MIJST
MIST International Journal of Science and Technology

Force based Design Approach for Seismic Evaluation of Padma Multipurpose Bridge Pier at Different Performance Levels

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ARTICLE INFO

Article History:

Received: 10th November 2022
Revised: 15th November 2022
Accepted: 20th November 2022
Published: 30th November 2022

Keywords:

Padma Multipurpose Bridge
Pier
Force Based Design
Performance Level
Soil-structure Interaction

ABSTRACT

The Padma Multipurpose Bridge (PMB) is one of the biggest megaprojects of Bangladesh connecting one third of the country with the capital city, Dhaka. The infrastructure is expected to produce considerable uplift on the nation's transport system, the national and regional economy, employment, household income, and ultimately, poverty reduction. From construction and river management points of view, it is the most difficult and engineering innovation-intensive project in the world. Hence the Padma Multipurpose Bridge (PMB) required analytical, computational and experimental studies. In this work, a 3D Finite Element (FE) model of the actual PMB containing a single (6x150m) 900m modules has been developed in MIDAS Civil, a commercial computer program for bridges. P-y soil spring model following API guideline has been developed to conform flexible support system of the bridge pier. Following BNBC 2020, the bridge's performance has been evaluated for the 475-year, 975 years, and 2475-year return periods for Service Level, Design Basis and the Maximum Credible Earthquake (MCE), respectively. The forced based design shows that the bridge pier reached only 28% and 36% of its axial and shear capacity respectively for an earthquake return period of 2475 years. On the other hand, the pier has reached a maximum of 41% of its total shear capacity for the same seismic level.

1. INTRODUCTION

Bangladesh is crisscrossed by over 230 rivers including two mighty rivers (the Gangages-Padma and the Brahmaputra-Jamuna). These two biggest rivers in South Asia merged in the middle of Bangladesh and discharge the water and sediments into the Bengal Sea (Bay of Bengal). The merged Padma and Jamuna Rivers separated south western Bangladesh from the rest of the country, creating economic disparity between the regions. To undertake the uniform economic development across the country, a multipurpose (road and rail) bridge contrustion requirement has become paramount. Padma multipurpose bridge (PMB) that connects major parts of Bangladesh is considered as the most important bridge but challenging project of the history of Bangladesh. The uncertain profile of the river and its turbulence in the monsoon, current, scour depth, subsoil conditions, river management were the key challenges. Relevant consultants, engineers and the management team worked hard to figure out the best engineering solutions and implementation techniques to overcome them.

Bridge piers and foundations are the key substructural elements of the bridges since any failure of them results catastrophic consequences. There are numerous evidences of bridge pier's collapse in extreme conditions particularly in the seismic events. Researchers, scientists, engineers and other stakeholders have paid a great deal of attention to improve pier performance and thus build more sustainable and hazard resilient piers. The hollow rectangular pier of PMB has gain interests and attention by the researcher's community. Previously, seismic response of hollow bridge pier was experimental and numerically investigated by (Calvi *et al.*, 2005). They claimed that the circular pier showed low strength but higher ductility and smaller equivalent damping. Recently, hybrid reinforcement like stainless steel is found to be more effective in concrete bridge pier than that of the conventional steel (Farzana and Ahmed, 2020, Farzana and Ahmed, 2022, Ahmed *et al.*, 2021a). In addition, post-earthquake retrofitting techniques for such concrete structures using grout jacket (Kennedy-Kuiper *et al.*, 2022), concrete jacket (Mahmud and Ahmed, 2020) and post installed rebar (Ahmed *et al.*, 2021b) have already been studied and found to be effective.

Force Based Design (FBD) approach is an elastic analysis procedure also termed as Response Spectrum Analysis (RSA) where response modification, ductility, design overstrength are involved. FBD is a very popular and widely used analysis technique that determines the seismic force demand of a structure. Response spectrum considers the spectrum of a response quantity like ground acceleration concerning the frequency of the structure. Seismic evaluation of hollow bridge pier is previously investigated by (Taucer *et al.*, 2010). They calibrated the response spectrum of the bridge pier using damping and hysteretic response of the pier.

Previously, soil-structure interaction of bridge pier was investigated by few researchers (Wu & Qiu, 2020; Stefanidou *et al.*, 2017; Manos *et al.*, 2015) to understand the actual response of the bridge. A study on dynamic soil-pile interaction on bridge pier has been conducted by (Manos *et al.*, 2015) where they claimed that non-linear response can result excessive pier displacement which should be addressed in the design process.

