Influence of Ground Motion Scaling on the Nonlinear Seismic Response of Reinforced Concrete Buildings.

Chinmay V. Malvankar[1], Dr. Sachin P. Patil[2] and Dr. Ravindra M. Desai[3]

[1]PG Student, Department of Civil Engineering, Sanjay Ghodawat University, A/P Atigre, Kolhapur, 416118, Maharashtra, India.

[2] Assistant Professor, Department of Civil Engineering, Sanjay Ghodawat University, A/P Atigre, Kolhapur, 416118, Maharashtra, India.

[3] Assistant Professor, Department of Civil Engineering, Sanjay Ghodawat University, A/P Atigre, Kolhapur, 416118, Maharashtra, India.

Abstract

Understanding the impact of various ground motion scaling methods on the seismic response of structures is vital for achieving accurate performance-based design. This study examines the nonlinear seismic behaviour of a G+10 reinforced concrete building subjected to five different ground motion scaling techniques: Peak Ground Acceleration (PGA) Scaling, SaT1 Scaling, Geometric Mean Scaling, One-Step Scaling, and Spectrum Matching. The structural model was developed in CSI-SAP2000 and analysed using seven pairs of actual earthquake ground motions obtained from the PEER database. The building was assumed to be located in Seismic Zone IV, resting on hard soil, and intended for commercial use. Key response parameters such as base shear, displacement, drift, and failure patterns were evaluated. Among the scaling methods, One-Step Scaling resulted in excessively high responses, frequently suggesting collapse-level drifts. PGA Scaling and Spectrum Matching, while yielding conservative values, tended to underestimate realistic structural demands. In contrast, SaT1 and Geometric Mean Scaling methods produced more stable and representative results, aligning well with the building's dynamic properties. These outcomes emphasize the critical role of selecting an appropriate ground motion scaling method in nonlinear time history analysis to ensure dependable seismic performance assessments.

Keywords: Ground motion scaling, Non-linear time history analysis, Seismic performance, RC building, Structural response, SAP2000, Scaling methods, Dynamic structural analysis.

1. Introduction

Every structure is at a serious risk from seismic events, which can cause catastrophic damage or collapse, causing loss of life, economy and infrastructure. Thus, it becomes necessary to ensure that the designed structure can resist seismic actions up to a certain scale. To achieve this, engineers depend on seismic analysis techniques that help in predicting the behaviour of the structure under the action of seismic excitation. This is done by evaluating the structure's response by applying various past recorded earthquake ground motions, also known as "Time History analysis. This approach of analysis of structural response to seismic excitation while considering the effects of non-linearities of the structure is known as "Performance-based Seismic Design".

To perform a time history analysis, it is essential to have a well-curated set of ground motion records that accurately reflect the seismic characteristics of the site under consideration, to ensure that the results are reliable, meaningful and align with the specific seismic conditions of the region. This arises as a major setback for this approach. As a solution for this problem various methods of ground motion selection and modification are deemed necessary to be used. The codes provided by the Bureau of Indian Standards suggest using time history analysis procedures but they do not have enough guidelines for selection and modification of seismic ground motions.

Codes provided by other countries have some guidelines for the selection and modification of ground motion but a detailed suite of criteria is yet to be given. Multiple studies have shown the impact of various methods individually and in groups but none have taken an approach towards their effects on a non-linear structure. This present study aims to evaluate and compare the impacts of five ground motion scaling methods on the seismic non-linear response of a multistoried reinforced concrete building. The methods include 1) Peak Ground Acceleration Scaling, 2) Geometric Mean Scaling, 3) SaT1 Scaling, 4) One-Step Scaling and 5) Spectrum Matching. The objectives of this study are 1) To compare and study various Ground Motion Scaling Methods, 2) To evaluate the effect of ground motion scaling on the structural non-linear response of multistoried structures, 3) To assess the failure pattern of an R.C building with and without scaling of ground motions.

2. Recent Findings on Ground Motion Scaling.

Ground motion modification can be done by scaling the ground motions up or down such that the adjusted motions better match the target seismic hazard levels, response spectrum, or site-specific ground motion characteristics while preserving the essential frequency content and dynamic properties of the original records or by matching the entire or a specified part of the ground motion to the design/target response spectrum. Intensity-based methods of modification of ground motions are generally favoured in performance-based analysis as they retain the original frequency characteristics and time-dependent features of the record while only altering its amplitude. Spectrum Matching on the other hand adjust the phasing and frequency parameters to match the target response spectrum, which compromises the natural characteristics of the motions. [Markous et al., 2014]

Multiple researchers and studies have focused on the intensity-based or amplitude-based scaling methods. These methods are easy to understand and apply, compared to spectrum matching techniques. Intensity measures such as peak ground acceleration, peak ground velocity, spectral acceleration at fundamental or multiple mode periods, Arias intensity, etc, are commonly used since they are readily available along with the ground motions. Scaling using Peak ground acceleration as the intensity measure was the earliest approach in this domain, however, it tends to result in large dispersion in engineering demand parameters (EDPs)[Shome et al., 1997]

Shome et al. suggested that, to reduce the dispersion in the EDPs, the use of the vibration period of the structure can help in better estimation of the results. This can be achieved by scaling the spectral acceleration of the structure for its fundamental or first mode period to the target values of spectral acceleration provided either by the Code provision or obtained through Probabilistic seismic hazard analysis based on uniform spectrum curves. [Shome et al., 1997] However, according to Kurama and Farrow this method of scaling has a limitation, the method's suitability depends on the factor that the structure is dominated by first mode only. For structures whose other modes than the first mode are dominating, it provides less accurate results.[Kurama & Farrow, 2003] Kurama and Farrow also stated that other scalar intensity measure such as Arias intensity, effective peak acceleration, and velocity also gives inaccurate estimates of the EDPs and are inefficient.[Kurama & Farrow, 2003]

According to Yin-Nan Huang et.al, “Somerville et al. developed a new procedure for scaling of ground motion, known as the geometric-mean scaling method. This method involves amplitude scaling a pair of ground motions by a single factor. The objective is to minimize the sum of squared errors between target spectral values and the geometric mean of the spectral ordinate for the pair, in which the user selects the periods for the calculation.”. When applied, this method preserves the irregular shape of response spectra and a reduced dispersion in the spectral demand is observed.[Huang et al., 2011]

Huang et.al investigated six different methods of scaling in their study, namely: 1) geometric mean scaling, 2) Spectrum Matching, 3) SaT1 scaling, 4) Maximum demand scaling, 5) Spectrum matching to code-compliant spectrum and 6) Model pushover-based scaling. These methods were thoroughly evaluated for their efficiency in reducing record-to-record variability and their ability to maintain consistency in predicted Engineering Demand Parameters (EDPs). This study concluded that accurately estimating both the median and the dispersion of peak floor acceleration responses in high-rise buildings requires considering the fundamental mode as well as the influence of higher modes. When it comes to peak inter-storey drift demands, the contribution of short-period modes is relatively less, especially in tall structures.[Shome et al., 1997]

In 2002 Vamvatsikos and Cornell proposed a new method of scaling known as "One Step Scaling" as part of a bigger development, of Incremental dynamic analysis. This method obtained scale factors by scaling the value of the spectral acceleration of the ground motion at the first mode period of the structure to 1g. This type of scaling made it easy to obtain graphs which started at a singular point and made it easy to generate IDA curves, estimate the capacities of the structure. [Vamvatsikos & Cornell, 1998].

