useful in seismic hazard and risk analysis in a more realistic way as it will help in improving the ground motion predictions in real-time applications.

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Data availability

The broadband seismic and strong motion acceleration data used in this study have been obtained from the Gujarat Seismological Network (GSNet) operated by the ISR, Gandhinagar, India and National Centre for Seismology, New Delhi, India. Data are available to researchers in collaborative mode and may be obtained by contacting the authors.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Aki K. 1988. Local site effect on ground motion. Proc Earthquake Eng Soil Dyn. II:103–155.
Aman A, Singh UK, Singh RP. 1995. A new empirical relation for strong seismic ground motion for the Himalayan region. Curr Sci. 69(9):772–776.
Bansal BK, Pandey AP, Singh AP, Suresh G, Singh RK, Gautam JL. 2021. National seismological network in India for real-time earthquake monitoring. Seismol Res Lett. 92(4):2255–2269.
Baruah S. 2008. A GIS based tectonic map of north eastern India. Curr Sci. 95(2):176–177.
Baruah S, Baruah S, Gogoi NK, Erteleva O, Aptikaev F, Kayal JR. 2009. Ground motion parameters of Shillong plateau: one of the most seismically active zones of northeastern India. Earthq Sci. 22(3):283–291.
Beyreuther M, Barsch R, Krischer L, Megies T, Behr Y, Wassermann J. 2010. ObsPy: a python toolbox for seismology. Seismol Res Lett. 81(3):530–533.
Biswa SK. 1987. Regional tectonic framework, structure and evolution of the western marginal basins of India. Tectonophysics. 135(4):307–327.
Biswa SK. 2005. A review of structure and tectonics of Kachchh basin, western India, with special reference to earthquake. Curr Sci. 88:1592–1600.
Bolt BA, Abrahamson NA. 2004. Estimation of strong seismic ground motion. In: Lee W, editor. International handbook of earthquake and engineering seismology. London, UK: Academic Press; p. 983–1001.
Borcherdt RD. 1970. Effects of local geology on ground motion near San Francisco Bay. Bull Seismol Soc Am. 60:29–61.
Bormann P, Wielandt E. 2013. Seismic signals and noise. Chapter 4. In: Bormann P, editor. New manual of seismological observatory practice (NMSOP-2) (2012). Potsdam, Germany: IASPEI, GFZ German Research Centre for Geosciences, p. 63. Available from: http://nmsop.gfz-potsdam.de.
Buland R, Chapman CH. 1983. The computation of seismic travel times. Bull Seismol Soc Am. 73(5):1271–1302.
Chopra S, Choudhury P. 2011. A study of response spectra for different geological conditions in Gujarat, India. Soil Dyn Earthquake Eng. 31(11):1551–1564.
Chopra S, Yadav RBS, Patel H, Kumar S, Rao KM, Rastogi BK, Hameed A, Srivastava S. 2008. The Gujarat (India) seismic network. Seismol Res Lett. 79(6):806–808.
Choudhury P, Chopra S, Kumar MR. 2018. A review of seismic hazard assessment of Gujarat: a highly active intra-plate Region. Earth Sci Rev. 187:205–218.
Choudhury P, Chopra S, Roy KS, Rastogi BK. 2014. A review of strong motion studies in Gujarat state of western India. Nat Hazards. 71(3):1241–1257.
Choudhury P, Chopra S, Roy KS, Sharma J. 2016. Ground motion modelling in the Gujarat region of Western India using empirical Green’s function approach. Tectonophysics. 675:7–22.
Choudhury P, Chopra S, Roy KS, Sharma J, Rastogi BK. 2017. Revisiting the 1956 Anjar earthquake in Western India: empirical Green’s function approach. Bull Seismol Soc Am. 107(2): 592–602.

Crotwell HP, Owens TJ, Ritsema J. 1999. The TauP toolkit: flexible seismic travel-time and ray-path utilities. Seismol Res Lett. 70(2):154–160.

Curray JR, Emmel FJ, Moore DG, Raitt RW. 1982. Structure, tectonics, and geological history of the northeastern Indian Ocean. In: Nairu AEM, Stehli FG, editors. The ocean basins and margins. Vol. 6. New York: Plenum; p. 399–450.

Dattatrayam RS, Suresh G, Baidya PR, Prakash R, Gautam JL, Shukla HP, Singh D. 2014. Standards and methodologies of seismological data generation, processing and archival & guidelines for data sharing and supply. Proc Ind Natl Sci Acad. 80(3):679–696.

Douglas J. 2003. Earthquake ground motion estimation using strong-motion records: a review of equations for the estimation of peak ground acceleration and response spectral ordinates. Earth Sci Rev. 61(1–2):43–104.

Field EH, Jacob KH, Hough SH. 1992. Earthquake site response estimation: a weak-motion case study. Bull Seismol Soc Am. 82(6):2283–2307.

Gupta ID. 2010. Response spectral attenuation relations for in-slab earthquakes in Indo- Burmese subduction zone. Soil Dyn Earthquake Eng. 30(5):368–377.

Havskov J, Ottemoller L. 1999. SeisAn earthquake analysis software. Seismol Res Lett. 70(5):532–534.