This research work aims to investigate the seismic performance of the Padma Multipurpose Bridge using force based design approach as per BNBC 2020 and AASHTO LRFD 2017 (American Association of State and Transportation, 2017). In the process, p-y soil structure interaction is adopted from the actual ground condition to conform the flexible support system. The investigation focuses on the maximum seismic force demand, elastic displacement and the demand to capacity ratio of the pier for combined flexure and axial, and shear as well.

2. MODELING OF THE INTEGRATED BRIDGE

Since the composite steel warren truss is composed of repetitive modules of 900m, the FE model is idealized for a six-span continuous straight module. The superstructure is separated by the Friction Pendulum Bearing (FPB) which is resting on the bridge pier. After accounting all sources of self-weights of the structure and superimposed dead loads, HL-93 vehicular live load as per AASHTO LRFD 2017 is considered for the upper deck and Dedicated Freight Corridor (DFC) loadings are assumed for the railway.

The basic geometric and structural features of the PMB is depicted in Table 1. Based on the actual geometry of the PMB, a repetitive six span ($150m$ each) 900m warren truss has been taken for analysis and design assessment. Considering the actual loading and boundary condition, a 3D integrated model has been developed for the main bridge Padma using commercial software Midas Civil v2016 as shown in Figure 1. The values of the loads coming from utilities services, non-structural items of the bridge and the superimposed dead loads have been included with sufficient contingency allowance for future requirements. Self-weights have been estimated from the actual geometry of the bridge section as observed in the drawings.

Table 1
Basic geometric and structural features of PMB

Parameters	Description	Remarks
Bridge Configuration	Steel Warren Truss	Concrete at the Upper deck
Total Length	6.15 km	Total 7 Modules, 6 spans in each module
Bridge Width	18.18m	Accommodates 4 lanes
No of Span	41	Each Span 150m
No of Pier	42 (40 Center piers)	Two transition piers at ends
Pile	Inclined Pile 1H:6V	Steel Tubular Driven Pile: 6 no in each pier Vertical bored pile 32 nos with a depth of 80m
Pile Diameter	3m	
Pile Length	128m	
Design Life	100 yrs	

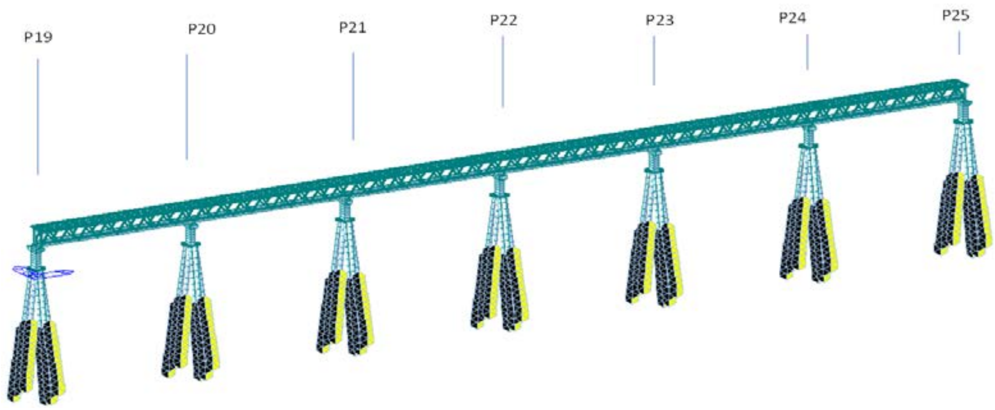

Figure 1: 3D Finite element model of the bridge module with soil-structure interaction

As vehicle live load HL-93 for the 4-lane upper deck and Dedicated Freight Corridor (DFC) loadings for the single lane railway at the lower deck are considered following AASHTO-LRFD guideline. Material non-linearity and significant displacement effects where appropriate are also considered in the finite element model. Permanent load effects locked into structures as a result of the proposed construction sequence have been accurately determined as a part of the analysis. In case where shear lag is significant, the study has taken into account the effects of shear lag under different loading patterns to examine the behavior of the bridge accurately.