3. Selection of Ground Motion Records.

Ground motion modification as mentioned previously, selection of ground motions plays a vital role in performance-based analysis of structures. Various studies have proposed multiple methods for selection of ground motions, including processes such as selection based on magnitude and rupture distance, selection based on Conditional Mean spectrum, etc. The commonly used approach for primary selection of ground motion is the Magnitude and rupture distance (M-R) approach, which uses a range for earthquake magnitude and distances of the source to site for selecting a primary bin of earthquake ground motions.[Najafi & Tehranizadeh, 2015] This method can be made more efficient by defining more parameters such as soil properties, earthquake characteristics, etc.[Katsanos et al., 2010][Kalkan & Chopra, 20108][Maniyar & Khare, 2011] The secondary selection can be done by using multiple approaches. This includes 1. selection based on shape of response spectrum of the ground motion vs the target spectrum[Najafi & Tehranizadeh, 2015], 2. Selection based on intensity measure and 3. Selection based on Code provisions.[Katsanos et al., 2010].

A key aspect to consider when selecting ground motions is the distance between the site to source. Ground motion recordings can either be near the fault or far away from the fault, this influences the parameters of the recording significantly as the shaking felt close to the fault and away from the fault differs. Even if the magnitude is the same, the shaking experienced at both locations is different. Considerations made taking into account both types result in more efficient outputs of the analysis. When considering the near-fault sites, spectral shape and presence of velocity pulses are two factors which play an important role in the selection of ground motions. For Far-field or Distant field sites, ground motion selections mainly depend on the spectral shape similarity in the response spectra of ground motion and the target spectrum.[Haselton et al., 2012]

Including the "M-R" approach, Leila Haj Najafi, Mohsen Tehranizadeh (2015) suggested three more methods for selection of ground, which included 1. Selection of records at random from the record library, abbreviated as the Arbitrary Records method, 2.Selection of records whose ε values reflect and align with the site hazards characteristics, and 3.Selection of records based on the spectral shape that matches the Conditional Mean Spectrum, known as the CMs- ε Methods.[Najafi & Tehranizadeh, 2015]

By performing a site-specific hazard analysis, seismic parameters on the site in question can be obtained. These parameters can also be used for the selection of ground motion. This method gives a higher probability of accurate selection of ground motions but is complex and time-consuming. To find these parameters, seismic hazard analysis of the site can be performed using two methods, i.e. by "Deterministic Seismic Hazard analysis" (DSHA) and "Probabilistic Seismic Hazard analysis" (PSHA).[Katsanos et al., 2010] DSHA works by estimating the maximum ground motion that can occur at a site by considering known active faults and the maximum credible earthquake (MCE) on these active faults. This approach is conservative and focuses on the worst-case scenario that can happen at the site. DSHA gives the peak ground parameters of the site such as peak ground acceleration, peak ground displacement, spectral acceleration etc, for the maximum credible earthquake.[Krinitzsky, 1995][Gupta, 2002]

In PSHA, multiple variations of possible earthquakes, their magnitudes, locations and recurrence rates are considered. Integration over all possible combinations of this and uncertainties is performed by using ground motion prediction equations to estimate the hazard in terms of probability of exceedance. Performing PSHA gives us outputs like Hazard curve, Uniform Hazard spectra and maps showing the ground motion levels and probabilities of exceedance.[Krinitzsky, 1995][Gupta, 2002]

For this study, the selection of ground motion is done as per the selection criteria given by the ATC-63 Ground motion data set.[ATC-63] The criteria are as mentioned in the Table 1.

Table 1 *Criteria used for selection of Ground Motion*

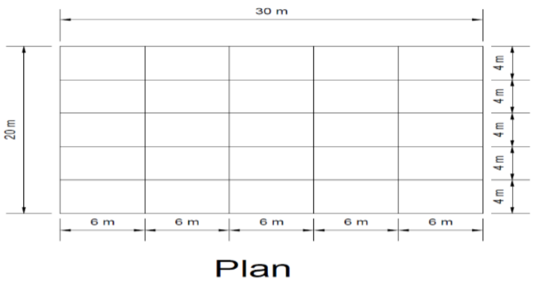
Criteria	Requirement
Magnitude	M > 6.5.
Fault Mechanism	Strike Slip and Reverse Thrust Faults.
Recording Site Soil Condition	Rock or Stiff Soil, Vs > 180 m/s
Distances for "Far Field Record"	R > 10 km
Distances for "Near Fault Record"	R < 10 km
Records per Fault Rupture Event	No more than 2 records per event
Peak Ground Acceleration	PGA > 0.2 g
Peak Ground Velocity	PGV > 15 cm/s
Lowest Usable Frequency	LUF < 0.25 Hz
Ground Motion Recording Site	Free-field or ground floor of small building

Earthquake ground motion records were downloaded from the Pacific Earthquake Engineering Research Centre (PEER) Ground Motion Database. Using the previously mentioned selection criteria, a large pool of records was gathered, forming the primary set of ground motion records. To narrow this down, a secondary selection was carried out based on the 'Spectral acceleration' intensity measure. The final selection included ground motions whose response spectra closely resembled the shape of the Target Response Spectrum, ensuring they were well suited for the objectives of this study.

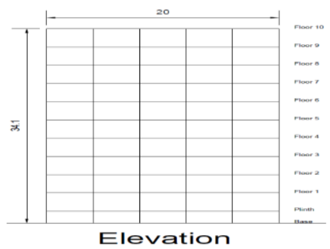
4. Mathematical Modelling and Seed Ground Motions.

4.1 Mathematical Modelling of the Structure.

This study focuses on the analysis and design of a G+10 reinforced concrete building using CSI-SAP2000 software. The structure is modelled as a bay frame system comprising of Special Moment Resisting Frame (SMRF) with fixed supports at the base. The plan dimensions are as shown in Figure 1.



(a)



(b)

Figure 1 (a) Plan view (b) Elevation view

The building consists of a uniform story height of 3.2m from the plinth to the terrace floor, while the base to plinth height is 2.1 m. The materials used for the members include concrete of Grade M40 and M30 for columns and beams respectively. While the rebars used conform to Grade Fe500 and Fe415.

