

Seismic Hazard Evaluation through Attenuation Law Derivation and Response Spectrum Design: Bangladesh Case Study

Md. Shariful Islam^{1,*}

Abstract

Bangladesh, positioned at the confluence of the Indian, Eurasian, and Burma tectonic plates, faces significant seismic hazards due to its complex geological setting. This research focuses on formulating empirical attenuation relationships and creating a design response spectrum for assessing seismic risks in Bangladesh, using data from ten large earthquakes with magnitudes ranging from 6.7 to 7.9. The study creates Ground Motion Prediction Equations (GMPEs) for various structural periods using the fundamental attenuation equation $\log A = k_1M + k_2\log R + k_3$. Using least-squares regression analysis, the coefficients k_1 , k_2 , and k_3 were estimated for ten distinct time periods ranging from 0.02 to 9.69 seconds. The method involved adjusting prediction equations tailored for each time period, doing matrix-driven computations in Excel, and methodically analyzing reaction acceleration data from recent earthquakes. This study created a design response spectrum for a possible earthquake with a magnitude of 7.0 occurring at a distance of 35.0 km from the epicenter, this represents a realistic scenario for future earthquakes in Bangladesh. The study's results indicate that the attenuation coefficients vary significantly depending on the period of ground motion. Moreover, the recently obtained equations provide precise predictions for response spectra and peak ground acceleration. In a nation that faces major earthquakes roughly every 100 to 120 years, this research offers essential methods for constructing buildings capable of withstanding seismic events. When it comes to earthquakes, Dhaka is among the most earthquake-prone cities worldwide.

Keywords: Attenuation relations, ground motion prediction equations, design response spectrum, seismic hazard assessment, Bangladesh seismicity, earthquake engineering

INTRODUCTION

Seismic hazard assessment represents one of the most critical aspects of earthquake engineering and disaster risk reduction, particularly for regions situated in tectonically active zones. Bangladesh, positioned close to the boundaries of the Indian, Eurasian, and Burmese tectonic plates, faces significant

seismic hazards due to its complicated tectonic environment [1]. The creation of trustworthy Ground Motion Prediction Equations (GMPEs) and design response spectra is crucial for understanding and reducing earthquake risks in such at-risk regions.

Ground motion prediction equations, also called ground-motion models or attenuation relations, are used to predict how much shaking, or strong ground motion, a certain area might feel during an earthquake of a specific size that happens nearby [2]. In fields like earthquake engineering and

*Author for Correspondence

Md. Shariful Islam
E-mail: islam.s.933@ms.saitama-u.ac.jp

¹M.Sc. student, Saitama University, Japan & Graduate, Raj Shahi University of Engineering & Technology, Bangladesh

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engineering seismology, these equations are crucial because they help predict the stresses that buildings and other structures can experience during future earthquakes [3].

In recent years, the need to assess earthquake risks has become much more important. This is a result of more people moving into cities, more buildings and roads being built, and the realization that earthquake preparedness is crucial for long-term, sustainable growth. When an earthquake happens, the shaking it causes can damage buildings and lead to ground problems not just near the earthquake's starting point, but also far away, depending on local conditions [4]. This makes the development of region-specific GMPEs particularly important because ground motion characteristics vary significantly based on local geological conditions, tectonic settings, and seismic source mechanisms.

Bangladesh's vulnerability to earthquakes is well documented in both historical records and current assessments. Bangladesh is a disaster-prone country that often experiences cyclones, floods, landslides, river erosion, and climate-related threats. Over the past 150 years, five earthquakes registering above 7.0 on the Richter scale have inflicted damage on the nation. The seismic history of the country indicates a trend of major earthquakes, with significant occurrences such as the Bengal earthquake of 1885 and the Srimongal earthquake of 1918, both of which had their epicenters located in Bangladesh and resulted in considerable destruction to infrastructure and communities. The contemporary seismic risk landscape in Bangladesh is particularly concerning given the rapid urbanization and population growth. While Bangladesh has been fortunate to avoid a significant earthquake in the past century, historical data suggests earthquakes are a threat [6]. The capital city, Dhaka, has been identified as one of the top 20 global cities most susceptible to earthquakes according to major disaster indices, highlighting the urgent need for comprehensive seismic risk assessment and mitigation strategies.

