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BEHAVIOUR OF THE JAMUNA MULTI-PURPOSE BRIDGE CONSIDERING SOIL-STRUCTURE INTERACTION

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ABSTRACT

The Jamuna Multipurpose Bridge, as yet the longest bridge in Bangladesh, is located in a seismically active region. The bridge is designed for a ground acceleration of 0.2g. The bridge is instrumented with sensors in order to monitor the performance of the seismic devices as well as the overall dynamic behavior of the bridge. A finite element three dimensional model of the super-structure of one module of the bridge has been developed considering all critical parameters of the bridge. Complex stiffness of the underlying batter piles have been determined considering the soil-structure interaction by the Thin Layered Element Method and have been included in the finite element model. Dynamic analyses have been performed incorporating the effect of soil structure interaction in the finite element model of the bridge. Results from the analyses of the model have been compared with the recorded responses of the bridge due to a seismic event which occurred in 2008. This study also emphasizes the importance of considering appropriate loading conditions to obtain accurate results from dynamic analysis.

Introduction

Dynamic response during earthquake is a very important factor for both the serviceability and safety of bridge structures. In Bangladesh only the Jamuna Multipurpose Bridge is instrumented with accelerometers. The bridge is located in a seismically active region and has been designed to resist dynamic forces due to earthquakes with peak ground acceleration of 0.2g (Bolt, 1987). Seismic pintles are used as isolation devices in the bridge for protection against earthquakes (BUET, 2001). The bridge is instrumented with sensors to record and collect noise, traffic vibration and earthquake data (BUET, 2003). A sophisticated model of the Jamuna Bridge has been developed using the Finite Element Method (Rahman, 2008). The objectives of the present study are to include the effect of soil-structure interaction in the dynamic analysis of the Finite Element model, to perform time history analysis of the bridge model for the earthquake of 2008 and to compare simulated response with the recorded response of the bridge deck.

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Bridge Description

The main bridge is slightly curved, about 4.8 km long, prestressed concrete box-girder type, and consists of 47 nearly equal spans of 99.375 m and 2 end spans of 64.6875 m. The total width of the bridge deck is 18.5 m. The main bridge is supported by twenty one 3-pile piers and twenty nine 2-pile piers. There are 128 m long road approach viaducts at both ends of the main bridge. There are six hinges (expansion joints) that separate the main bridge structure into seven modules: two end modules, four 7-span modules and a 6-span module in the middle.
The bridge consists of four lane roads with a single-track meter gauge railway and a footpath. The crossing has been designed to carry a dual two-lane carriageway, a dual gauge (broad and meter) railway, a high voltage (230 kilo volts) electrical inter-connector, a 750 mm diameter high-pressure natural gas pipeline and telecommunication cables. The carriageways are 6.315 m wide separated by a 0.57 m width central barrier; the rail track is located along the north side of the deck. On the main bridge, electrical pylons are positioned on brackets cantilevered from the north side of the deck. Telecommunication ducts run through the box girder deck and the gas pipeline is located under the south cantilever of the box section. The height of the pier stem varies from 2.72 to 13.05 m. They are founded on concrete pile caps, whose shells were precast and filled with in-situ reinforced concrete.

Sub-Soil Information

The Toe level of each pile in the Jamuna Multipurpose Bridge is -70m from Public Works Department (PWD) datum. Pile cap top level and bottom level of each pile cap is +14m and +4m respectively. River bed level is 10m below the pile cap in Pier1. River bed level is above pile cap bottom in case of Pier 2 to Pier 7 and Pier 11. Soil properties have been found in the form of CPT (Cone Penetration Test) from the geotechnical field data. The shear wave velocities have been found at different levels of soil using CPT to SPT (Standard Penetration Test) conversion formula (Bowles,) and SPT to shear wave velocity conversion formula (Tamura, 2002). Soil property of Pier3 and Pier4 is similar to that of Pier5. And soil profile of Pier7 is same as that of Pier 6. Fig. 1 shows that shear wave velocity profiles at different pier locations do not vary significantly.