A. p-y Soil Structure Interaction

The lateral soil resistance to deformation (p-y) interactions for sand are non-linear that may be approximated at any specific depth H, by the following expression as per American Petroleum Institute (API) guideline.

$$P = A \times p_u \times tanh\left[\frac{k \times H}{A \times p_u} \times y\right] \quad (1)$$

Here, A is a factor accounted based on the loading conditions. $A = 0.9$ for cyclic loading, $A = (3.0 - 0.8\frac{H}{D}) \geq 0.9$ for static loading. P_u = ultimate bearing capacity at depth H $lbs./in.$ (kN/m), k = initial modulus of subgrade reaction, lb/in^3 $(kN/\ m^3)$. φ' = angle of internal friction and y = lateral deformation (m).

B. Design Response Spectrum at Different Performance Level

Force-based analysis approach is used on the integrated model to determine the force demand and bridge responses. The authority, owner, or those with jurisdiction must classify the bridge into one of three categories: (i) Critical Bridges, (ii) Essential Bridges, or (iii) Other Bridges. The classification criteria must include social and defense requirements. In classifying a bridge, consideration should be given to possible future changes in conditions and requirements. Essential bridges are generally those that should be open to emergency vehicles as a minimum, and for security/defense purposes immediately after the design earthquake. However, some bridges must remain open to all traffic after the designed earthquake and be usable by emergency vehicles for security and defense purposes immediately after a large earthquake. These bridges should be regarded as critical structures.

Bangladesh National Building Code is usually developed for building structures where the recommended design life of buildings is 50 years. The design basis earthquake for building structure is set to be 10 percent probability of exceedance in 50 years i.e. a return period of 475 years. AASHTO LRFD guideline is generally used for bridges and infrastructures that recommends the design life of 75 year. The guideline uses an earthquake have a return period of 1000 year which 7 percent probability of exceedance in 75 years.

In the performance based design approach two or three hazard levels are considered based on the requirement and usage of the bridges. As an example, the Service Level Earthquake (SLE) might be considered at a 65% probability of exceedance in the design life or 100 years of return periods. In SLE events, the bridge will survive the events without any damage and full service is available to all i.e., vehicle operation immediately after the earthquake events. The contingency / Design Basis Level of Earthquake (DLE) events has a 20% probability of being exceeded in the design life of 100 years or a return period of 475 years. The bridge is expected to survive the DBE events with moderate, readily detectable, and repairable damage. There is no collapse and no threat to life. Damage can be repaired to restore the full operational functioning of the structure without demolition and replacement of components. For gravity structures, residual displacement shall be limited following AASHTO LRFD requirements. In the formation of plastic hinges that take place at the ends of pier stems the pile foundation should remain elastic when subjected to DBE events. On the other hand, Federal highway admistration (Marsh *et al.*, 2014) recommended that the highest hazards level like collapse prevention of bridges must consider a rare earthquake having a return period of 2475 yrs.

In this study, the bridge's performance has been evaluated for the 475-year, 975 years, and 2475-year return periods for the ground acceleration values of 0.12g, 0.15g, and 0.2g.

Geotechnical investigations and structural loads will be required to ensure that the pile toe level will be resting on very dense soils or soft rock. The response spectrum curves have been plotted for the 475-years, 975 years, and 2475-years return periods with PGA values of 0.12g, 0.15g, and 0.2g. According to Bangladesh National Building Code (BNBC-2020), the site class has been taken as SC. The Site parameters for the seismic analysis have been taken from the BNBC 2020 (Appendix C).