Seismic hazard assessment in Bangladesh is complicated for several reasons. These include the types of buildings that are at risk, fast-growing cities, soils that can lose strength during an earthquake, buildings that aren't built properly, and weak enforcement of building rules[7]. These factors enhance the inherent seismic risk, making it essential to conduct thorough risk evaluations for disaster readiness and reduction.

The development of attenuation relations, which form the backbone of seismic hazard assessment, has evolved significantly over the past several decades. The mathematical basis for attenuation connections typically relies on logarithmic relationships that consider factors such as earthquake magnitude, the distance from the source to the site, and various site-specific parameters.

Nonetheless, there remain considerable challenges in formulating equations that function effectively for particular locations, especially in areas where there is limited understanding of intense shaking. These equations were created based on a narrow range of earthquake sizes and distances, not enough data from close to the earthquake source, not many examples of very large earthquakes, and sometimes used data from other regions instead [9]. This limitation is particularly acute for Bangladesh, where strong motion recording networks are relatively sparse compared to more seismically active regions.

Seismic hazard assessment includes several parts, and GMPEs are important because they connect earthquake sources to how strong the shaking might be. The results show that some newer local GMPEs might give incorrect estimates of shaking because their data and the way they are built have some limits [10]. This emphasizes the need for careful validation and selection of appropriate GMPEs for specific regional applications.

Right now, researchers are focusing a lot on having good data and using better ways to analyze it when making ground-motion prediction equations (GMPEs). These equations are used to predict spectral accelerations, which are important for understanding how buildings respond during earthquakes. In the past, these equations mainly looked at the range of response periods that match how buildings usually move[11]. But now, people are realizing that these equations need to cover a wider

range of frequencies and be useful for different kinds of engineering projects.

The significance of this research lies in its potential contribution to earthquake risk reduction in Bangladesh and similar tectonic environments. It presents an opportunity for rural areas, minimizing human and infrastructural losses of an earthquake [12]. Developing region-specific attenuation relations and design response spectra is essential for enhancing seismic safety and resilience in Bangladesh. Recent developments in seismic hazard assessment have also highlighted the importance of considering multiple earthquake scenarios and uncertainty quantification. The purpose of such a model selection is for use by the GEM Foundation in their global seismic hazard analysis, rather than for regional and local seismic hazard studies [13]. This demonstrates the growing recognition of the need for both global and regional approaches to seismic hazard assessment.

The continuous evolution of GMPE development reflects the growing understanding of earthquake processes and ground motion characteristics. Ground motion prediction equations (GMPEs) work best for modeling how Australian earthquakes behave, helping to understand possible risks and dangers in a specific study area [14].

ATTENUATION RELATION

Peak Ground Acceleration (PGA) and Epicentral distance relation is given below:

$$\log A = k_1 M + k_2 \log R + k_3 \quad (i)$$

Where,

A = Peak Ground Acceleration (PGA) R = Epicentral Distance

M = Magnitude of an Earthquake

and k_1, k_2, k_3 = Constants

To find the Constants (k_1, k_2, k_3) of this linear relation, 10 earthquake data are used as summarized below Table 1.

Table 1. The Constants (k_1, k_2, k_3) of this linear relation, 10 earthquake data are used as summarized.