Joshi A, Kumar A, Mohan K, Rastogi BK. 2013. Hybrid attenuation model for estimation of peak ground accelerations in the Kutch region, India. Nat Hazards. 68(2):249–269.

Joshi V, Chopra S, Mahesh P, Kumar S. 2017. Joint modeling of velocity structure and hypocentral locations in the seismically active Kachchh, Saurashtra, and Narmada regions of Western India: an active intraplate region. Seismol Res Lett. 88(5):1390–1402.

Kennett BLN, Engdahl ER. 1991. Travel times for global earthquake location and phase association. Geophys J Int. 105(2):429–465.

King JL, Tucker BE. 1984. Observed variations of earthquake motion across a sediment-filled valley. Bull Seismol Soc Am. 74(1):137–151.

Kumar V, Chopra S, Choudhury P, Kumar D. 2020. Estimation of near surface attenuation parameter kappa (κ) in Northwest and Northeast Himalaya region. Soil Dyn Earthquake Eng. 136:106237.

Mandal P, Kumar N, Satyamurthy C, Raju IP. 2009. Ground-motion attenuation relation from strong motion records of the 2001Mw 7.7 Bhuj earthquake sequence (2001–2006), Gujarat, India. Pure Appl Geophys. 166(3):451–469.

Merh SS. 1995. Geology of Gujarat. Bengaluru: Geological Society of India, p. 222.

Nandy DR. 2001. Geodynamics of Northeastern India and the adjoining region. Calcutta: ABC Publications; p. 209.

Nath S, Vyas M, Pal I, Sengupta P. 2005. A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry. J Geophys Res. 110(B1):3199.

NDMA. 2011. Development of probabilistic seismic hazard map of India. Technical Report of the Working Committee of Experts (WCE) constituted by the National Disaster Management Authority Govt. of India, New Delhi. Available from: https://ndma.gov.in/sites/default/files/PDF/Technical%20Documents/Indiapshafinalreport.pdf.

Niazi M, Bozorgnia Y. 1991. Behaviour of near-source peak horizontal and vertical ground motions over smart-1 array, Taiwan. Bull Seismol Soc Am. 81(3):715–732.

Python Core Team. 2015. Python: a dynamic, open source programming language. Python Software Foundation. Available from: https://www.python.org.

Ramkrishnan R, Sreevalsa K, Sitharam TG. 2020. Strong motion data based regional ground motion prediction equations for North East India based on non-linear regression models. J Earthquake Eng. doi: 10.1080/13632469.2020.1778586
Saikia S, Chopra S, Baruah S, Singh UK. 2017. Shallow sedimentary structure of the Brahmaputra valley constraint from receiver functions analysis. Pure Appl Geophys. 174(1):229–247.

Sharma B, Chopra S, Chingtham P, Kumar V. 2016. A study of characteristics of ground motion response spectra from earthquakes recorded in NE Himalayan region: an active plate boundary. Nat Hazards. 84(3):2195–2210.

Sharma ML. 1998. Attenuation relationship for estimation of peak ground horizontal acceleration using data from strong-motion arrays in India. Bull Seismol Soc Am. 88(4):1063–1069.

Sharma ML, Douglas J, Bungum H, Kotadia J. 2009. Ground-motion prediction equations based on data from the Himalayan and Zagros Regions. J Earthquake Eng. 13(8):1191–1210.

Shukla AK, Prakash R, Pandey AP, Singh RK, Mandal HS, Singh D, and Baidya PR. 2011. Overview of seismic hazard and mitigation in North East India Region. New Delhi: IMD Publication.

Shukla AK, Singh RK, Prakash R. 2018. Instrumentation seismology in India. In: Sharma M, Shrikhande M, Wason H, editors. Advances in Indian earthquake engineering and seismology. Cham: Springer.

Singh R, Aman A, Prasad YJJ. 1996. Attenuation relations for strong seismic ground motion in the Himalayan region. PAGEOPH. 147(1):161–180.

Somerville PG, Abrahamson N. 1995. Ground-motion prediction for thrust earthquakes. In: Proceedings of SMIP95 Seminar. San Francisco, CA: California Division of Mines and Geology; p. 11–23.

Spudich P, Fletcher J, Hellweg M, Boatwright J, Sullivan C, Joyner W, Hanks T, Boore D, McGarr A, Baker L, et al. 1996. Earthquake ground motions in extensional tectonic regimes. U.S. Geological Survey Open-File Report, 96-292, 351p. Available from: https://pubs.usgs.gov/of/1996/0292/report.pdf.

US Geological Survey (USGS). 2017. ShakeMap – earthquake ground motion and shaking intensity maps. Available from:.

Wu YM, Ta-Liang T, Tzay-Chyn S, Nai-Chi H. 2003. Relationship between peak ground acceleration, peak ground velocity, and intensity in Taiwan. Bull Seismol Soc Am. 93(1):386–396.

Zalachoris G, Rathje EM, Eeri M. 2019. Ground motion model for small-to-moderate earthquakes in Texas, Oklahoma, and Kansas. Earthquake Spectra. 35(1):1–20.

Zhang J, Hao J, Zhao X, Wang S, Zhao L, Wang W, Yao Z. 2016. Restoration of clipped seismic waveforms using projection onto convex sets method. Sci Rep. 6:39056.