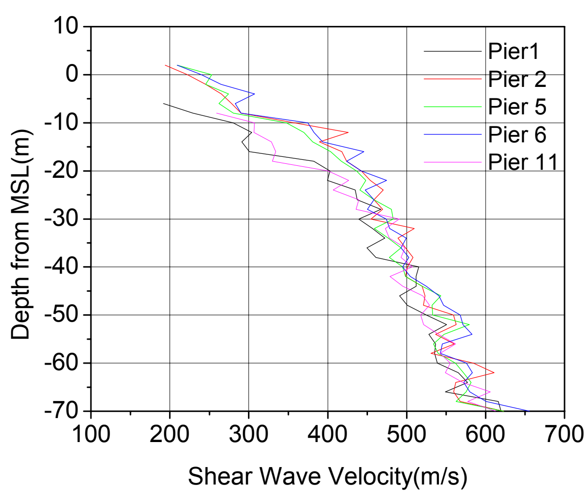


Figure 1. Shear wave velocity and pile thickness data under different piers.

Pile Properties

2.5m diameter and 3.15m diameter steel hollow piles have been used in the bridge. Hollow piles have been filled up with concrete. Thickness of piles has been varied along the length. In the Jamuna Multipurpose Bridge 2-pile and 3-pile piers are present. Piles of the second module of the bridge have been considered, where soil level is over the pile-cap bottom level.

Dynamic Soil-Pile Interaction Analysis

In this study the soil-pile interaction has been analyzed using a computer program based on the Thin Layered Element Method (TLEM). The numerical scheme presented by Tajimi and Shimomura (1976) allows soil-embedded foundation interaction effects to be rigorously evaluated. The TLEM is a method for describing soil strata rather than for foundations. In this method, a soil deposit is treated as an infinite stratified medium with the inclusion of a cylindrical hollow in which the foundation is fitted. The piles are assumed to be upright Timoshenko beam. The real part and imaginary part of the stiffness of the pile-head, shown in figures 2 and 3, have been calculated by the TLEM. The damping has been found to be relatively small.

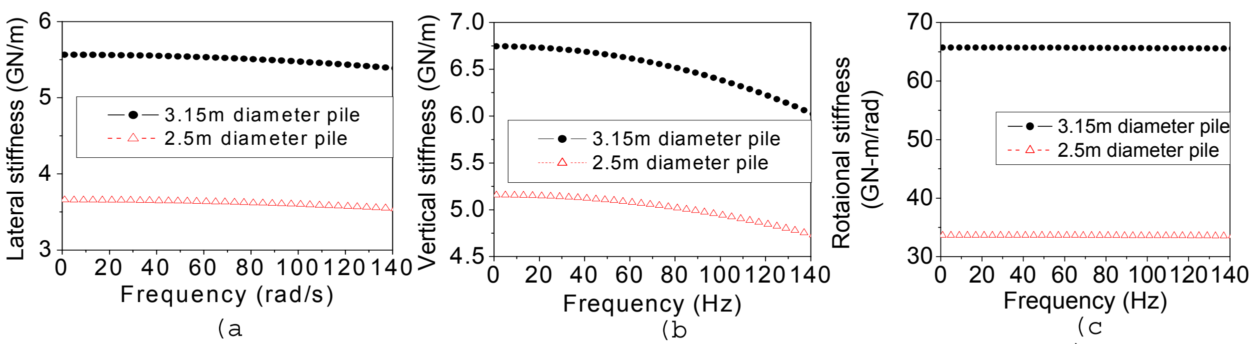


Figure 2. Stiffness of pile-head, (a) Lateral, (b) Vertical and (c) Rotational.