Eq no.	Earthquake name	Origin date	Origin time	Epicentral distance (km)	Magnitude M
1	HKD067201809060308	9/6/2018	03:08:00 JST	45	6.7
2	YGT067201906182222	6/18/2019	22:22:00 JST	33	6.7
3	MYGF073202102132307	2/13/2021	23:07:00 JST	55	7.3
4	MYGM070202103201809	3/20/2021	18:09:00 JST	54	6.9
5	NKD073202203162336	3/16/2022	23:36:00 JST	63	7.3
6	NTO067202305051442	5/5/2023	14:42:00 JST	49	6.7
7	NTO075202401011610	1/1/2024	16:10:00 JST	42	7.6
8	HYU071202408081642	8/8/2024	16:42:00 JST	25	7.1
9	MYK068202501131219	1/13/2025	12:19:00 JST	80	6.8
10	OGS079201505302023	5/30/2015	20:23:00 JST	189	7.9

From 10 earthquakes, 10 time periods are selected. The response acceleration of each 10 time periods of 10 earthquakes for analysis are as follows table 2 and Figure 1

Table 2. From 10 earthquakes, 10 time periods are selected. The response acceleration of each 10 time

periods of 10 earthquakes for analysis.

S.N.	Period, T (sec)	Response acceleration (gal)									
		EQ-1	EQ-2	EQ-3	EQ-4	EQ-5	EQ-6	EQ-7	EQ-8	EQ-9	EQ-10
1	0.02	25.27	42.4	33.32	22.85	26.57	21.92	70.96	101.31	10.71	7.83
2	0.05	43.12	67.47	53.61	39.25	44.07	38.13	101.98	141.27	20.45	14.99
3	0.1	42.1	68.5	82.55	43.96	66.7	36.83	206.61	204.69	20.12	31.95
4	0.31	46.27	73.8	29.76	33.57	24.26	40.7	41.66	102.16	19.01	4.04
5	0.51	27.78	53.34	15.93	18.11	11.97	23.23	26.25	87.41	8.1	1.04
6	0.61	23.87	55.2	16.99	15.6	11.77	18.96	38.98	133.83	5.21	0.74
7	1	18.12	38.26	7.43	10.19	5.36	14.75	11.61	56.94	4.23	0.25
8	1.5	8.94	18.34	4.02	5.24	2.93	7.34	6.34	27.89	2.23	0.16
9	6.08	1.14	1.57	0.35	0.68	0.3	1.05	0.28	1.08	0.54	0.04
10	9.69	0.48	0.8	0.23	0.31	0.18	0.41	0.3	0.98	0.17	0.02

