SEISMIC BEHAVIOR OF CONCRETE BRIDGE PIERS OF DIFFERENT DIMENSIONS

Ahmed Farhan Ahnaf Siddique*[1] and Tahsin Reza Hossain[2]

[1]*Lecturer, Department of Civil Engineering, BUET, Bangladesh, e-mail: ahnafrcs2011@gmail.com*
[2]*Professor, Department of Civil Engineering, BUET, Bangladesh, e-mail: tahsin.hossain@gmail.com*

***Corresponding Author**

ABSTRACT

Bridges are vital structures for a country, failure of any of them would be devastating. Situated at the northwestern end of the Indo-Australian plate, Bangladesh lies in a seismically active region where several destructive earthquakes have occurred historically and in recent times which is alarming for the bridge designers.

The local Code, BNBC (2017), is intended to aid building design. However, the available earthquake parameters in BNBC can be rationally applied to determine the seismic forces on bridges. The structural design and seismic performance evaluation of bridges of different pier heights located in high seismic zone of Bangladesh have been done following the AASHTO (2011, 2012) specifications in this study.

The contribution of earthquake forces decrease for bridges of higher pier heights as these bridges tend to have higher fundamental time periods compared to shorter pier bridges. Longer pier height bridges also have higher flexibility which increases its deflection capacity.

Bridges designed by the force based concept fails to determine the nonlinear behavior which is required to predict the performance of a bridge under different levels of seismic events.

In this research, concrete bridges of varying pier heights have been designed by the force based concept of which the performance targets were checked by nonlinear static pushover analysis. All the bridges studied in this research satisfied the performance criteria in response to different levels of earthquake. However, the change in pier heights highly affects the seismic base shear on the bridges as well as the displacement demands and capacities of the piers which implies the importance of appropriate knowledge and application of earthquake engineering and also the necessity of performance based design.

Keywords: *Earthquake; Bridge Design Codes; Pier Dimension; Flexibility; Pushover.*

1. INTRODUCTION

Bangladesh lies at the northwestern end of the Indo-Australian plate, which has been subjected to the long-term process of subduction between the plate margins of Indo-Australian and Eurasian plates. As a result, several devastating earthquakes have occurred in this region over the time and it has been marked as a seismically active region. Subsequently, considerations of seismic effects on structures became essential for structural engineers as well as the architects and the users. The increased number of occurrences of earthquake events in the recent times is so alarming for the engineers that it has drawn special attention and provisions for earthquake engineering (Indian Institute of Technology, Kanpur, 2002).

However, the design Code followed in Bangladesh, namely BNBC (2017), does not provide any guideline to the engineers regarding the design and construction of highway bridges as it mainly focuses on the design and construction of buildings. Alternatively, bridges are popularly designed following the specifications provided by AASHTO (2011, 2012).

The seismic force determining parameters used in AASHTO specifications are more suited for regions within and around the United States of America. The earthquake forces and all other related parameters should represent the earthquake events occurring in Bangladesh which is already available in the BNBC. Therefore, it is more rational to apply the BNBC to determine earthquake forces and follow the AASHTO guidelines to design a bridge in Bangladesh (Siddique, 2018).

The effect of earthquake on structures, especially as massive as a bridge, largely depends on the size and shape of the structure itself. Small structures are more affected, or shaken, by high frequency short and frequent waves. Whereas, large structures are more affected by long period or slow shaking (USGS, n.d.). Therefore, bridges with varying pier dimensions will affect its behavior under seismic events which is studied in this research. The bridges studied are two lane three span prestressed concrete I-girder bridges supported by intermediate piers on site class C located in Sylhet which is in seismic zone 4 according to BNBC.

Bridges are conventionally designed by linear static analysis, or the force-based design method which calculates the seismic force demands by equivalent static procedure, but it fails to determine the seismic behavior of the bridge under earthquake events. AASHTO clearly states the necessary methods of analysis for bridge design with respect to seismic design categories, seismic zonings and number of bridge spans to determine the seismic behavior of bridges under such events. Federal Highway Administration (2014) and Caltrans (2015) extensively describes the AASHTO guidelines for bridge design.