The building is assumed to be in Seismic Zone IV, where the peak ground acceleration is estimated to be 0.24g as per I.S.1893:2016.[Bureau of Indian Standards, 2016] The soil type is classified as hard soil and the importance factor is taken as 1.5 as the building is a commercial building. The floor levels are assumed to be a rigid type of diaphragm to ensure the effective distribution of lateral forces. The building is subjected to dead loads, live loads, and seismic loads, determined according to the Code provisions for load given by the Indian standards.

To accurately capture the non-linear behaviour of the structure, two types of non-linearity are used in the model. The first is the Lumped Plastic Hinge approach, in which plastic hinges are assigned at both ends of beams and columns. This assignment allows for the localised inelastic deformation to occur. These hinges are automatically assigned by the software in accordance with Tables 10-7, 10-8 and 10-9 of ASCE 41-17[American Society of Civil Engineering, 2017]. The second type of non-linearity is Geometric non-linearity. In this, the effects of P-Delta that is the formation of secondary forces arising due to the lateral displacement under various loading conditions are considered.

4.2 Seed Ground Motions

The correct number of ground motions to be used is the question that is yet to be answered definitively. Various researchers and building codes suggest different recommendations about the number of ground motions that can be used. Shome and Cornell (1999) suggested that, when analysing for a mid-rise building use of 10 to 20 ground motion records is sufficient to record a reasonable level of accuracy in the results provided that an efficient intensity measure is used.[Shome et al., 1997] The guidelines of ASCE 7-22 clause 16.2.2 suggest using a minimum 11 number of ground motions in a suite.[American Society of Civil Engineering, 2022] According to clause 4.4.2 from FEMA p-58-1, if the shape of the response spectrum is a good fit to the target spectrum for specific period range then 7 pairs of ground motions are sufficient whereas if it is a poor fit then 11 or more than 11 ground motions are recommended.[Federal Emergency Management Agency, 2018] The Eurocode 8 suggests using a minimum of 3 ground motions in its clause number 3.2.3.1.2.[European Standards, 2004]

While the minimum number of ground motions varies based on different guidelines, it can be assumed that a suite of 7 ground motions can be considered for performing analysis and obtaining fairly accurate results, provided that the shape of the response spectra of the ground motion has a good fit to the target response spectrum. Based on this assumption, a set of 7 pairs of ground motions is selected from the PEER database of Ground motions. The details of the selected ground motions are mentioned in Table 2.

Table 2 *Details of Selected Ground Motions*

RSN	Event	Year	Mag.	Fault	PGA
126	Gazli, USSR	1976	6.8	Reverse	0.864
170	Imperial Valley-06	1979	6.53	Strike slip	0.235
802	Loma Prieta	1989	6.93	Reverse	0.326
848	Landers	1992	7.28	Strike slip	0.417
879	Landers	1992	7.28	Strike slip	0.789

1633	Manjil, Iran	1990	7.37	Strike slip	0.497
4451	Montenegro, Yugoslavia	1979	7.1	Reverse	0.368

5. Ground Motion Scaling.

Since ground motions originate from different earthquakes and site conditions, their raw intensities often vary. To ensure that these ground motions represent a consistent level of seismic demand, proper scaling of them is necessary. From the studies, multiple methods of scaling have been found out. This necessitates the need of comparing these methods to understand their influence on structural response. To do so, five different methods of ground motion scaling/modification are studied in this paper. They include, 1) Peak Ground Acceleration Scaling, 2) Geometric Mean Scaling, 3) SaT1 Scaling, 4) One – step Scaling, and 5) Spectrum Matching. These methods are explained below.

5.1 Peak Ground Acceleration Scaling.

Peak Ground Acceleration scaling is a simple and most commonly used form of intensity scaling of ground motions. In this method the peak value of acceleration of the ground motion is scaled to a target value of ground motions. The formula for obtaining scale factor using this method is simple and mentioned below,

$$Scale\ factor\ (SF) = \frac{Target\ Value\ of\ Peak\ Acceleration}{Peak\ Acceleration\ of\ GM}$$

5.2 Geometric Mean Scaling.

This method of scaling involves amplitude scaling a pair of ground motions by a single factor, obtained through minimizing the sum of squared errors between the target spectral values and the geometric mean of the spectral ordinate for the pair, in which the user selects the periods for the calculation. The formula for obtaining the scale factor is given below.

$$Scale\ factor\ (SF) = \frac{\Sigma S_{geo}(T) \times S_{target}(T)}{\Sigma S_{geo}(T)^2}$$

5.3 SaT1 Scaling.

In this method the ground motions are scaled by the scaling factor obtained by matching the spectral value of ground motion at the fundamental period of structure to the target value of spectral acceleration for fundamental period. The formula for obtaining the scale factor is given below.

$$Scale\ factor\ (SF) = \frac{Target\ Spectral\ acceleration\ at\ T_1}{Spectral\ acceleration\ of\ GM\ at\ T_1}$$

5.4 One step Scaling.

This method of scaling uses normalization of temporal values. Through this method, the scale factor is obtained by normalizing the values of ground motions at the fundamental time period of the structure to spectral acceleration value of 1g. The formula for obtaining the scaling factor is given below.

$$Scale\ factor\ (SF) = \frac{1}{Spectral\ acceleration\ of\ GM\ at\ T_1}$$

5.5 Spectrum Matching.

Spectrum matching is a more complex method than amplitude scaling. This method not only depends on the Amplitude adjusted to the earthquake intensity but also considers the frequency or period spectra of the target response spectrum. Spectrum Matching can be done either in Frequency domain or in Time domain. For the purpose of this study, spectrum matching was done in Time domain. To perform spectrum matching in time domain, a software known as Seismo-Match was used.

5.6 Scale factors for various methods of scaling.

The various scale factors obtained after scaling of the selected ground motions using various methods is listed below in Table 3.