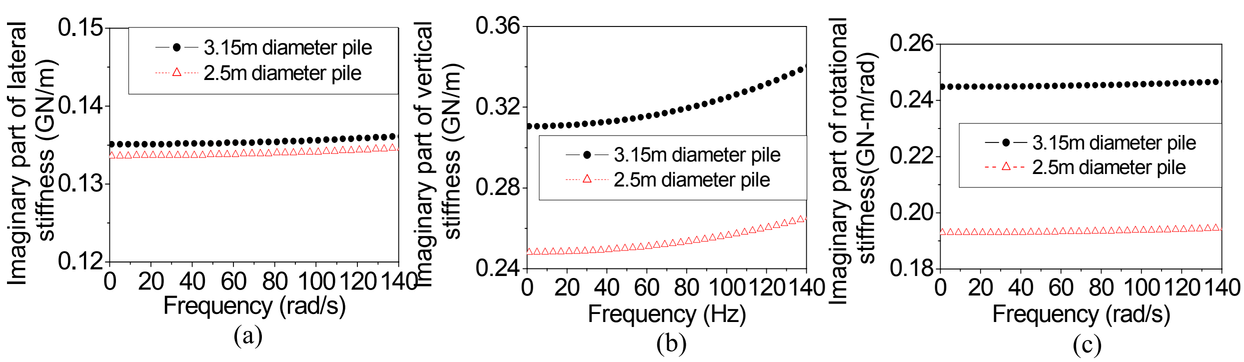
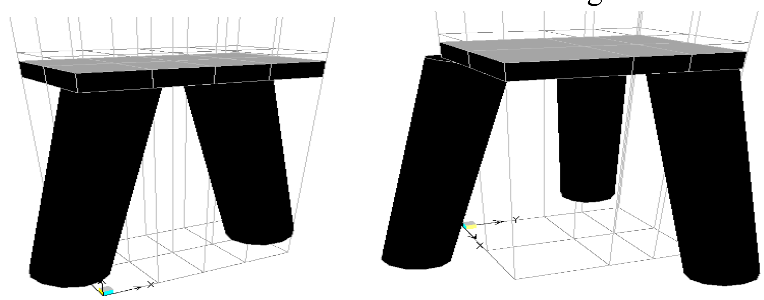


Figure 3. Imaginary part of stiffness of pile-head, (a) Lateral, (b) Vertical and (c) Rotational.

Pile cap stiffness

Each individual pile will contribute stiffness in the pile cap. Pile cap will provide stiffness to the pier. Spring supported pile cap has been modeled for analysis by the Finite Element Method considering the batter angle of the piles. Fig. 4 shows the schematic diagram of the pile cap models. The top stiffness of single pile at soil level has been assigned as the supports beneath the pile over the soil. Center to center distance between piles are 4.1 m and 6.06 m in 2 pile and 3 pile systems respectively. Pile cap properties are shown in Table 1 taking X as longitudinal direction and Y as transverse direction of the bridge.



(a) (b)

Figure 4. Pile cap models of (a) 2-Pile and (b) 3-Pile system.

Table 1. Pile cap stiffness for pier 2 and pier 5.

Pier location	Pile cap stiffness					
	K_X (GN/m)	K_Y (GN/m)	K_Z (GN/m)	K_{thetaX} (GN-m/rad)	K_{thetaY} (GN-m/rad)	K_{thetaZ} (GN-m/rad)
Pier 2	11.2	11.2	13.4	188	127	50.7
Pier 5	11.1	11.1	15.3	193	193	137

Finite Element Modeling of the Bridge

The Jamuna Multipurpose Bridge has seven 695.625 m long modules, which have identical superstructures. These modules separated by expansion joints, longitudinally free and fixed in transverse and up-down direction with respect to adjacent module. The superstructure of the second module of the bridge (from the west bank of the river) was modelled by Rahman (2008). The model starts from pier number 8 and ends at pier number 14 as shown in Fig. 5(a). Fig. 5(b) shows the pile arrangements beneath the piers. Piers containing 2 piles and 3 piles have been assigned with pile-cap properties of Pier 2 and and Pier 5 respectively. This portion is divided into six equal spans with seven piers and two extended portions. The 26.325m extended portion is directed towards the west-side and the 73.05 extended portions is directed towards the east-side. The structural behaviour of the bridge was assumed to be linear ignoring material and other nonlinearity. Only the nonlinearity of the isolators was considered. The longitudinal curvature of the bridge was considered. As per the actual condition, parabolic variations of the depth and width of the deck along its length were modelled.