The current force-based design method has several shortcomings; the major limitation being that it cannot explicitly relate to the performance of the bridges as there are many uncertainties in achieving the expected level of performance. This method ignores the fact that displacement is more important than strength for inelastic structural components whereas it is the most direct reason that cause structural damages. In order to reduce the underlying uncertainties of force-based design method, researchers have developed the framework of performance based design (Zhang, 2015).

Therefore, whenever it is specified, undertaking the inelastic analysis of a bridge is more rational approach compared to the elastic analysis. In this research, pushover analysis method (nonlinear static procedure) have been followed to capture the inelastic behavior of structures under the action of seismic activity.

2. METHODOLOGY

The main focus of this study is to determine the seismic behavior of concrete bridges of varying pier dimensions designed as per AASHTO guidelines and considering the earthquake demand parameters of BNBC.

Piers are the interior supports of a bridge. The piers are designed for the loads that it requires to resist which includes the vertical loads coming from the dead and vehicular live loads along with the lateral loads coming from the seismic demand. Taly (1998) provided a detailed outline of the loads that are to be considered. The design forces shall be those determined for strength and extreme event limit states.

At the preliminary design stage, design strength interaction diagrams of trial sections are built and these are checked with the aforementioned design loads to be resisted. The loads were determined in accordance with the codes which has been reviewed extensively by Siddique (2018). However, this is the force-based design approach and it must be reviewed by performance evaluation later on.

In the performance-based approach, standard bridges, classified as "other bridges" by AASHTO, are designed with at least two hazard levels. At the lower hazard level, bridges are designed to achieve the target performance which is to remain essentially elastic for expected/serviceability earthquakes having a return period of 150 years. However, at the higher hazard level, collapse prevention of bridges must be assured for rare/maximum considered earthquakes having a return period of 2500 years. The performance requirements of bridges are shown in Table 2.1.

Table 2.1: Performance Requirements of Bridges for Different Hazard Levels

Bridge Operational Category	**Performance Requirement for Hazard Level**		
	Expected Earthquake	Design Earthquake	Maximum Considered Earthquake
Standard/Other	Immediate Occupancy	Collapse Prevention	Collapse Prevention
Essential	Immediate Occupancy	Immediate Occupancy	Collapse Prevention
Critical	Immediate Occupancy	Immediate Occupancy	Immediate Occupancy

The term "Immediate Occupancy" refers to the requirement that the bridge elements should remain essentially elastic immediately after the earthquake event. The term "Collapse Prevention" refers to the requirement that the bridge elements may sustain significant damage during the earthquake event and service may significantly disrupt, but life safety must be assured by collapse prevention. In such cases, the bridge may need to be replaced after a large earthquake.

2.1 Analysis Procedure to Determine Seismic Demand

Earthquake loads are given by the product of the elastic seismic response coefficient and the equivalent weight of the superstructure. The equivalent weight is a function of the actual weight and bridge configuration and is automatically included in both the single-mode and multimode methods of analysis. This is the equivalent static method to determine the earthquake loads according to BNBC. However, AASHTO provides a more detailed guideline about the seismic demand determination procedure which is discussed in this section. Minimum requirements for the selection of an analysis method to determine seismic demand may be taken as specified in Table 2.2 (AASHTO 2012).
Where, * = no seismic analysis required; UL = uniform load elastic method
SM = single-mode elastic method; MM = multimode elastic method
TH = time history method

Table 2.2: Minimum Analysis Requirements for Seismic Effects

Seismic Design Category	**Single-Span Bridges**	**Multispan Bridges**					
		Other Bridges		**Essential Bridges**		**Critical Bridges**	
		Regular	**Irregular**	**Regular**	**Irregular**	**Regular**	**Irregular**
A	No Seismic Analysis Required	*	*	*	*	*	*
B		SM/UL	SM	SM/UL	MM	MM	MM
C		SM/UL	MM	MM	MM	MM	TH
D		SM/UL	MM	MM	MM	TH	TH

However, multimode elastic method has been followed in this study. In order to do so, demand response spectrum have been developed as guided by BNBC, 2017. The considered seismic parameters have been provided in Table 2.3.