Table 3 *Details of Scale factor for different methods of scaling.*

RSN	Event	PGA Scaling	Geometric Mean Scaling	SaT1 Scaling	One Step Scaling

126	Gazli, USSR	2.73	3.41	3.05	43.26
170	Imperial Valley-06	10.00	3.79	2.74	38.82
802	Loma Prieta	7.22	4.19	4.55	64.45
848	Landers	5.64	10.08	7.97	112.96
879	Landers	2.98	3.99	5.89	83.48
1633	Manjil, Iran	4.74	2.80	2.04	28.91
4451	Montenegro, Yugoslavia	6.40	3.12	3.01	42.62

6. Results and Discussion.

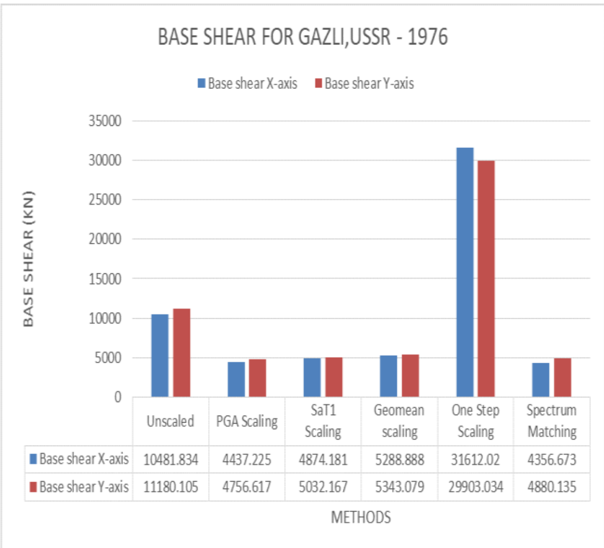
The present paper focuses on the non-linear response of a reinforced concrete building under various scaling methods. To understand this, results of various structural parameters are taken into account, those include, 1.Base shear, 2. Displacement and 3.Drift. Using this results a detailed discussion can be put forth regarding the effects of various scaling methods.

6.1 Results

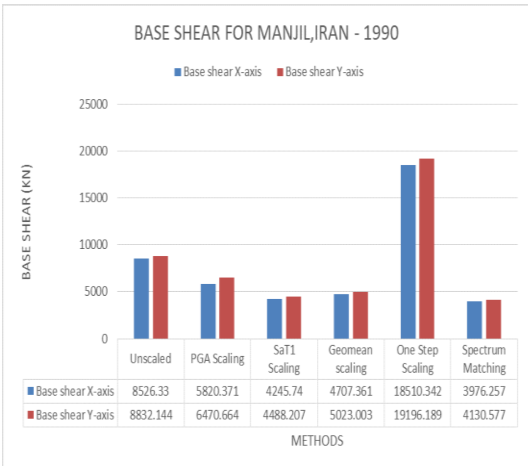
Non-linear time history analysis was performed on the structure and its results for base shear, displacement and drift were obtained. These results were obtained for each of the seven-ground motion records under every scaling method. Given the extensive volume of data, the results for two representative earthquakes are presented here.

6.1.1 Results for Base Shear

The results for base shear corresponding to both unscaled and scaled earthquake ground motions are presented here.



(a)



(b)

Figure 2: (a) Base Shear for Gazli, USSR (b) Base shear for Manjil, Iran

6.1.2 Results for Displacement

6.1.3 The results for displacement corresponding to both unscaled and scaled earthquake ground motions for X & Y axis are shown in Figure 3 and Figure 4.

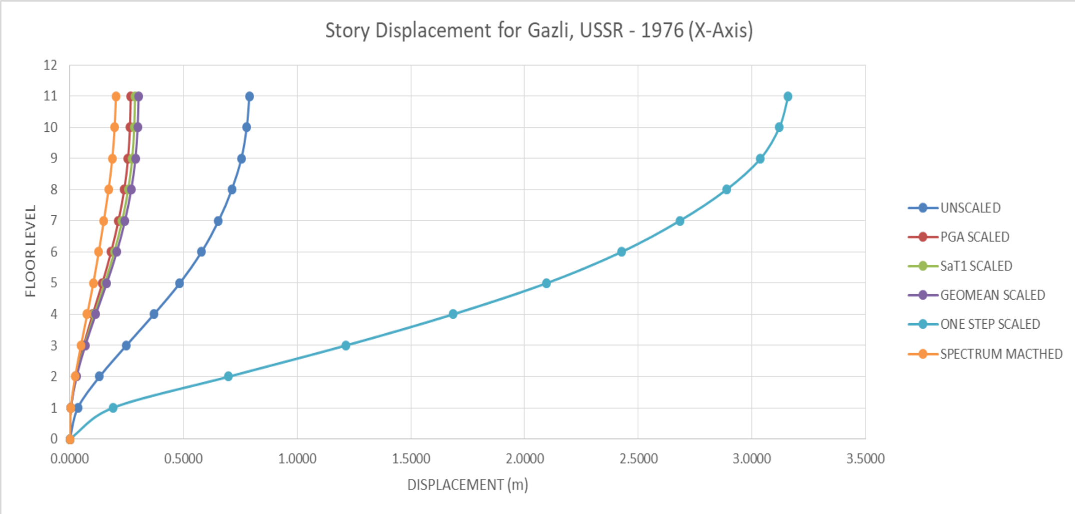


Figure 3(a)

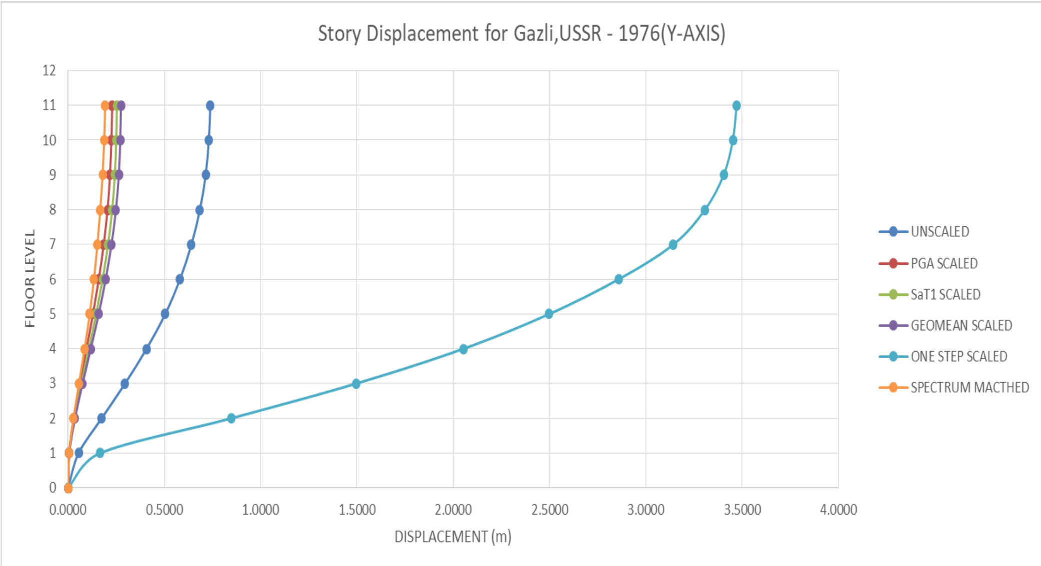


Figure 3(b)

Figure 3: (a) Displacement for Gazli, USSR (x-axis) (b) Displacement for Gazli, USSR (y-axis)