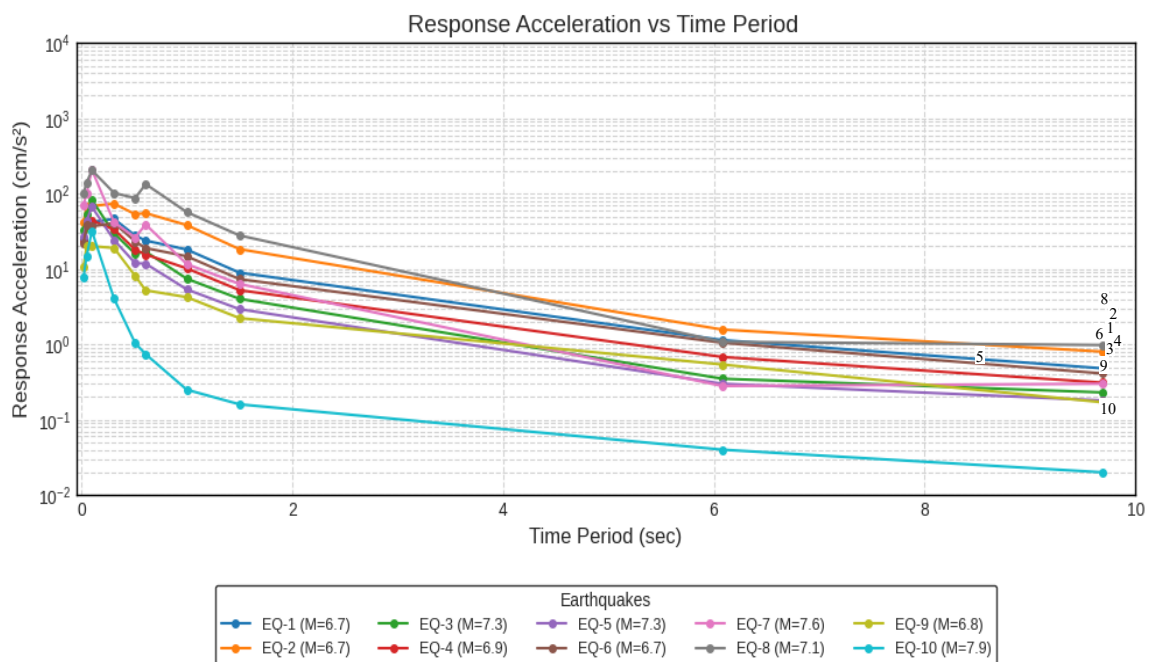


Figure 1. Response acceleration vs time period graph in semi-log scale.

METHOD TO FIND THE EQUATION (k1, k2, k3)

We have 10 earthquakes data and select 4 time periods (T). Every 10 time periods we can write 10 equations using equation (i),

$$\begin{pmatrix} \log A_1 \\ \log A_2 \\ \log A_3 \\ \vdots \\ \log A_{10} \end{pmatrix} \approx \begin{pmatrix} M_1 & \log R_1 & 1 \\ M_2 & \log R_2 & 1 \\ M_3 & \log R_3 & 1 \\ \vdots & \vdots & \vdots \\ M_{10} & \log R_{10} & 1 \end{pmatrix} \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix}$$

Since $n > 3$, the left-hand side is not equal to the right-hand side. The difference between the two is error.

$$\begin{pmatrix} e_1 \\ e_2 \\ e_3 \\ \vdots \\ \vdots \\ \vdots \\ e_{10} \end{pmatrix} = \begin{pmatrix} \log A_1 \\ \log A_2 \\ \log A_3 \\ \vdots \\ \vdots \\ \vdots \\ \log A_{10} \end{pmatrix} - \begin{pmatrix} M_1 & \log R_1 & 1 \\ M_2 & \log R_2 & 1 \\ M_3 & \log R_3 & 1 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ M_{10} & \log R_{10} & 1 \end{pmatrix} \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix}$$

Above equation can be written as

$$e = a - G \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix}$$

To minimize the error taking the least square solution

$$G^T a = G^T G \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix}$$

The above equation can be written as,

$$\begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix} = (G^T a) * (G^T G)^{-1} \quad (ii)$$

(Here G is a 10 × 3 matrix, G^T a is a 3 × 1 matrix or a column vector, and G^TG is a 3 × 3 matrix) For Time period **T = 0.02**sec, after solving the data from above table by using excell we get the values of G^TG, (G^TG)⁻¹ and G^Ta as follows,

$$G^T G = \begin{pmatrix} 505.68 & 123.55 & 71.00 \\ 123.55 & 30.56 & 17.33 \\ 71.00 & 17.33 & 10.00 \end{pmatrix}$$

$$(G^T G)^{-1} = \begin{pmatrix} 0.8861 & -0.8360 & -4.8423 \\ -0.8360 & 2.7602 & 1.1510 \\ -4.8423 & 1.1510 & 32.4851 \end{pmatrix}$$

$$G^T a = \begin{pmatrix} 102.5491 \\ 24.4263 \\ 14.4570 \end{pmatrix}$$

Putting the values of G^Ta and (G^TG)⁻¹ in equation (ii) we get the values of (k₁, k₂, k₃) as follows,

$$\begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix} = \begin{pmatrix} 0.4427 \\ -1.6688 \\ 1.1951 \end{pmatrix}$$

So, the equation (i) can be written as for Time period **T = 0.02** sec is,

Similarly, for the other 9 time periods, we can find the respective values of k₁, k₂, k₃, and get the equations for each time periods by using excel as follows: Table 3

DESIGN RESPONSE SPECTRUM

We have established dependable equations for predicting acceleration response spectra, these equations become instrumental in developing a design response spectrum. This spectrum graphically illustrates the anticipated maximum structural response across various vibration periods when subjected to earthquake ground motion[15-17].