Table 2.3: Seismic Factors for Bridges Designed in Sylhet

Parameter	Description
Site class	SC
Soil factor, S	1.15
T_B	0.20 sec
T_C	0.60 sec
T_D	2.0 sec
Damping correction factor, η	1
Seismic zone coefficient, Z	0.36
Importance factor, I	1
Response modification factor, R	5

The Response spectrums have been developed based on these factors for expected earthquake (EE), design earthquake (DE), and maximum credible earthquake (MCE). Figure 2.1 shows the unmodified response spectrum for the bridge under consideration.

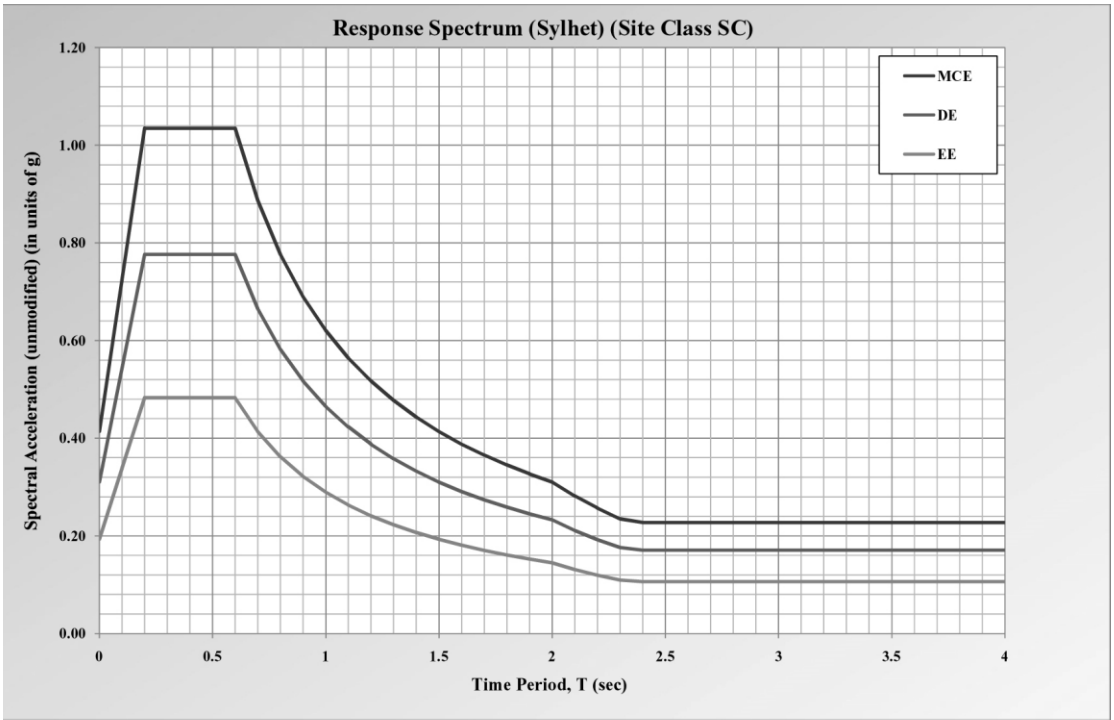

Figure 2.1: Unmodified Response Spectrum for SC Soil in Sylhet

The software runs a modal analysis to determine the time periods corresponding to the mode shapes of the bridge. Using these time periods, the software runs a response spectrum analysis to obtain the seismic forces. The unmodified response spectrum has been scaled according to the provisions of AASHTO.