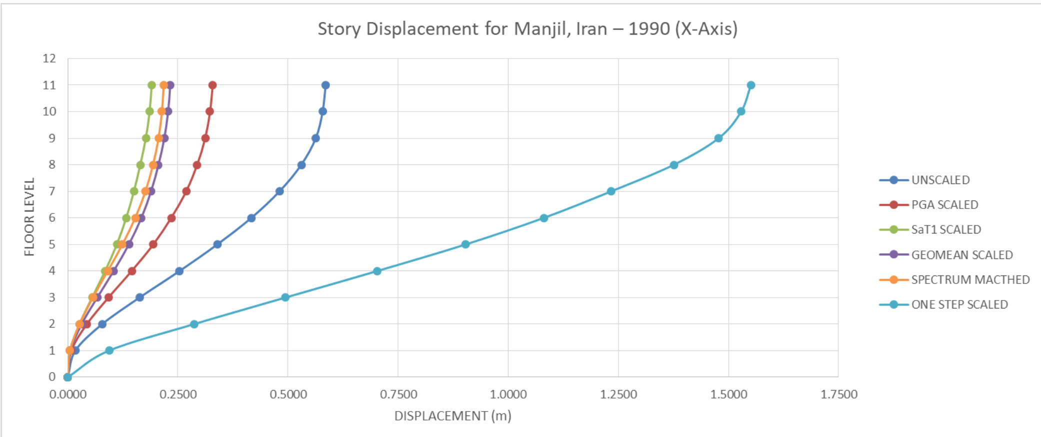


Figure 4(a)

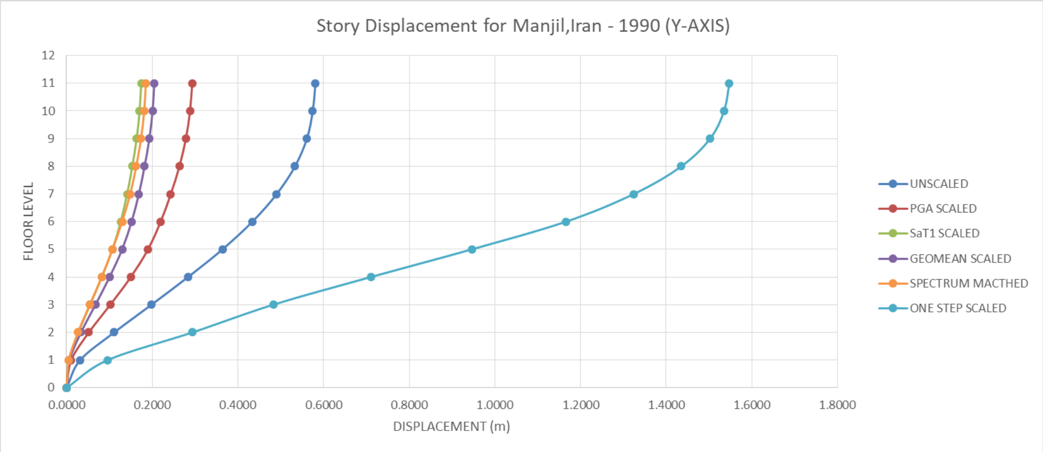


Figure 4(b)

Figure 4: (a) Displacement for Manjil, Iran (x-axis) (b) Displacement for Manjil, Iran (y-axis)

6.1.4 Results for Drift

The results for drift corresponding to both unscaled and scaled earthquake ground motions for X & Y axis are shown in Figure 5 and Figure 6.

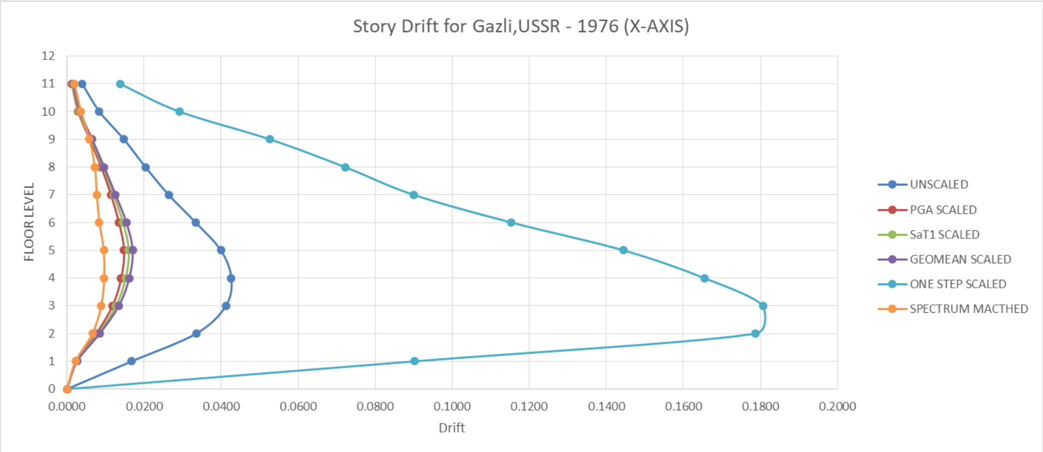


Figure 5(a)

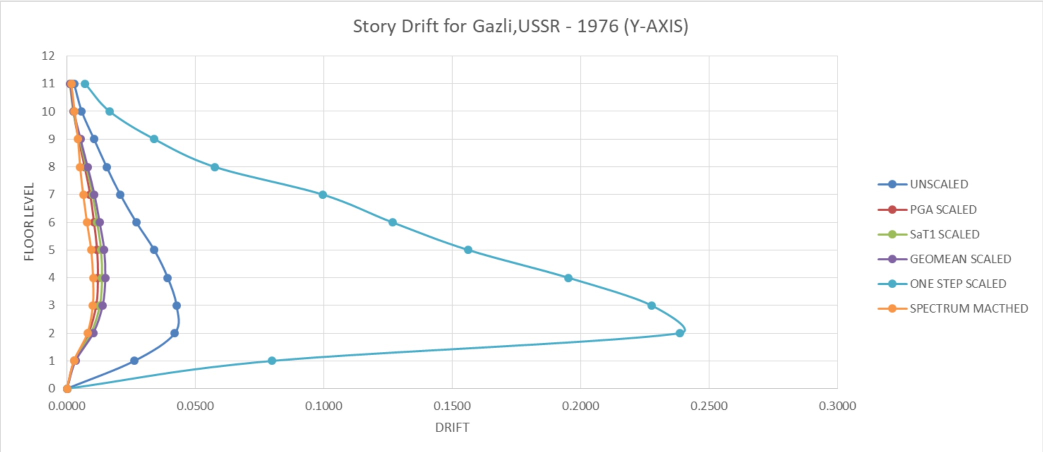


Figure 5(b)

Figure 5: (a) Drift for Gazli, USSR (x-axis) (b) Drift for Gazli, USSR (y-axis)