Table 3. The other 9 time periods, we can find the respective values of k_1 , k_2 , k_3 , and get the equations for each time periods

S.N.	Time period (s)	k_1	k_2	k_3	Equation
1	0.02	0.4427	-1.6688	1.1951	$\log A = 0.44270M - 1.66880 \log R + 1.19510$
2	0.05	0.36732	-1.44347	1.55998	$\log A = 0.36732M - 1.44347 \log R + 1.55998$
3	0.1	0.71538	-1.56959	-0.57388	$\log A = 0.71538M - 1.56959 \log R - 0.57388$
4	0.31	-0.10066	-1.50526	4.82818	$\log A = -0.10066M - 1.50526 \log R + 4.82818$
5	0.51	-0.09718	-2.10226	5.57036	$\log A = -0.09718M - 2.10226 \log R + 5.57036$
6	0.61	0.14678	-2.7032	4.8633	$\log A = 0.14678M - 2.70320 \log R + 4.86330$
7	1	-0.29592	-2.41362	7.23124	$\log A = -0.29592M - 2.41362 \log R + 7.23124$
8	1.5	-0.24599	-2.32636	6.44632	$\log A = -0.24599M - 2.32636 \log R + 6.44632$
9	6.08	-0.70369	-0.99155	6.40933	$\log A = -0.70369M - 0.99155 \log R + 6.40933$
10	9.69	-0.28075	-1.67143	4.32126	$\log A = -0.28075M - 1.67143 \log R + 4.32126$

To develop such a design response spectrum, it's crucial to consider several factors, including local building codes, the specific characteristics of the structure, the geological conditions of the site, and the prevailing seismic hazard level. The equations derived earlier can then be applied to a particular design scenario. By inputting the relevant parameters and design criteria, we can generate a design response spectrum that is specifically tailored to that project's needs.

It is paramount to recognize that the precision and dependability of the resulting design response spectrum are directly linked to the quality and relevance of the data used to formulate the initial prediction equations. Therefore, it is always advisable to seek expertise from seismic engineering professionals and adhere to the unique requirements and regulations pertinent to your location or project [18-20].

For a specific location, a standard design spectrum needs to be formulated. In Bangladesh, a country situated in a seismically active zone, its capital city Dhaka is ranked among the top 20 global cities most susceptible to earthquakes by a significant disaster index. Historically, Bangladesh experienced five earthquakes exceeding Magnitude 7 on the Richter scale between 1869 and 1930. Notably, the 1885 Bengal earthquake and the 1918 Srimongal earthquake, both with epicenters within Bangladesh, caused substantial damage. The region typically experiences a major earthquake of Magnitude 7.2 or higher every 100-120 years (Table 4).

Table 4. The response acceleration for each specific time period, thereby constructing the design response spectrum.

S.N.	Time period, T (sec)	k_1	k_2	k_3	M	R (km)	$\log A$	Response acceleration A (gal)
1	0.02	0.4427	-1.6688	1.1951	7	35	0.5284	3.38
2	0.05	0.36732	-	1.55998	7	35	1.0028	10.06
			1.44347					
3	0.1	0.71538	-	-	7	35	1.8385	68.95
			1.56959	0.57388				
4	0.31	-	-	4.82818	7	35	1.9469	88.5
		0.10066	1.50526					
5	0.51	-	-	5.57036	7	35	1.9566	90.49
		0.09718	2.10226					
6	0.61	0.14678	-2.7032	4.8633	7	35	1.0967	12.5
7	1	-	-	7.23124	7	35	1.7088	51.14
		0.29592	2.41362					
8	1.5	-	-	6.44632	7	35	1.1578	14.38
		0.24599	2.32636					
9	6.08	-	-	6.40933	7	35	-0.5841	0.26
		0.70369	0.99155					
10	9.69	-	-	4.32126	7	35	-0.1982	0.63
		0.28075	1.67143					