2.1.1 Determination of Seismic Displacement Demand

The global seismic displacement demands were determined independently along two perpendicular axes, typically the longitudinal and transverse axes of the bridge. A combination of orthogonal seismic displacement demands shall be used to account for the directional uncertainty of earthquake motions and the simultaneous occurrences of earthquake forces in two perpendicular horizontal directions (AASHTO, 2011). The seismic displacements resulting from analyses in the two perpendicular directions were combined to form two independent load cases as follows:

- Load Case 1: Obtained by adding 100 percent of the absolute value of the member seismic displacements resulting from the analysis in one of the perpendicular direction (longitudinal) to 30 percent of the absolute value of the corresponding member seismic displacements resulting from the analysis in the second perpendicular direction (transverse).
- Load Case 2: Obtained by adding 100 percent of the absolute value of the member seismic displacements resulting from the analysis in the second perpendicular direction (transverse) to 30 percent of the absolute value of the corresponding member seismic displacements resulting from the analysis in the first perpendicular direction (longitudinal).

The seismic demand displacements are obtained by running a response spectrum analysis for the demand response spectrum. The software generates demand displacements for X-direction and Y-direction using directional combination for a scale factor of 0.3. This is done to take into account the aforementioned directional load combinations.

2.2 Determination of Seismic Displacement Capacity

For piers, displacement capacity can be evaluated using a nonlinear static analysis procedure referred to as pushover analysis. Although it is recognized that force redistribution may occur as the displacement increases, particularly for frames with piers of different stiffness and strength, the objective of the capacity verification is to determine the maximum displacement capacity of each pier.

Nonlinear static procedure, or pushover analysis, is an incremental linear analysis method that captures the overall nonlinear behavior of the elements, including soil effects, by pushing them laterally to initiate plastic action. Each increment of loading pushes the frame laterally, through all possible stages, until the potential collapse mechanism is achieved. Because the analytical model used in the pushover analysis accounts for the redistribution of internal actions as components respond inelastically, pushover analysis is expected to provide a more realistic measure of behavior than may be obtained from elastic analysis procedures (AASHTO, 2011).

For the immediate occupancy criterion, the elastic displacement capacity is determined from the pushover curve obtained for "first hinge at limit state" bent failure criterion. The displacement capacity is the point on the curve after which the curve is no longer linear.

For the collapse prevention criterion, the ultimate displacement capacity of bent is determined from the pushover curve obtained for "pushover curve drop" bent failure criterion. The ultimate displacement capacity is determined as the displacement at which the base shear first drops from its absolute maximum in the pushover curve to a value 1% less than that maximum. The full pushover displacement is used if the base shear does not decrease 1% from the maximum.

2.3 Seismic Displacement Demand to Capacity Ratio for Bridges

The objective of the determination of the displacement demand and capacity is to check the performance of the bridge which is done by verifying that each bridge bent satisfies equation 2.1.

$$\Delta_D \leq \Delta_C \tag{2.1}$$

where,

Δ_D = displacement demand taken along the local principal axis of the ductile member.

Δ_C = displacement capacity taken along the local principal axis corresponding to Δ_D of the ductile member.

Therefore, the seismic displacement demand to capacity ratio must be less than 1 in order to satisfy the performance targets.

3. ANALYSIS, DESIGN, AND PERFORMANCE EVALUATION

The bridges considered are 350' long and 36' wide consisting of two 14' lanes located in Sylhet which lies in seismic zone 4 and seismic design category D. The bridge has 3 spans of lengths 100', 150', and 100' respectively. The bridge rests on abutments at its ends and is supported by intermediate bents in between. The superstructure consists of 8" thick deck slab laid on four 6' deep AASHTO type VI precast concrete I-girders which are simply supported at its bottom by abutments and bents. The bents consist of circular columns and 32'-6" long rectangular bent caps. The columns are assumed to be fixed supported at its base. The cross-sectional dimensions of bent caps and columns have been found through force-based design for each bridge. The bridge operational category is "Other" for the bridges. The performance targets of these bridges have been evaluated subsequently on the basis of BNBC and AASHTO guidelines as discussed before. The first, second, and third bridges consist of two 45', 55', and 65' long piers respectively in each bent. The fourth bridge consists of one 55' long pier in each bent. Modeling, analysis, design, and seismic performance evaluation of the bridges have been done using CSIBridge 19.2.0.