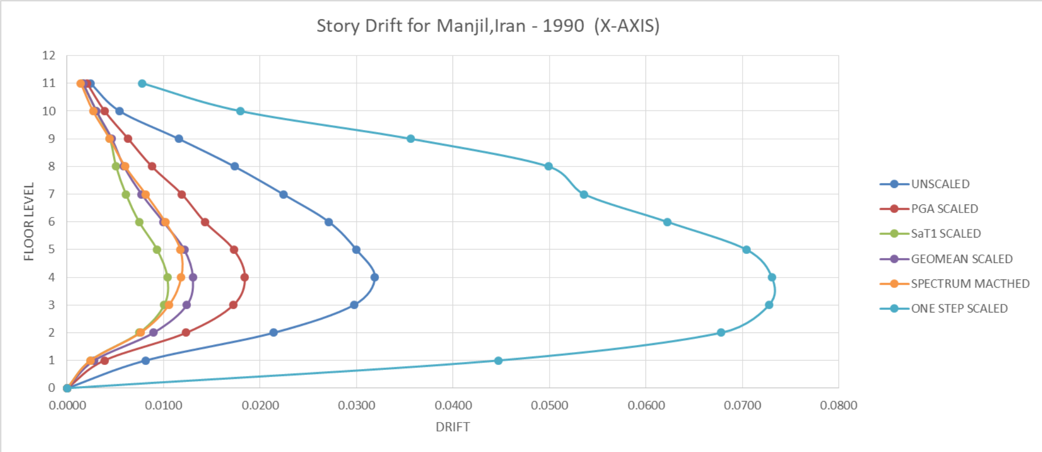


Figure 6(a)

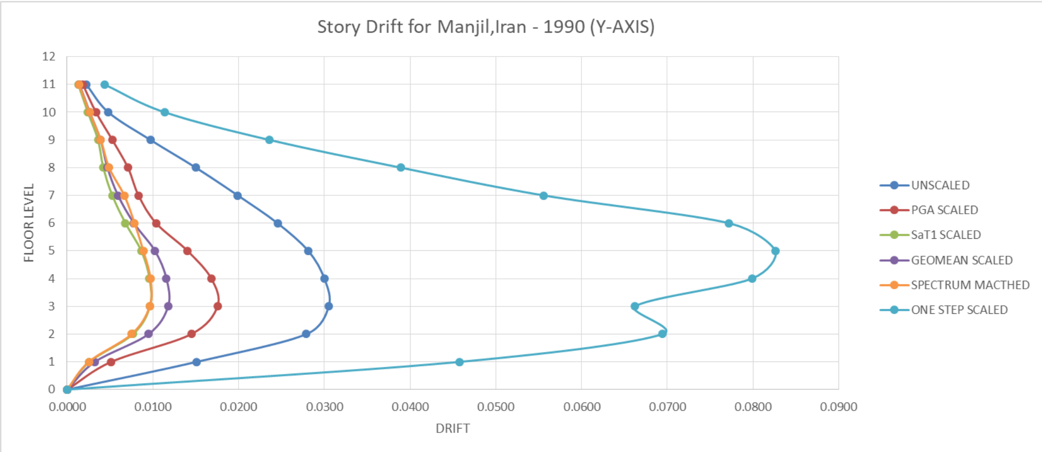


Figure 6(b)

Figure 6: (a) Drift for Manjil, Iran (x-axis) (b) Drift for Manjil, Iran (y-axis)

6.1.5 Results for Failure Pattern

The results for failure pattern corresponding to both unscaled and scaled earthquake ground motions are presented here. These results are made on the basis of limitation for drift percentage for respective failure limits given in FEMA356 – Table C1-3 [(Federal Emergency Management Agency, 2000]. According to FEMA 356, structural performance can be classified into Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) states based on interstorey drift limits.

Table 4 *Details of failure pattern for Gazli,USSR (X-axis).*

Floor	Unscaled	PGA Scaled	SaT1 Scaled	Geomean Scaled	One Step Scaled	Spectrum Matched
Base	IO	IO	IO	IO	IO	IO
Plinth	LS	IO	IO	IO	Collapse	IO
1st	CP	IO	IO	IO	Collapse	IO
2nd	Collapse	LS	LS	LS	Collapse	IO
3rd	Collapse	LS	LS	LS	Collapse	IO
4th	CP	LS	LS	LS	Collapse	IO

5th	CP	LS	LS	LS	Collapse	IO
6th	CP	LS	LS	LS	Collapse	IO
7th	CP	IO	IO	IO	Collapse	IO
8th	LS	IO	IO	IO	Collapse	IO
9th	IO	IO	IO	IO	CP	IO
10th	IO	IO	IO	IO	LS	IO

Table 5 *Details of failure pattern for Gazli,USSR (Y-axis).*

Floor	Unscaled	PGA Scaled	SaT1 Scaled	Geomean Scaled	One Step Scaled	Spectrum Matched
Base	IO	IO	IO	IO	IO	IO
Plinth	CP	IO	IO	IO	Collapse	IO
1st	Collapse	IO	IO	LS	Collapse	IO
2nd	Collapse	LS	LS	LS	Collapse	LS
3rd	CP	LS	LS	LS	Collapse	LS
4th	CP	LS	LS	LS	Collapse	IO
5th	CP	LS	LS	LS	Collapse	IO
6th	CP	IO	IO	LS	Collapse	IO
7th	LS	IO	IO	IO	Collapse	IO
8th	LS	IO	IO	IO	CP	IO
9th	IO	IO	IO	IO	LS	IO
10th	IO	IO	IO	IO	IO	IO

Table 6 *Details of failure pattern for Manjil, Iran (X-axis).*

Floor	Unscaled	PGA Scaled	SaT1 Scaled	Geomean Scaled	One Step Scaled	Spectrum Matched
Base	IO	IO	IO	IO	IO	IO
Plinth	IO	IO	IO	IO	Collapse	IO
1st	CP	LS	IO	IO	Collapse	IO
2nd	CP	LS	LS	LS	Collapse	LS
3rd	CP	LS	LS	LS	Collapse	LS
4th	CP	LS	IO	LS	Collapse	LS
5th	CP	LS	IO	IO	Collapse	LS
6th	CP	LS	IO	IO	Collapse	IO

7th	LS	IO	IO	IO	Collapse	IO
8th	LS	IO	IO	IO	CP	IO
9th	IO	IO	IO	IO	LS	IO
10th	IO	IO	IO	IO	IO	IO