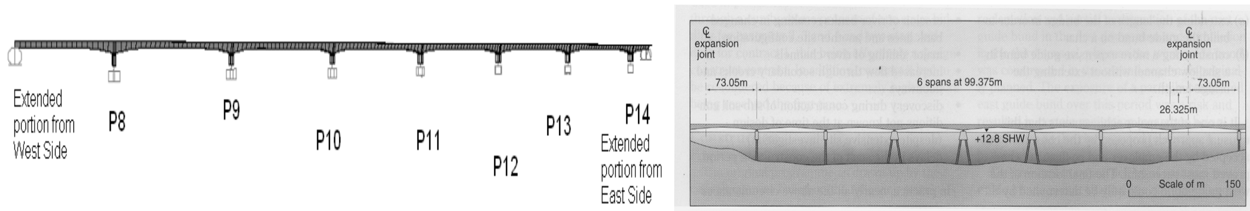


Figure 5. (a) Longitudinal profile of the model, (b) Pile arrangement.

Four different Finite Element (FE) models were developed (Rahman, 2008). Model-I does not consider prestressing in the deck. Pier system is modeled with solid elements. Hollow sections at the top of the piers are also considered. Internal diaphragm and exterior rail girder are modeled with shell elements. Model-II does not consider prestressing in the deck. Pier system is modeled with shell elements Hollow sections at the top of the piers are not considered. Internal diaphragm and exterior rail girder are modeled with shell elements. Model-III does not consider lateral prestressing in the deck. Pier system is modeled with solid element. A hollow section at the top of the piers is also modeled. Internal diaphragm and exterior rail girder are modeled with frame elements. Model-IV considers lateral prestressing in the deck. Pier system is modeled with solid element. A hollow section at the top of the piers is also modeled. Internal diaphragm and exterior rail girder are modeled with shell elements. Model-III is a simplified model, since its exterior rail girder was modelled with frame element. Model-IV is the most rigorous model among these four models.

Modal Analysis

The Modal analysis involves determination of natural frequencies and vibration modes of the structure by eigenvector or ritz-vector method. Table 2 shows the modal periods of the four FE models considering and not considering the effect of soil-structure interaction. Soil-structure interaction introduces four extra modes to the fixed supported models. All the mode shapes of the fixed supported models are present in the models considering soil-structure interaction. However, mode 3 is present in Model I and Model IV, and mode 4 is absent in Model IV. Mode 4 may be considered as a spurious mode since Model IV is the most rigorous model and Model III is the simplest one among the four models (Rahman 2008). The modal periods incorporated by soil-structure interaction in Model III is almost the half of those in other models. These modes are affected by the lateral bending stiffness of the bridge models. Use of frame elements rather than shell elements for the internal diaphragm and exterior rail girder, has made the Model III stiffer in lateral bending, inducing modes with shorter periods. Thus, incorporation of soil-structure interaction in dynamic analysis requires rigorous modeling since simplified models may change the predominant periods.

Table 2. Modal period for different bridge models considering soil structure interaction and fixed base.

Mode	Period (sec)							
	Mode I		Model II		Model III		Model IV	
	SSI	Fixed base	SSI	Fixed base	SSI	Fixed base	SSI	Fixed base
1	9.6671	-	9.7124	-	4.3773	-	9.7738	-
2	4.6673	-	4.7651	-	2.3838	-	5.003	-
3	3.8284	-	-	-	-	-	4.2783	-
4	3.2832	-	3.6142	-	2.0171	-	-	-
5	1.3595	1.3594	1.3615	1.3614	1.3871	1.3876	1.3608	1.3607
6	1.1805	1.1803	1.1814	1.1814	1.2025	1.203	1.1814	1.1814
7	0.9968	0.9963	0.9986	0.9979	1.0137	1.0131	0.9989	0.9982
8	0.8491	0.8484	0.8503	0.8497	0.8639	0.8637	0.8514	0.8508
9	0.7096	0.7088	0.7148	0.7121	0.7251	0.7234	0.7157	0.714
10	0.6077	0.6054	0.6173	0.6109	0.6277	0.6252	0.6173	0.6137
11	0.5748	0.5694	0.5816	0.5768	0.6108	0.6102	0.584	0.5795
12	0.5200	0.5174	0.5258	0.5237	0.5833	0.5806	0.5324	0.5312