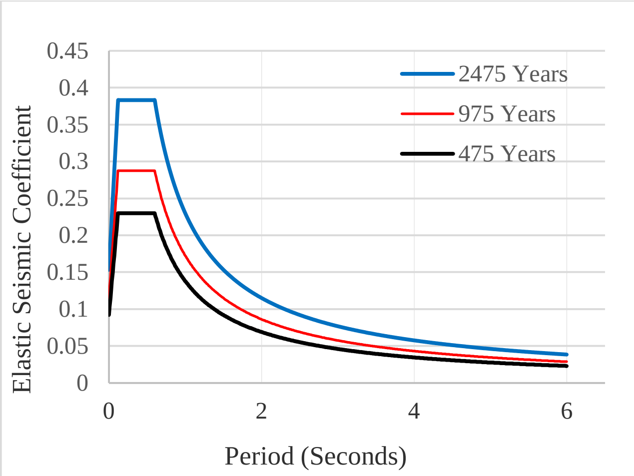

Figure 2: Response spectrum curves for the different earthquake return periods

3. RESULTS AND DISCUSSION

Mode shapes and natural frequencies are very important to understand the dynamic response of the structure and sometimes controls the design of structures. Here, the natural frequencies of the three lowest modes are presented. It is very important to know the natural frequency of the structure as it should be outside the operating frequency range. If the direction of the load is known, examine the mass participation factor and the direction of each mode. In each mode, if the acting direction of the load and the highest mass participation factor do not match, the mode does not harm the stability of dynamic behavior. If they match or close, the structural design should be overwritten to avoid resonance. In order to conduct a safer design, the structure's natural frequency should be no more than a third of or at least three times the operating frequency. The modal analysis shows that the periods of the first three modes are 3.77s, 3.62s, and 3.60s, respectively as presented in Table 2. The deflected shape of the first mode is in the lateral direction whereas 2nd mode takes place in the longitudinal direction. The displacement demand of the bridge pier has been presented for both longitudinal and transverse directions of the bridge pier in Figure 3.

Table 2
Frequency and period for the 1st of 3 modes

Mode	Frequency (rad/sec)	Frequency (cycle/sec)	Period (sec)
1	1.6655	0.2651	3.77
2	1.7356	0.2762	3.62
3	1.7435	0.2775	3.60

It is to be noted that full seismic force in the longitudinal/transverse axis and 30% earthquake force applied at the transverse/longitudinal axis as per AASHTO LRFD guideline. Based on the Force based analysis, the displacement of the bridge pier in the longitudinal and transverse directions are shown in the tables 3 and 4, respectively. The table shows that the maximum pier top displacement is observed in Pier number 23 (one of the middle piers) for all earthquake return periods.

The maximum pier tip displacement is 106mm for 2475 earthquake return period where as 83mm for 975 yrs and 66mm period for 475 earthquake return period. Similar observation is found for the other piers of the bridge module. The maximum transverse displacement is observed in the pier no 22 for all earthquake return periods. Due to the deflected shape of the pier, the location of the maximum lateral displacement is at the pier bottom rather at the pier top. The maximum displacement at the 2475 earthquake return period is 100mm which is 83mm for 975 yrs and 75mm for 475 yrs return period.

The maximum base shear demand for the Pier P19 to P25 has been evaluated at the Pier Top and bottom for both long and transverse direction. The summary of the shear force yielding at the pier base in the longitudinal and transverse directions for pier top and pier bottom have been shown in Tables 5 and 6 respectively. Table 6 shows that the maximum base shear demand is observed in pier number 23 where maximum displacement was observed. The maximum base shear demand for longitudinal direction for 2475yrs, 975 yrs, and 475 yrs return periods are 8327kN, 6674kN, and 3887 kN respectively.