Table 7 *Details of failure pattern for Manjil, Iran (Y-axis).*

Floor	Unscaled	PGA Scaled	SaT1 Scaled	Geomean Scaled	One Step Scaled	Spectrum Matched
Base	IO	IO	IO	IO	IO	IO
Plinth	LS	IO	IO	IO	Collapse	IO
1st	CP	LS	IO	IO	Collapse	IO
2nd	CP	LS	IO	LS	Collapse	IO
3rd	CP	LS	IO	LS	Collapse	IO
4th	CP	LS	IO	LS	Collapse	IO
5th	CP	LS	IO	IO	Collapse	IO
6th	LS	IO	IO	IO	Collapse	IO
7th	LS	IO	IO	IO	CP	IO
8th	IO	IO	IO	IO	CP	IO
9th	IO	IO	IO	IO	LS	IO
10th	IO	IO	IO	IO	IO	IO

6.2 Discussion.

This study aims to investigate the effects of various ground motion scaling techniques on the seismic nonlinear behaviour of a multistoried reinforced concrete building. To evaluate the performance three key engineering response parameters that is base shear, story displacement and story drift were taken into consideration under seven real earthquake records. These records were scaled using five different methods to understand their influence on the structural response parameters. The discussion below states the findings obtained through the analysis of the scale factors and the performance under certain response parameters.

6.2.1 Discussion on scale factors

During this study, 5 methods of ground motion scaling were studied. It included Peak ground acceleration scaling, Geometric mean Scaling, SaT1 Scaling, One step scaling and spectrum matching. A set of 7 ground motion pairs was used to study and compare the scaling factor obtained through this method. It is to be taken into account that, the values of scale factors are mainly dependent on the selection of ground motion and its parameters. According to Shome et al, an upper limit to the scale factors can be imposed as 3 [Shome et al., 1997] and Lervolino and Cornell suggested a limit of 4 [Theophilou, 2018]. According to Curt B. Haselton, “While not specified by the building codes, some analysts prefer to limit the maximum amount by which a ground motion is scaled.” [Haselton, 2009]. Soysal et.al suggested that, “when selecting the records, those having a scaling factor more than 5 or less than 0.2 have been rejected by aiming both to limit the disproportionate modification and to have a fair amount of accelerogram that yield a reasonable match with the target” [Soysala et al., 2017]. Yan Naung and Teraphan Ornthammarath also suggest using a limit of 4 for the scaling factor. [Ko & Ornthammarath, 2020]

In the PGA Scaling method, the scale factor was obtained by dividing the target peak acceleration by the peak acceleration of the ground motion. The scale factors obtained through these methods ranged from 0.25 to 1.2. The One step scaling method suggests obtaining a scaling factor by normalising the spectral acceleration values of the ground motion to 1g. The scale factors by this method ranged from 2 to 12. The Geometric mean methods of scaling, involve amplitude scaling a pair of seed motions by a single factor to minimise the sum of the squared errors between the target spectral values and the geometric mean of the spectral ordinates for the pair at multiple periods. The scaling factor obtained through these methods is used for both components of the ground motions. The scale factor ranges from 0.25 to 1.2. The SaT1 method gives a scale factor by dividing the target spectral acceleration obtained through the response spectrum of values of deterministic seismic hazard analysis by the spectral acceleration of the ground motion at the fundamental period. The scale factors obtained through this method range from 0.20 to 1.0.

The scale factors obtained through these five methods vary individually but excluding the one-step scaling have a similar range. The reason behind the scale factor obtained through PGA scaling, geo mean scaling and SaT1 scaling being similar is that the target values for respective methods are based on the intensity parameter at the site in question for its fundamental time. Whereas in one-step scaling as the scale factors obtained, have been normalised to 1g of spectral acceleration, the gap between the spectral acceleration of ground motion and the target spectral acceleration is too large. The scale factors thus go beyond the preferred limit assumed by researchers to avoid the ground motion being disproportionate.

6.2.2 Discussion on base shear

Among all the scaling methods studied in this research, the One step scaling method consistently produced the highest base shear values. These high results were obtained due to the high scale factor obtained by this method. In several ground motions, the values of base shear were observed to be four to six times higher than the values of base shear for unscaled ground motions. For example, in the Loma Prieta earthquake, the X-direction base shear increased greatly from 8,138.5KN in unscaled to 36,613.8 KN in one step scaling. This significant amplification of seismic energy tends to overestimate the realistic force demands of the structure and could lead to heavy design of the structural members.

The SaT1 method of scaling generated moderate and consistent base shear values that closely aligned with the results of unscaled ground motions. For example, for the Manjil earthquake, the SaT1 scaled base shear is nearly identical to the unscaled case, indicating that the spectral characteristics of the ground motion are preserved around the fundamental period of the structure. The Geometric mean methods of ground motion scaling showed similar results to those of the SaT1 method. These results were slightly higher than those produced by PGA and Spectrum Matching, but significantly lower than those of One step scaling.

Concerning this method, the PGA Scaling method consistently resulted in the lowest base shear values, sometimes even lower than the unscaled ground motions. Since this method only focuses on the peak ground acceleration and ignore the parameters which take the structure and the earthquake both into account, it tends to under-represent the actual demand of the structure. Whereas Spectrum matching though effectively aligns the earthquake with the defined target spectra, it often dampens sharp motion peaks, resulting in a conservative response of the base shear values.

6.2.3 Discussion on displacement.

The One step scaling method resulted in the largest displacement, often far exceeding the realistic expectations. In the Gazli record for example, the top story displacement crossed 3.1meters, compared to just 0.79 meters for the unscaled case. In contrast, the SaT1 method of scaling yielded well distributed and moderate displacements, typically between 0.25 and 0.35 meters at the top storey.

These values were consistent with those from the unscaled cases, reflecting the methods strength in preserving dynamic nature.

Geometric Mean scaling produced slightly higher displacements than SaT1, generally within 0.30 to 0.40 meters, but maintained a smooth and gradual increase from the base to the top. The PGA method gave the lowest displacements, usually below 0.20 meters, and nearly uniform across all floors. While this might appear safe, it can mask actual nonlinear behavior, particularly in flexible structures. Similarly, Spectrum Matching showed low to moderate displacements, with peak values typically under 0.25 meters. Though it performs better than PGA in capturing dynamic features, the reduction in motion peaks may lead to under estimation of critical displacement.

6.2.4 Discussion on drift and failure pattern.

Drift results for all the ground motions when scaled by One-Step Scaling method were most severe, especially in the lower stories where drift ratios reached as high as 17–22%. These percentage of drift exceeds the collapse prevention limits by a large margin and indicates unstable and highly localised deformations, often associated with soft-storey behaviour. On the other hand, the SaT1 method produced a balanced and realistic drift profile, with peak drift percentage values generally between 1% and 2% concentrated in mid-level stories. This aligns with the Life Safety performance level and shows a clear progression from inelastic to elastic behaviour toward the upper floors.

