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Seismic performance evaluation of bridge piers resting on different soil classes

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ABSTRACT: Failure of important bridges in any country brings a catastrophic change in its economy and its society as bridges are lifeline structures for a country. Bangladesh lies in a seismically active region, situated at the northwestern end of the Indo-Australian plate near the fault line with Eurasian plate, where several devastating earthquakes have occurred historically and in recent times which is alarming for the bridge designers. The local Code, BNBC (2020), is intended to serve the building designers. 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 located in different site classes situated in high seismic zone of Bangladesh have been done following the AASHTO (2011, 2012) specifications in this study. The contribution of earthquake forces increase for bridges situated in poorer site classes as these bridges are exposed to more severe shaking during an earthquake event. 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, the bridges have been designed by the force based concept of which the performance targets were checked by nonlinear static pushover analysis. The bridges studied in this research satisfied the performance criteria in response to different levels of earthquake. However, the changes in the dimensions of different components of the bridge 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.

1 INTRODUCTION

Bangladesh lies at the north-western 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 vital 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 that it has drawn special attention and provisions for earthquake engineering (Indian Institute of Technology, Kanpur, 2002).

Bangladesh National Building Code (BNBC) (2020), has also been upgraded and includes development in knowledge in the field of earthquake engineering among other things. However, as the name suggests, it is a building code and does not provide any specific guidelines to the engineers regarding the design and construction of highway bridges as its main focus is the design and construction of buildings. In absence of any national bridge code, it is a common practice in Bangladesh is to design bridges following the specifications provided by AASHTO (2011, 2012).

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 capture the seismic response in the nonlinear domain which is common for the bridges under earthquake events. However, AASHTO has stated 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 earthquake force determining parameters used in AASHTO specifications are more suitable for regions within and around the United States of America. Nevertheless, the seismic 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).

Verdugo et. al. (2018) demonstrates that local properties and conditions of soil deposits determine the damage caused by large earthquakes. Therefore, it is vital that the subsoil conditions are taken into consideration while designing bridges in high seismic zones. In this research, two lane three span prestressed concrete I-girder bridges supported by intermediate piers have been studied on site classes SC and SD in order to evaluate the performances of these bridges under the varying conditions. The bridges are located in Sylhet which is in seismic zone 4 according to BNBC.

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).

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.). Siddique and Hossain (2020) have shown the differences in performance of bridges with varying pier dimensions under seismic events.

Therefore, whenever it is specified by the design codes, a bridge designer must undertake the inelastic analysis of a bridge which is more rational approach compared to the elastic analysis. In this research, push-over analysis method (nonlinear static procedure) has been followed to capture the inelastic performance evaluation of structures under the action of seismic activity.

2 METHODOLOGY

The main objective of this study is to determine the seismic performance of concrete bridge piers located in different site classes designed as per AASHTO guidelines and considering the seismic 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 loads and vehicular live loads considering HL-93 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.

BNBC has recommended the design life of buildings to be 50 years. The design basis earthquake for buildings has a return period of approximately 475 years corresponds to a probability of exceedance of 10 percent over this exposure period of 50 years. On the other hand, AASHTO has adopted the design life of 75 years for ordinary bridges. The 1000 year return period used in design corresponds to a probability of exceedance of 7 percent over this 75 year exposure period. Therefore, the design seismic force for bridges must be determined considering the hazard level of a 1000 year return period earthquake. The bridge designer must be careful in determining the design seismic forces for bridges as it will be higher than that considered while designing buildings.

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 AASHTO and BNBC guidelines which have been reviewed extensively by Siddique (2018). However, this is the force based design approach and it must be reviewed by performance evaluation later on for high seismic design categories as specified by AASHTO.

In the performance based design approach, standard bridges, classified as "other bridges" in AASHTO, are designed with at least two hazard levels which has been extensively reviewed by Federal Highway Administration (2014). 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 1.

Table 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. 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	*	*	*	*	*	*
B	Analysis	SM/UL	SM	SM/UL	MM	MM	MM
C	Required	SM/UL	MM	MM	MM	MM	TH
D		SM/UL	MM	MM	MM	TH	TH

2.2 *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.

2.3 *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 performance 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 the performance of the structure 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.

2.4 *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.

$$\Delta_D \leq \Delta_C \qquad (1)$$

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 ANALYSES, 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. Each bent consists of two 55' long piers. 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 detailed measurements of the bridges are shown in Figures 1 to 3. 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. 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.

Table 3. Seismic factors for bridges designed in Sylhet.