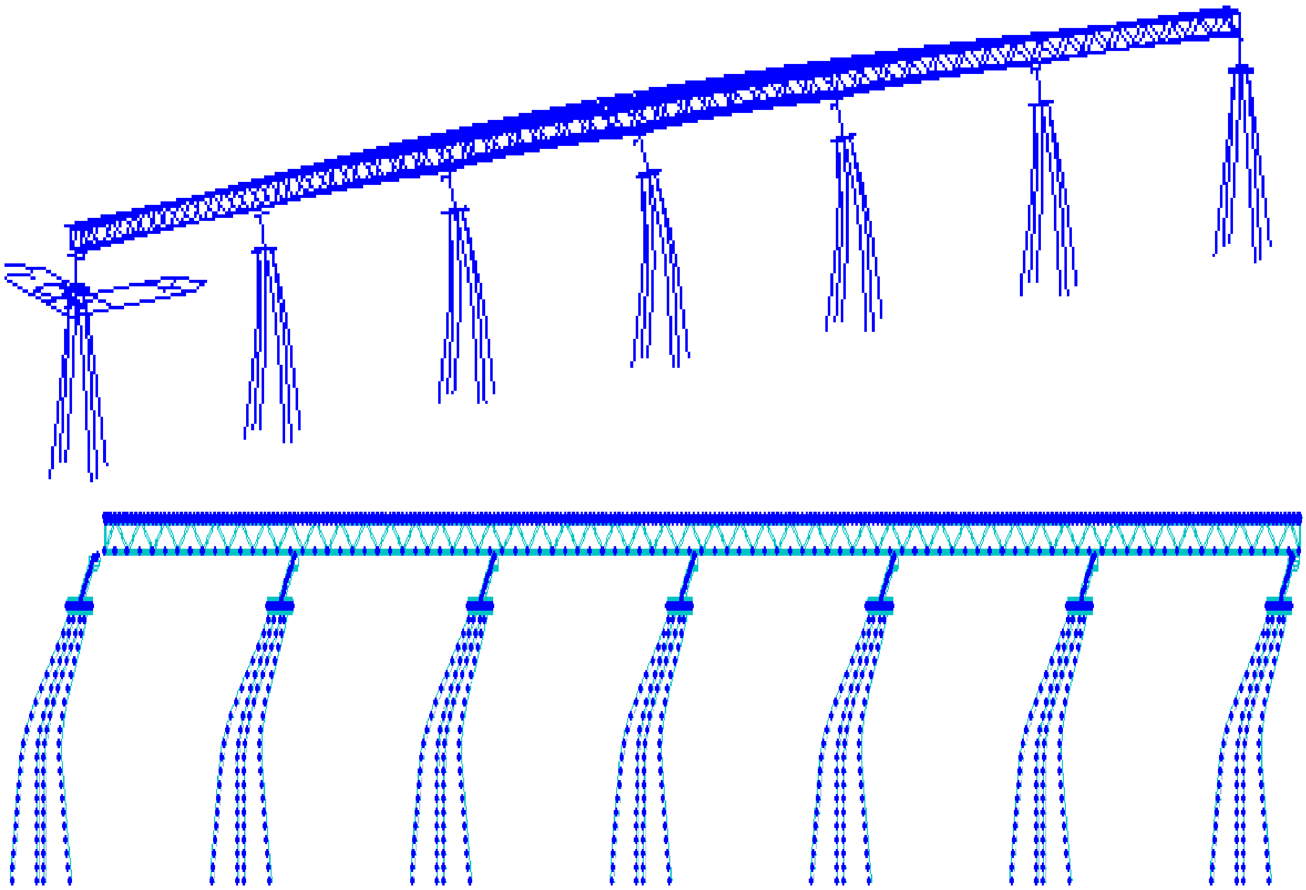

Figure 3. Deflected shape of the bridge in the transverse and longitudinal direction

Table 3
Displacement demand longitudinal direction P19 TO P25

Pier No	2475 Years Displacement, long. DX (mm)		975 Years Displacement, DX (mm)		475 Years Displacement, DX (mm)	
	Pier Top	Pier Bottom	Pier Top	Pier Bottom	Pier Top	Pier Bottom
P19	91	55	72	62	70	55
P20	106	66	84	75	69	66
P21	104	66	82	73	69	66
P22	105	66	83	74	69	66
P23	106	66	84	75	69	66
P24	104	66	82	73	69	66
P25	88	68	69	81	52	68

Table 4
Displacement demand transverse direction P19 to P25

Pier No	2475 Years Displacement, Trans (mm)		975 Years Displacement, Trans (mm)		475 Years Displacement, Trans (mm)	
	Pier Top	Pier Bottom	Pier Top	Pier Bottom	Pier Top	Pier Bottom
P19	62	97	50	80	48	75
P20	71	99	57	81	49	75
P21	79	100	63	82	49	75
P22	82	100	65	83	50	75
P23	79	100	63	82	50	75
P24	71	99	57	81	49	75
P25	61	97	50	80	48	75

Table 5
Shear of the Piers top P19 to P25

Pier No	Pier Top Shear, 2475 Years		Pier Top Shear, 975 Years		Pier Top Shear, 475 Years	
	Long. (KN)	Trans. (KN)	Long. (KN)	Trans. (KN)	Long. (KN)	Trans. (KN)
P19	5164	2634	3897	1977	2833	1539.18
P20	8288	5679	6636	4263	3884	2250.42
P21	8067	7039	6414	5286	3877	2412.59
P22	8208	7669	6554	5758	3882	2471.14
P23	8327	7039	6674	5293	3887	2415.06
P24	8083	5677	6431	4263	3878	2246.66
P25	7389	2651	6121	1993	2908	1538.71