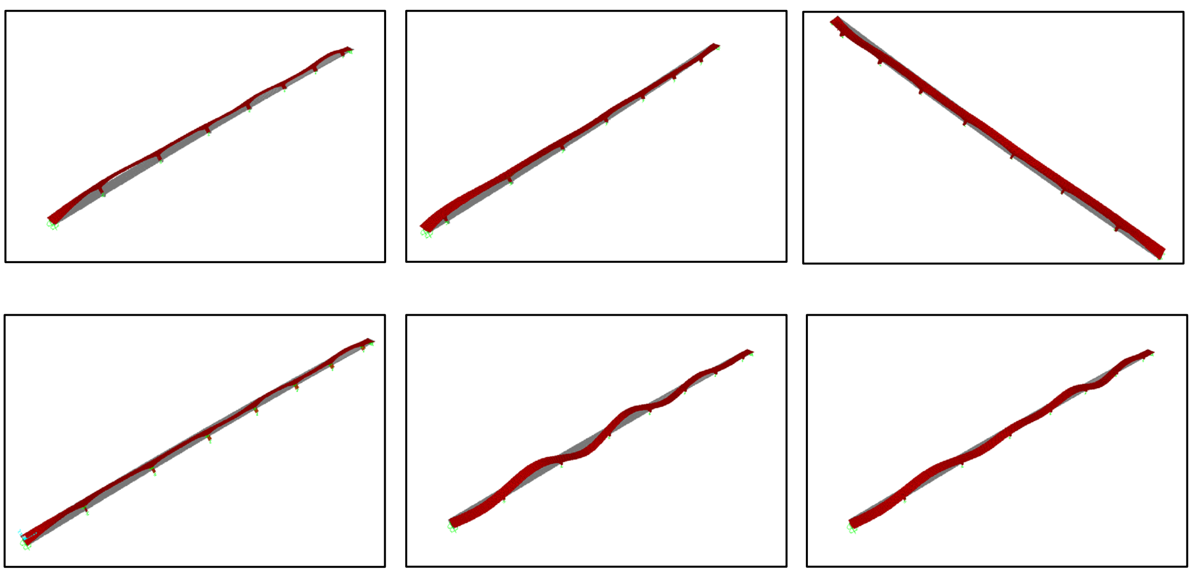


Figure 6. First six mode shapes of the Model IV of the second module of the bridge.

Instrumentation

The seven-span module next to the west-end module is instrumented with two triaxial, one biaxial, and five uniaxial accelerometers. The module was chosen because of its proximity to the most likely source of a major earthquake. Besides, two free field stations were setup to measure the ground motions on each side of the bridge.

Ground Motion of the Earthquake on 26 July 2008

Figs. 7, 8 and 9 shows the time history and Fast Fourier Transform (FFT) of the ground motion of the Mymenshigh earthquake on 26 July 2008 at the west and east ends of the Jamuna Multipupose Bridge. The epicenter of the earthquake 2008 was approximately 120 km from the bridge site with the depth of 39.3 km. Its magnitude was 4.8. The PGA of the east end ground motion is smaller than that of the west end with lower predominant frequencies. The PGA of the earthquake in the west end occurred 44 sec earlier than that of the east end.

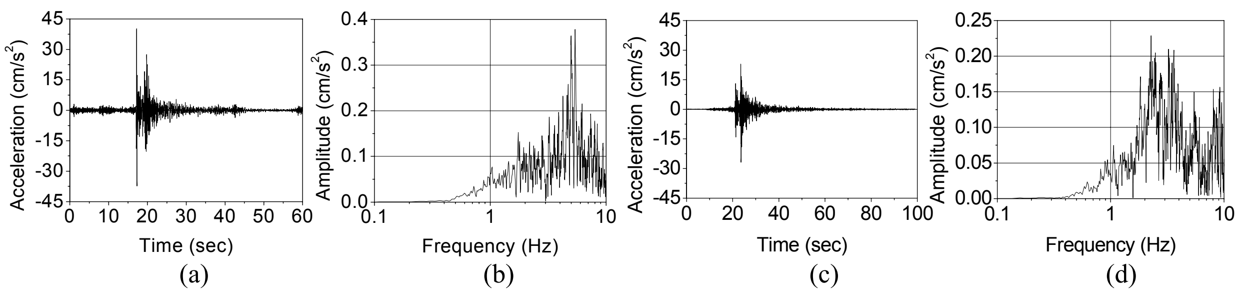


Figure 7. Ground motion along the **longitudinal direction** of the Mymensingh Earthquake 2008, *at the west end* of the bridge (a) Acceleration, (b) FFT; *at the east end* of the bridge (c) Acceleration, (d) FFT.