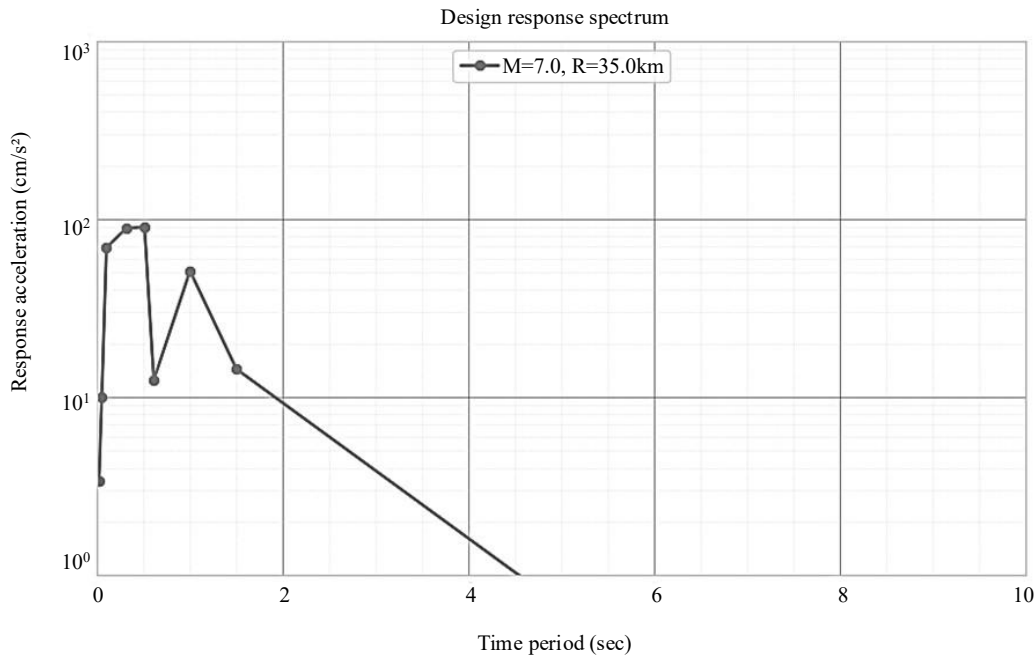


Figure 2. Design response spectrum.