Table 6
Shear at the Pier bottom; P19 to P25

Pier No	Pier Bottom Shear, 2475 Years		Pier Bottom Shear, 975 Years		Pier Bottom Shear, 475 Years	
	Long. (KN)	Trans. (KN)	Long. (KN)	Trans. (KN)	Long. (KN)	Trans. (KN)
P19	5385	3315	4062	2488	3455	2226.92
P20	8433	5974	6745	4485	4383	2769.89
P21	8212	7344	6523	5514	4375	2900.96
P22	8352	7923	6663	5949	4380	2947.98
P23	8472	7344	6783	5521	4385	2903.44
P24	8227	5975	6540	4485	4377	2766.84
P25	7610	3329	6287	2501	3530	2227.26

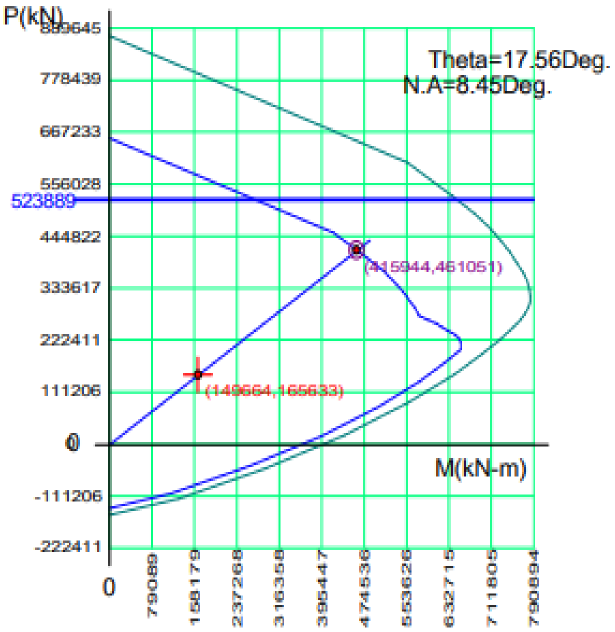

Figure 4. P-M interaction diagram

On the other hand, Pier P22 has been designed to observe its flexure and shear capacity as per the FBD approach. Forces demands are estimated from the envelope of all load combinations. The pier interaction diagram is presented in Figure 4. For the most critical case i.e. forces envelop to result highest demand capacity ratio, the bridge pier reached only 28% of its pure axial capacity and 36% of its flexural capacity for a seismic situation of 2475 return period. On the other hand, the pier has reached only 41% of its shear capacity and only 24% of the shear capacity of the applied reinforcements of the section.

4. CONCLUSION

In this study, seismic evaluation of PMB pier has been performed using force based analysis and design approach where P-Y soil-structure interaction has been considered to confirm the actual flexible foundation system. With a view to understanding the performance of the bridge pier at SLE, DBE, and MCE, the displacement demand of the hollow concrete piers has been estimated for the seismic return period of 475, 975, & 2475 years, respectively. The key findings of this study are

a. The modal analysis of the module indicated that the periods of the first three modes of the bridge module are in the range of 3.60 to 3.72s. The first two modes of the bridge module are found in the transverse and longitudinal directions, respectively. The third mode is found in the torsional direction.

b. Force based analysis shows that the drift at the top of the pier evaluated for the longitudinal and transverse directions for the three seismic events. In longitudinal directions, the displacements of the piers from P19 to Pier P25 are studied. The displacement record shows that the P22 and P23 experiences maximum displacements for all earthquake return periods.

c. At the Extreme Event-1, the maximum displacements at the pier top in longitudinal directions are 75 mm, 84 mm, and 106 mm. In transverse directions, the displacement values are 50mm, 65mm, and 82 mm for the return periods of 475-year, 975 years, and 2475 years respectively. The maximum base shears in longitudinal directions are 4385 KN, 6783 KN, and 8472 KN. In transverse directions, the base shear values are 2948 KN, 5949 KN, and 7923 KN for the return periods of 475 years, 975 years, and 2475 years, respectively.

d. FBD investigation reveals that the bridge pier reached only 28% of its axial capacity and 36% of its flexural capacity at MCE (for an earthquake return period of 2475 yrs). In the critical case of shear demand, the pier has reached only 41% of its shear capacity and only 24% of the shear capacity is neutralized by the seismic shear demand. Therefore, it can be concluded based on this forced analysis that the bridge has been designed on the conservative side (well below the capacity) which is very much justified for this lifeline structure connecting the south-side of the country with the capital.

ACKNOWLEDGMENTS

The authors would like to thank the department of Civil Engineering of MIST for their full support in conducting this MSc level thesis. The authors are grateful to Bangladesh Bridge Authority for allowing them to use the feasibility study reports and Tender drawings.

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