Parameter	Description	
	Site class - SC	Site class - SD
Soil factor, S	1.15	1.35
T_B	0.20 sec	0.20 sec
T_C	0.60 sec	0.80 sec
T_D	2.0 sec	2.0 sec
Damping correction factor, η	1	1
Seismic zone coefficient, Z	0.36	0.36
Importance factor, I	1	1

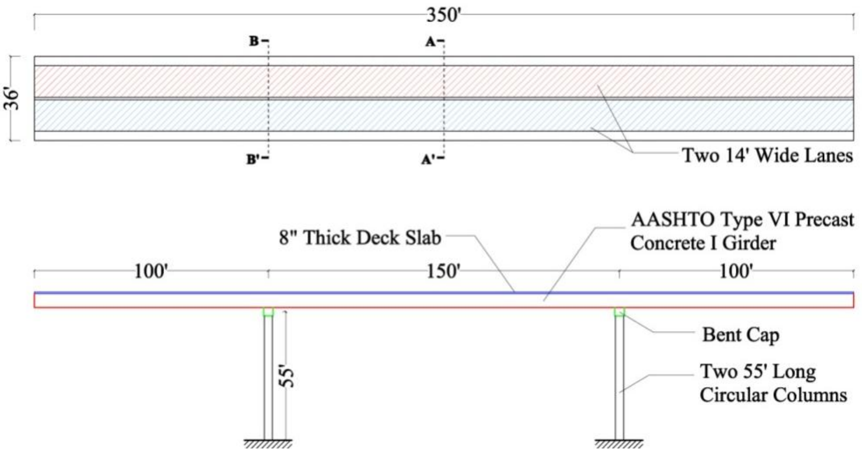

Figure 1. Detailed dimensions of the bridge under consideration.

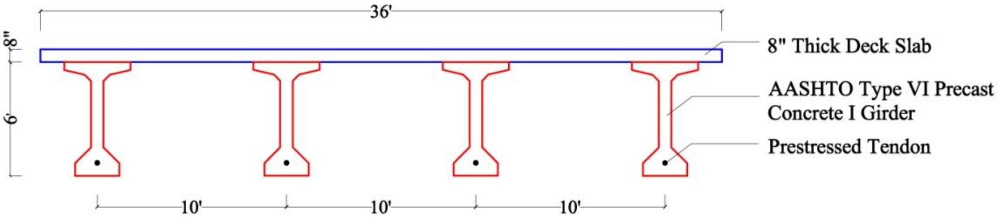

Figure 2. Section A-A'.

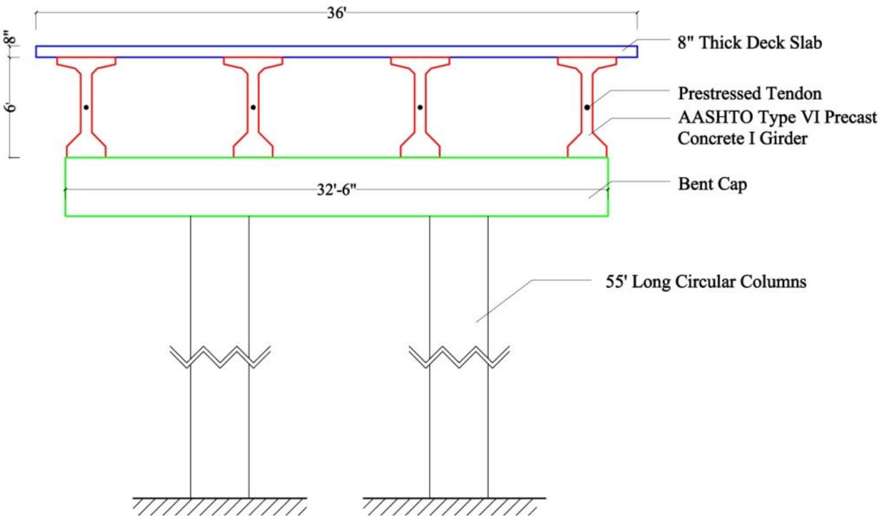

Figure 3. Section B-B'.

Multimode elastic method have been followed in this study to determine the seismic demand. In order to do so, demand response spectrum have been developed as guided by BNBC, 2020. The considered seismic parameters have been provided in Table 3.

The Response spectrums have been developed based on these factors for expected earthquake (EE) having a return period of 150 years which is taken as 70% of design basis earthquake (two-thirds of maximum considered earthquake having a return period of 475 years) of BNBC; design earthquake (DE) having a return period of 1000 years which is taken as 75% of maximum credible earthquake; and maximum credible earthquake (MCE) having a return period of 2500 years. Figure 4 shows the elastic response spectrum for the bridge located in site class SC and Figure 5shows the elastic response spectrum for the bridge located in site class SD.