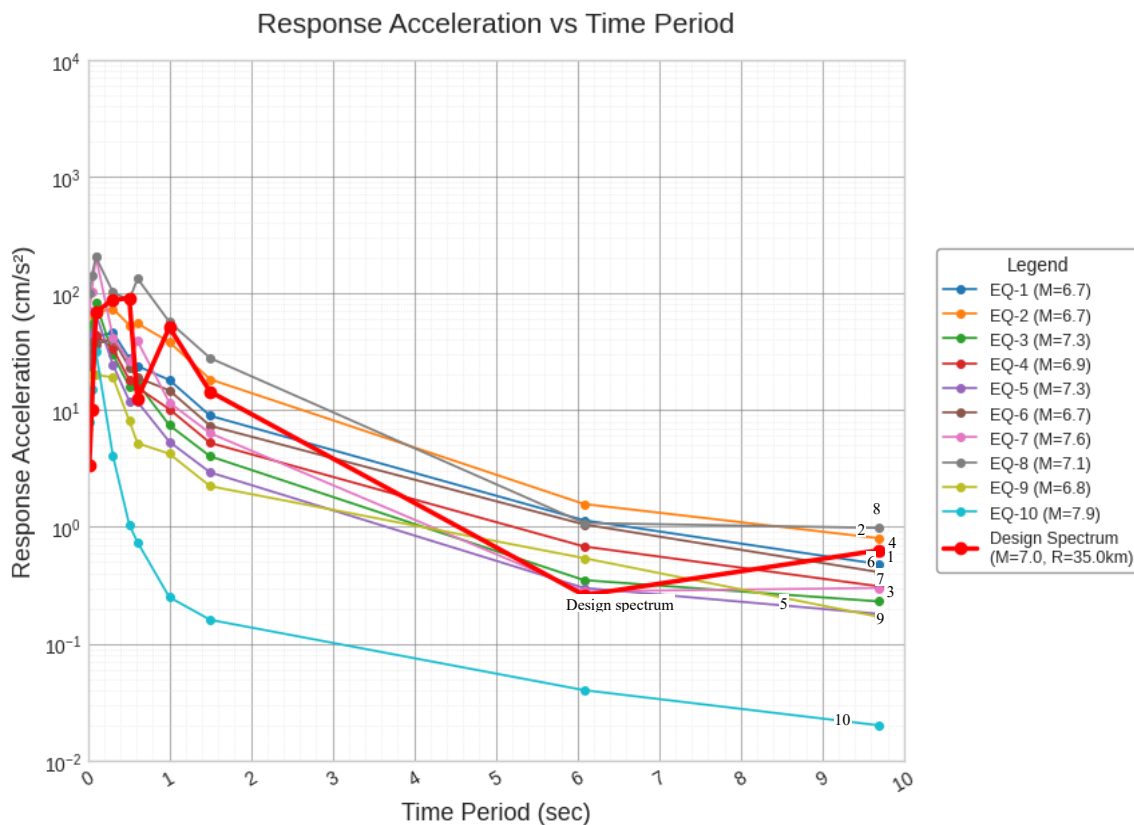


Figure 3. Downloaded earthquake response spectrum and design response spectrum relationship.

Considering a hypothetical design scenario with a Magnitude (M) of 7.0 and an Epicentral Distance (R) of 35.0 km, we can utilize the previously determined equations (which predict acceleration for different time periods) to calculate the response acceleration for each specific time period, thereby constructing the design response spectrum.

The best fit line can be drawn using the above equation for data set. The following graph shows the Design Response Spectrum (Response Acceleration and Time Period Relationship) in semi- log scale

The following graph shows the 10 downloaded earthquake response spectrum and equation-based response spectrum of Response Acceleration and Time Period Relationship in semi-log scale. The red color line represents the Design Response Spectrum line get by equation Figure 2.

This Design Response Spectrum for Magnitude $M=7.0$ and Epicentral Distance $R=35.0$ km for Bangladesh is motivated by several critical factors related to seismic risk and engineering safety. Here are the key reasons and benefits of using these specific parameters Figure 3.

Engineering Safety Margins and Seismic Risk Consideration

Developing a reliable design response spectrum is crucial for engineering safety, particularly in seismically active areas like Bangladesh. Dhaka is among the top 20 global cities most susceptible to earthquakes, with a history of major quakes exceeding Magnitude 7. The precision of this spectrum depends on the quality of input data and the specific characteristics of the structure and site conditions. Adhering to these considerations helps ensure structures can withstand anticipated seismic events.

Building Code Requirements

Building codes are fundamental in developing a design response spectrum, which graphically represents a structure's anticipated maximum response to earthquake ground motion. The established acceleration response spectra equations are instrumental for this. These equations, when applied with relevant parameters and design criteria, yield a tailored design response spectrum for a project's specific needs. Therefore, adherence to local building regulations is paramount

Epicentral Distance Relevance

Epicentral distance (R) is a key parameter in the attenuation relation $\log A = k_1 M + k_2 \log R + k_3$, directly influencing the predicted response acceleration. For a design scenario, using an Epicentral Distance of 35.0 km along with a Magnitude of 7.0 illustrates how this parameter is applied. By incorporating R , the model accounts for the geographical proximity of seismic events, which is crucial for accurately determining the forces structures will experience. This ensures the design spectrum reflects location-specific seismic characteristics

Resilience and Disaster Preparedness

The design response spectrum is a vital tool for enhancing structural resilience and disaster preparedness. Given Bangladesh's significant seismic risk and historical major earthquakes, this tool helps engineers anticipate structural behavior during seismic events. Utilizing the derived equations, engineers can calculate expected accelerations for different time periods, aiding in building robust and earthquake-resistant structures. This proactive approach helps minimize damage and ensures safety in earthquake-prone regions.