The Geometric Mean method gave drift values similar to SaT1 but with a slightly broader range of Life Safety-level performance. Peak drift values were around 1.5% to 2%, typically between the 3rd and 6th floors, suggesting a stable and controlled inelastic response. The PGA method produced the lowest drifts, which were typically below 1% and within Immediate Occupancy limits. While this may appear conservative, it risks underrepresenting energy dissipation and hinge formation, making it less useful in performance-based assessments. Spectrum Matching resulted in mostly IO-level drift, with occasional LS performance in the mid-stories. Though slightly better than PGA, it still tends to underpredict deformation potential, especially in highly nonlinear analyses.

7. Conclusion.

The use of scaled ground motion helps in effectively estimating the response of a structure to a specific ground motion. To do so it is necessary to select a proper method to obtain scaled ground motions. To do so, this study was conducted with the main objective of evaluating the effects of various ground motion scaling methods on the structural non-linear response of the structure. For this purpose, five methods of ground motion scaling were taken into consideration. Those were Peak ground acceleration-based scaling, SaT1-based scaling, Geometric mean-based scaling, One step scaling and spectrum matching. Using these methods analysis was performed on the G+10 structure and the following conclusions were made:

1. Scaling using one step method resulted in unrealistically high values of base shear and displacement, with drift ratios exceeding collapse limits.

2. SaT1 method and Geometric mean methods gave the most realistic results, as they take structures fundamental period into account ensuring balanced demand estimation.

3. PGA scaling consistently underestimated the response parameters, making it unsuitable for capturing true non-linear behaviour in seismic design.

4. Though spectrum matching can achieve a perfect fit to the target spectrum, it results in smoothening of the actual peak motions thus reducing its energy input and reliability in non-linear analysis.

5. Using the SaT1 method and the Geometric mean methods a realistic failure pattern could be observed, whereas PGA scaling and Spectrum matching showed minimal damage, and One step scaling showing collapse in multiple floors.

6. One step scaling is not appropriate for understanding detailed performance of the structure but can be used to understand about collapse mechanism.

7. PGA scaling and Spectrum matching are less reliable and less suited for non-linear, performance-based seismic analysis.

8. References.

1. American Society of Civil Engineering. (2017). *ASCE 41-17 - Seismic evaluation and retrofit of existing buildings*.
2. American Society of Civil Engineering. (2022). *ASCE 7-22 Minimum design loads and associated criteria for buildings and other structures*.
3. Bureau of Indian Standards. (2016). *IS 1893:2016 - Criteria for earthquake resistant design of structure*.
4. Deierlein, G. G., Liel, A. B., Haselton, C. B., & Kircher, C. A. (n.d.). ATC 63 methodology for evaluating seismic collapse safety for archetype buildings. *Applied Technology Council*.
5. European Standards. (2004). *Euro Code 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings*.
6. Fedral Emergency Management Agency. (2000). *FEMA 356: Prestandard and commentary for the seismic rehabilitation of buildings*.
7. Fedral Emergency Management Agency. (2018). *FEMA P 58-1: Seismic performance assessment of buildings*.
8. Gupta, I. D. (2002). The state of the art in seismic hazard analysis. *ISET Journal of Earthquake Technology, 39*(4), 311–346.
9. Haselton, C. B. (2009). Evaluation of ground motion selection and modification methods: Predicting median interstory drift response of buildings. *Pacific Earthquake Engineering Research Center*. [Technical report]
10. Haselton, C. B., Whittaker, A. S., Hortacsu, A., Baker, J. W., Bray, J., & Grant, D. N. (2012). Selecting and scaling earthquake ground motions for performing response-history analyses. *WCEE*.
11. Huang, Y.-N., Whittaker, A. S., Luco, N., & Hamburger, R. O. (2011). Scaling earthquake ground motions for performance-based assessment of buildings. *Journal of Structural Engineering – ASCE, 137*(3), 311–321.
12. Kalkan, E., & Chopra, A. K. (2010). Practical guidelines to select and scale earthquake records for nonlinear response history analysis of structures. *Earthquake Engineering Research Institute*. [Technical report]
13. Katsanos, E. I., Sextos, A. G., & Manolis, G. D. (2010). Selection of earthquake ground motion records: A state-of-the-art review from a structural engineering perspective. *Soil Dynamics and Earthquake Engineering, 30*, 157–169.
14. Ko, Y. N., & Ornthammarath, T. (2020). The effect of ground motion selection methods for seismic design of tall buildings: A case study of Mandalay City. *Walailak Journal, 17*, 1348–1355.
15. Krinitzsky, E. L. (1995). Deterministic versus probabilistic seismic hazard analysis for critical structures. *Engineering Geology, 40*, 1–7.
16. Kurama, Y. C., & Farrow, K. T. (2003). Ground motion scaling methods for different site conditions and structure characteristics. *Earthquake Engineering and Structural Dynamics, 32*, 2425–2450.
17. Maniyar, M. M., & Khare, R. K. (2011). Selection of ground motions for performing incremental dynamic analysis of existing reinforced concrete buildings in India. *Current Science, 100*(5), 701–713.
18. Markous, N. A., Mehanny, S. S. F., & Bakhoum, M. M. (2014). Scaling of earthquake ground motion records for seismic analysis and design of bridges. *JL. Egyptian Society of Engineer, 53*(2), 2–18.
19. Najafi, L. H., & Tehranizadeh, M. (2015). Ground motion selection and scaling in practise. *Periodica Polytechnica Civil Engineering*.
20. Shome, N., Cornell, C. A., Bazzurro, P., & Carballo, J. E. (1997). Earthquakes, records and non-linear MDOF responses. *Department of Civil Engineering, Stanford University*. [Technical report]

21. Soysala, F. B., Ayb, B. Ö., & Aricia, Y. (2017). An investigation of the ground motion scaling procedures for the nonlinear seismic analyses of concrete gravity dams. *Journal of Earthquake Engineering*, 1–24.

22. Theophilou, A.-A. I. (2018). A ground motion selection and modification method through stratified sampling. *Bulletin of Earthquake Engineering*.

23. Vamvatsikos, D., & Cornell, C. A. (n.d.). The incremental dynamic analysis and its application to performance-based earthquake engineering. *12th Conference of Earthquake Engineering by Elsevier*, 1–10.

Declarations

1. Funding Declarations:
This research received no external funding.

2. Competing Interests:
I declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

3. Authors Contributions:
C.V.M. conducted the ground motion analysis, performed the modelling and drafted the main manuscript text. S.P.P. and R.M.D assisted with data interpretation and figure preparation. All authors reviewed and approved the final manuscript.

4. Data Availability:
The ground motion records used in this study were obtained from the PEER Ground Motion Database, which is publicly accessible at https://ngawest2.berkeley.edu. Also, the code provisions mentioned in the paper can be found on their specific websites. All other data generated or analysed during the study are included in this published article.