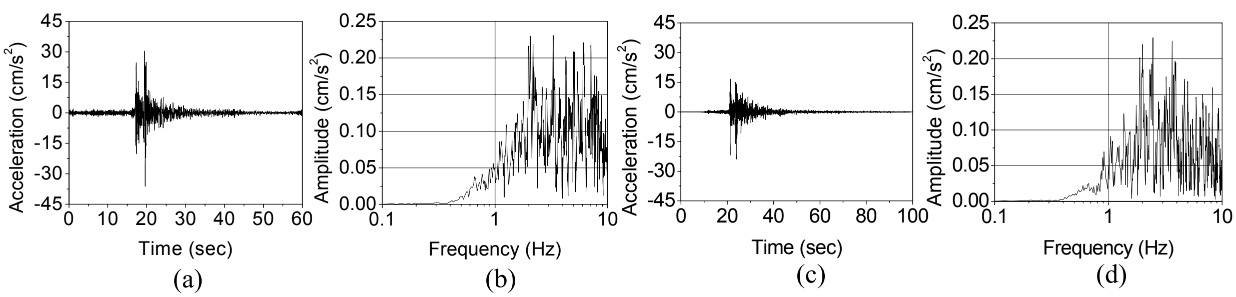


Figure 8. Ground motion along the **transverse direction** of the Mymensingh Earthquake 2008, *at the west end* of the bridge (a) Acceleration, (b) FFT; *at the east end* of the bridge (c) Acceleration, (d) FFT.

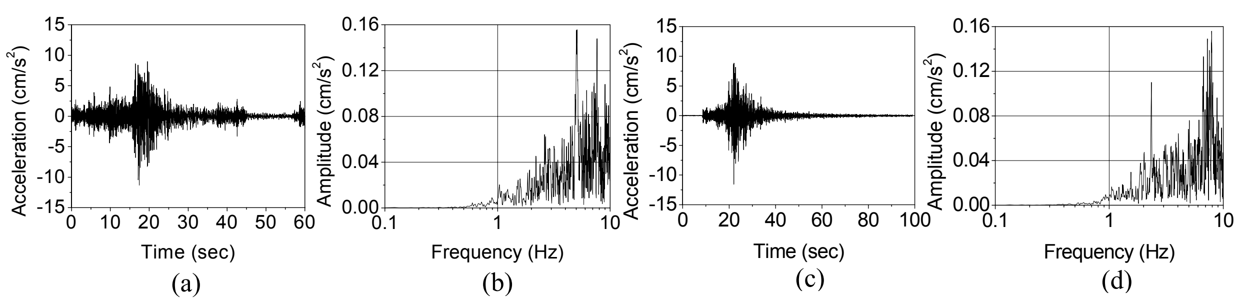


Figure 9. Ground motion along the **up-down direction** of the Mymensingh Earthquake 2008, *at the west end* of the bridge (a) Acceleration, (b) FFT; *at the east end* of the bridge (c) Acceleration, (d) FFT.

Time History Analysis

The actual deck response of the bridge at Pier 10 and the responses found from the time history analysis for the east and the west end ground motion with and without including soil-structure interaction are shown in Figs. 10 to 12. Simulated peak accelerations of the deck, for west end ground motion as input motion, are larger than that of the actual response, however, peaks of acceleration are very close to that of the actual case for the east end ground motion. Soil-structure interaction incorporates modes of lower frequencies. Therefore, effect of soil-structure interaction is not significant for this earthquake. For distant earthquakes with higher magnitude, the effect of soil-structure interaction might be significant (Kramer, 1996). The predominant frequencies of the actual responses along longitudinal, transverse and up-down directions are near 1Hz. However, time history analysis yields responses with predominant frequency near to 2 Hz for longitudinal and up-down directions; and the frequency content for transverse direction remains same as the input ground motion frequency content.