The following material properties have been used in this research.
Concrete strength for all members except girders, f_c' = 4 ksi
Modulus of elasticity of concrete for all members except girders, E_c = 3605 ksi
Concrete strength for girders, f_c' = 6 ksi
Modulus of elasticity of concrete for girders, E_c = 4415 ksi
Yield strength of reinforcing steel, f_y = 60 ksi
Modulus of elasticity of steel, E_s = 29000 ksi
Yield strength of prestressing steel tendons, f_{py} = 243 ksi
Ultimate strength of prestressing steel tendons, f_{pu} = 270 ksi
Modulus of elasticity of prestressing steel, E_{ps} = 28500 ksi

3.1 Bridge Consisting of Two 45' Long Columns Located in Sylhet

The forces due to dead load and design earthquake on each column base have been found to be **672.643 kips** and **67.91 kips** respectively. Design earthquake force on the column base is **10.1%** of the dead load coming on it.

The force-based design results show that the required circular column section is of **3'-6"** diameter with **2.76%** steel ratio which is provided using **39-#9** bars. The design is governed by extreme event I limit state. The lateral steel obtained from shear criterion does not govern over the minimum seismic criteria.

For this bridge, the results of performance evaluation through the determination of seismic displacement demands and capacities of the bents along with corresponding demand-capacity ratios have been provided in Table 3.1.

Table 3.1: Demand Capacity Ratios for 45' Long Column Bridge Located in Sylhet

Performance Target	Hazard Level	Direction	Demand (inches)	Capacity (inches)	Demand-Capacity Ratio
Immediate Occupancy	EE	Transverse	5.07"	5.68"	0.8929
Immediate Occupancy	EE	Longitudinal	5.11"	11.49"	0.4444
Collapse Prevention	MCE	Transverse	10.86"	11.17"	0.9722
Collapse Prevention	MCE	Longitudinal	10.94"	17.75"	0.6163

3.2 Bridge Consisting of Two 55' Long Columns Located in Sylhet

The forces due to dead load and design earthquake on each column base have been found to be **687.402 kips** and **50.832 kips** respectively. Design earthquake force on the column base is **7.4%** of the dead load coming on it.

The force based design results show that the required circular column section is of **3'-6"** diameter with **2.41%** steel ratio which is provided using **34-#9** bars. The design is governed by extreme event I limit state. The lateral steel obtained from shear criterion does not govern over the minimum seismic criteria.

For this bridge, the results of performance evaluation through the determination of seismic displacement demands and capacities of the bents along with corresponding demand-capacity ratios have been provided in Table 3.2.

Table 3.2: Demand Capacity Ratios for 55' Long Column Bridge Located in Sylhet

Performance Target	**Hazard Level**	**Direction**	**Demand (inches)**	**Capacity (inches)**	**Demand-Capacity Ratio**
Immediate Occupancy	EE	Transverse	6.81"	8.17"	0.8333
Immediate Occupancy	EE	Longitudinal	6.73"	17.71"	0.4019
Collapse Prevention	MCE	Transverse	14.58"	16.15"	0.9029
Collapse Prevention	MCE	Longitudinal	14.41"	26.47"	0.5445

3.3 Bridge Consisting of Two 65' Long Columns Located in Sylhet

The forces due to dead load and design earthquake on each column base have been found to be **719.847 kips** and **46.078 kips** respectively. Design earthquake force on the column base is **6.4%** of the dead load coming on it.

The force-based design results show that the required circular column section is of **3'-10"** diameter with **1.76%** steel ratio which is provided using **30-#9** bars. The design is governed by extreme event I limit state. The lateral steel obtained from shear criterion does not govern over the minimum seismic criteria.