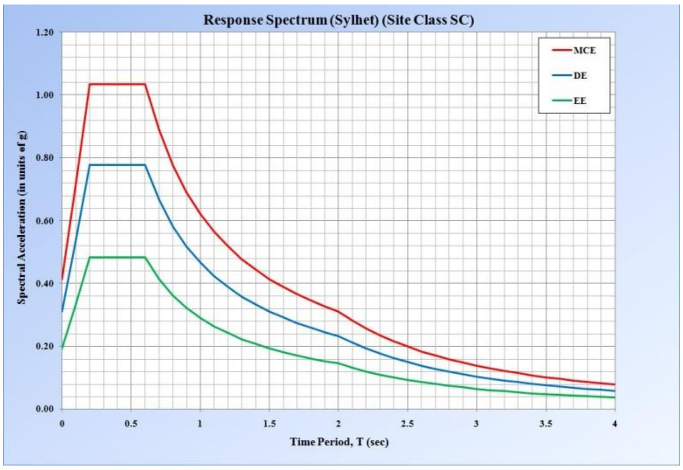

Figure 4. Elastic response spectrum for SC soil in Sylhet.

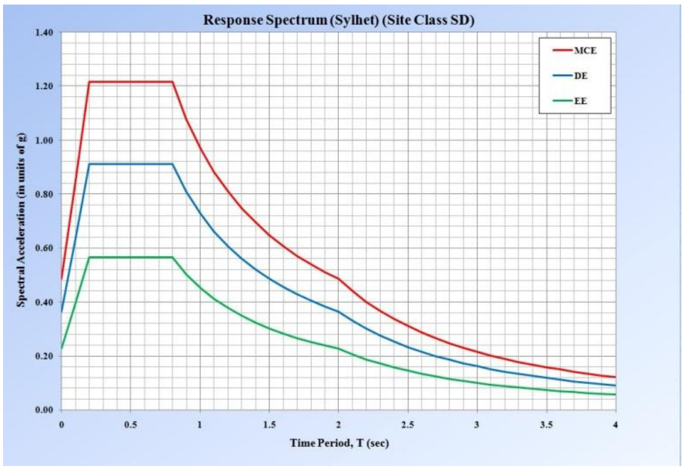

Figure 5. Elastic response spectrum for SD Soil in Sylhet.

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 elastic response spectrum has been scaled according to the provisions of AASHTO. The response modification factors for bridges are shown in Table 4. The response modification factors for both the bridges under consideration are 5.0.

Table 4. Response modification factors for bridges.

Substructure Type	Operational Category		
	Critical	Essential	Other
Wall-type piers—larger dimension	1.5	1.5	2.0
Reinforced concrete pile bents			
– Vertical piles only	1.5	2.0	3.0
– With batter piles	1.5	1.5	2.0
Single columns	1.5	2.0	3.0
Steel or composite steel and concrete pile bents			
– Vertical piles only	1.5	3.5	5.0
– With batter piles	1.5	2.0	3.0
Multiple column bents	1.5	3.5	5.0

3.1 *Bridge Located in Site Class SC*

The forces due to the dead loads and design earthquake on each column base have been found to be 687 kips and 50.8 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 5.

Table 5. Demand capacity ratios for bridge located in site class SC.

Performance Target	Hazard Level	Direction	Demand (inches)	Capacity (inches)	Demand-Capacity Ratio
Immediate Occupancy	EE	Transverse	6.81"	8.17"	0.833
Immediate Occupancy	EE	Longitudinal	6.73"	16.74"	0.402
Collapse Prevention	MCE	Transverse	14.58"	16.15"	0.903
Collapse Prevention	MCE	Longitudinal	14.41"	26.47"	0.545

3.2 *Bridge Located in Site Class SD*

The forces due to the dead loads and design earthquake on each column base have been found to be 736 kips and 123 kips respectively. Design earthquake force on the column base is 16.7% 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 3.07% steel ratio which is provided using 46-#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 6.

Table 6. Demand capacity ratios for bridge located in site class SD.

Performance Target	Hazard Level	Direction	Demand (inches)	Capacity (inches)	Demand-Capacity Ratio
Immediate Occupancy	EE	Transverse	6.39"	6.65"	0.962
Immediate Occupancy	EE	Longitudinal	6.49"	13.03"	0.498
Collapse Prevention	MCE	Transverse	14.41"	15.10"	0.955
Collapse Prevention	MCE	Longitudinal	14.65"	21.79"	0.672

4 CONCLUSIONS

The authors have found from this research that the contribution of earthquake forces increase significantly for bridges located in poorer site classes as the percentage of earthquake force to dead load raised to 16.7% from 7.4% for site classes SD and SC respectively. This is because, for the same magnitude of earthquake on the bedrock, the effect of earthquake magnifies on a larger scale for poorer soils. As a result, poorer soils are subjected to more severe shaking during a earthquake hazard event. The design column section is found to be essentially larger for bridges designed in poorer site classes as they are subjected to higher seismic forces. The larger column sections reduce the flexibility of the bridge and make it stiffer. As a result, the contributions of earthquake forces are found to be higher. However, the contribution of earthquake force may be considerably different for bridges of different time periods. The seismic displacement demand to capacity ratios significantly increase for bridges located in poorer site classes. This is because, bridges located in poorer site classes will have poorer subsoil condition below its piers which will lead to the structure having to deal with more severe ground shaking and higher seismic demands. Both the bridges located in site class SC and SD, 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.

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