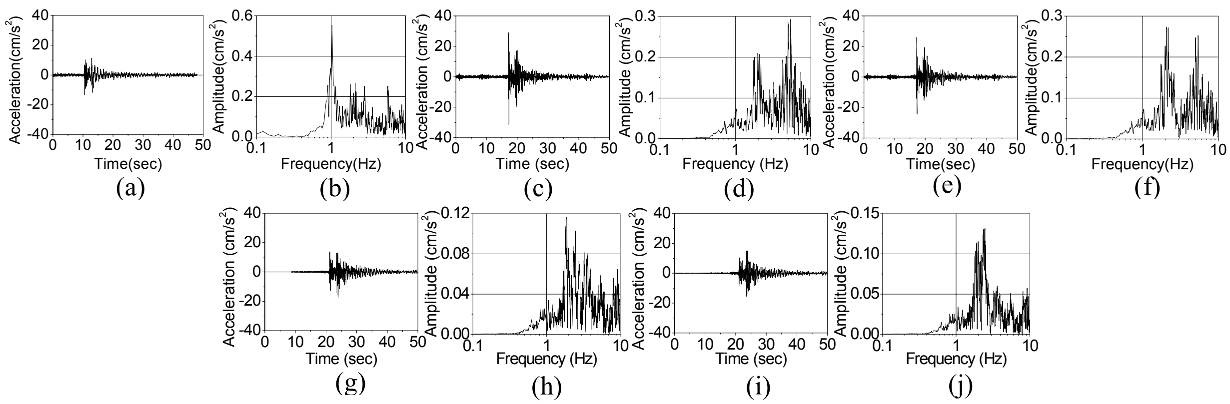


Figure 10. Bridge deck response in **longitudinal direction** at pier 10: *Recorded* (a) acceleration, (b) FFT; *Simulated* response for west end ground motion, considering SSI (c) acceleration, (d) FFT and not considering SSI (e) acceleration, (f) FFT; for east end ground motion, considering SSI (g) acceleration, (h) FFT and not considering SSI (i) acceleration, (j) FFT.

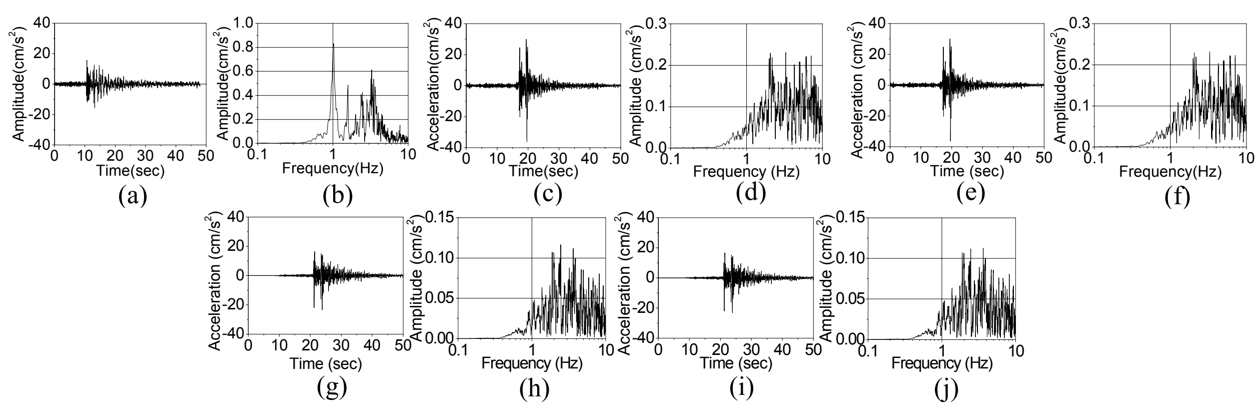


Figure 11. Bridge deck response in **transverse direction** at pier 10: *Recorded* (a) acceleration, (b) FFT; *Simulated* response for west end ground motion, considering SSI (c) acceleration, (d) FFT and not considering SSI (e) acceleration, (f) FFT; for east end ground motion, considering SSI (g) acceleration, (h) FFT and not considering SSI (i) acceleration, (j) FFT.