CONCLUSION

By analyzing strong ground motion data from ten significant earthquakes, response acceleration values were computed across ten different structural time periods. Using a logarithmic regression approach and matrix-based least squares method, period-specific attenuation coefficients were derived, enabling the formulation of reliable ground motion prediction equations (GMPEs).

These GMPEs were then employed to generate a design response spectrum for a hypothetical earthquake scenario with a magnitude of 7.0 and an epicentral distance of 35 km—conditions representative of the seismic threats facing major cities like Dhaka.

The findings highlight the crucial need for seismic hazard assessments tailored to specific localities, particularly in countries like Bangladesh that are located in tectonically active and sensitive regions.

The methodology and findings presented in this work contribute to the foundational tools needed for earthquake-resistant design, urban planning, and disaster preparedness. Though limited by the size of the dataset and simplifications in the model, the study provides a significant step forward in enhancing seismic resilience and offers a basis for future research, including more comprehensive probabilistic hazard assessments and the incorporation of local soil and site effects.

LIMITATIONS

Despite the valuable insights provided by this study, several limitations should be acknowledged:

1. *Limited data set*: The derivation of the attenuation relation constants (k_1, k_2, k_3) was based on a relatively small dataset of 10 historical earthquake events. While these data points were crucial for the analysis, a larger and more diverse dataset, encompassing a wider range of magnitudes, epicentral distances, and geological settings, would significantly enhance the statistical robustness and generalizability of the derived equations.
2. *Hypothetical design scenario*: The design response spectrum was developed for a single hypothetical scenario with a specific Magnitude ($M=7.0$) and Epicentral Distance ($R=35.0$ km). This provides a valuable illustration but does not represent a universally applicable design spectrum for all locations or seismic events within Bangladesh. Real-world applications would require site-specific analyses considering varying seismic sources and distances.
3. *Simplistic attenuation model*: The attenuation relation used ($\log A = k_1 M + k_2 \log R + k_3$) is a simplified model. It does not explicitly account for complex geological factors such as local soil conditions (e.g., soil type, depth to bedrock), basin effects, or directivity effects, all of which can significantly influence ground motion characteristics. More advanced GMPEs often incorporate these parameters for greater accuracy.
4. *Quantification of uncertainty*: While the least squares approach minimizes errors, the study does not quantify the degree of uncertainty in the estimated response accelerations or derived constants. Risk-based engineering design choices and probabilistic seismic hazard assessment depend on an understanding of these uncertainties.

FUTURE ASPECTS

1. *Expansion and refinement of earthquake database*: Future work should focus on compiling a more extensive and comprehensive database of strong-motion earthquake records for Bangladesh and the surrounding region. This would involve incorporating data from a wider range of magnitudes, focal depths, fault mechanisms, and site conditions to develop more robust and regionally specific attenuation relations.
2. *Probabilistic seismic hazard assessment (PSHA)*: The derived attenuation relations can serve as a fundamental input for conducting a comprehensive Probabilistic Seismic Hazard Assessment (PSHA) for Bangladesh. PSHA provides a more complete picture of seismic hazard by accounting for all possible earthquake sources, their recurrence rates, and the uncertainties in ground motion prediction, leading to hazard curves and uniform hazard spectra.
3. *Integration with advanced structural analysis*: To evaluate the seismic performance of different structural types under a range of earthquake scenarios, the generated design response spectrum can be used in conjunction with advanced numerical modeling and structural analysis software (such as non-linear time history analysis). A more thorough comprehension of structural behavior and potential weaknesses would be made feasible by this method.
4. *Contribution to building code development*: The findings and methodology can contribute to the ongoing refinement and updating of the Bangladesh National Building Code (BNBC) by providing empirically derived parameters for seismic design. This would help ensure that design standards are based on the latest scientific understanding of regional seismicity.
5. *Development of early warning systems and disaster preparedness strategies*: The understanding gained from predicting ground motion characteristics can inform the development of earthquake early warning systems and more effective disaster preparedness and response strategies for urban centers like Dhaka.

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