For this bridge, the results of performance evaluation through the determination of seismic displacement demands and capacities of the bents along with corresponding demand-capacity ratios have been provided in Table 3.3.

Table 3.3: Demand Capacity Ratios for 65' Long Column Bridge Located in Sylhet

Performance Target	**Hazard Level**	**Direction**	**Demand (inches)**	**Capacity (inches)**	**Demand-Capacity Ratio**
Immediate Occupancy	EE	Transverse	9.45"	9.82"	0.9615
Immediate Occupancy	EE	Longitudinal	9.35"	20.24"	0.4617
Collapse Prevention	MCE	Transverse	20.24"	20.99"	0.9639
Collapse Prevention	MCE	Longitudinal	20.02"	34.38"	0.5822

3.4 Bridge Consisting of One 55' Long Columns Located in Sylhet

The forces due to dead load and design earthquake on each column base have been found to be **1347.21 kips** and **141.202 kips** respectively. Design earthquake force on the column base is **10.5%** of the dead load coming on it.

The force-based design results show that the required circular column section is of **4'-6"** diameter with **2.93%** steel ratio which is provided using **43-#11** bars. The design is governed by extreme event I limit state. The lateral steel obtained from shear criterion does not govern over the minimum seismic criteria.

For this bridge, the results of performance evaluation through the determination of seismic displacement demands and capacities of the bents along with corresponding demand-capacity ratios have been provided in Table 3.4.

Table 3.4: Demand Capacity Ratios for 55' Long Single Column Bridge Located in Sylhet

Performance Target	Hazard Level	Direction	Demand (inches)	Capacity (inches)	Demand-Capacity Ratio
Immediate Occupancy	EE	Transverse	8.04"	13.50"	0.5952
Immediate Occupancy	EE	Longitudinal	5.71"	13.29"	0.4293
Collapse Prevention	MCE	Transverse	17.21"	20.40"	0.8438
Collapse Prevention	MCE	Longitudinal	12.23"	20.11"	0.6079

4. CONCLUSIONS

The authors have found from this research that the contribution of earthquake forces increase for shorter height column bridges. This is because, due to the higher flexibility of longer column bridges, these tend to have higher fundamental time periods compared to shorter column bridges. The higher fundamental time periods results in a shift towards lower spectral acceleration in the seismic demand response spectrum which eventually leads to lower contribution of seismic forces. The fewer number of columns in a bent results in a much larger design column section. The larger column sections reduces the flexibility of the bridge and makes it stiffer. As a result, the contribution of earthquake forces on single column bent bridges are higher than that on multi-column bent bridges of same pier heights. However, the contribution of earthquake force may be considerably higher for bridges of different time periods.

The seismic displacement demand increases for longer column height bridges as the pier slenderness increases in such cases. Also, the moments and subsequently the deflections of the piers increase with longer dimensions of the piers. Similar to the displacement demand, the displacement capacity of bents also increases for longer column height bridges as well as for smaller column cross-sections and higher steel ratios which is due to the increased flexibility possessed by such bents.

Both single column bent and multi-column bent prestressed concrete I-girder bridges, properly designed for seismic forces, satisfy the seismic performance targets. However, the demand capacity ratios change for different selections of combination of column section and steel ratio. Therefore, it is necessary to evaluate the performance of a bridge prior to finalizing the design.

This research can be further extended in the following fields:

- The AASHTO (2011, 2012) specifications recommend the consideration of liquefaction assessment of subsoil which has not been done in this study. The performance of bridges subjected to liquefaction of subsoil can be studied.
- The column base have been assumed to be fixed at its bottom in this research. However, the soil-structure interaction between piles that support the columns can be researched. Piles are likely to induce additional deflection to the bents.
- All the columns for both bents of the bridges considered in this study have the same height. Bridges having columns of varying heights may be studied.
- The bridges studied in this study consist 3 spans of certain lengths. The number of spans and their lengths can be varied in further researches.

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