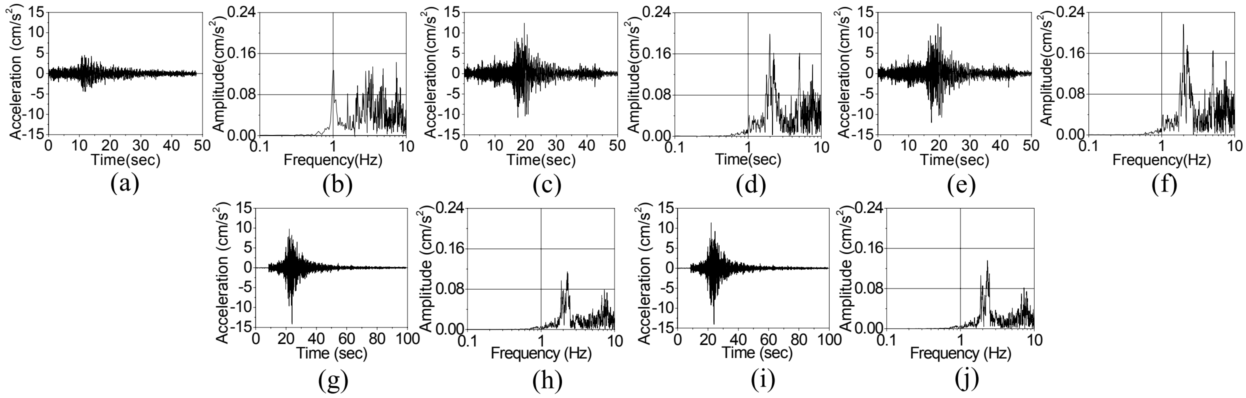
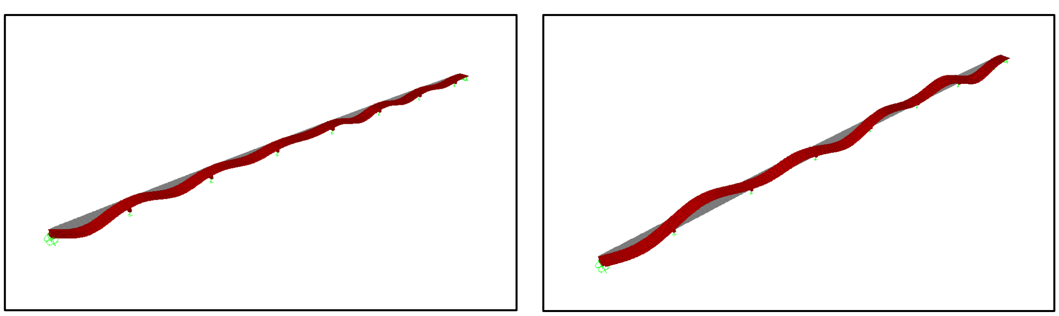


Figure 12. Bridge deck response in **up-down direction** at pier 10 due to the earthquake 2008: *Recorded* (a) acceleration, (b) FFT; *Simulated* response for west end ground motion, considering SSI (c) acceleration, (d) FFT and not considering SSI (e) acceleration, (f) FFT; for east end ground motion, considering SSI (g) Acceleration, (h) FFT and not considering SSI (i) Acceleration, (j) FFT.

Discussion on Results

The peak acceleration of the response of the FEM has been found higher than the actual response for the input of the west end ground motion, on the other hand it has been found very close for the input of the ground motion recorded in the east end of the bridge. The actual ground motion at Pier 10 is in between the west end and east end ground motion, which is not known due to lack of sensors. The ground motion excitation does not occur at the same time in the east and west ends of the Jamuna Bridge. However, in the time history analysis the input motion is simultaneous along the whole structure, causing the movement of bridge structure like that of Fig. 13(a), which is the Mode shape 11 found in the modal analysis. Here all the panels sag at a time. The corresponding frequency of Mode shape 11 is 1.7 Hz, which is close to the predominant frequency of the simulated responses. Piers begin to move sequentially in the actual case, as the ground excitation propagates from one end to another end of the bridge. Therefore, sag and crest occurs in alternate spans of the superstructure, as shown in Fig. 13(b), which is in fact the shape of mode 7 with the modal frequency is of 1.0 sec. Mode 5 to 8 shows similar type of deformation having frequencies in between 0.735 Hz and 1.174 Hz.



(a) (b)

Figure 13. (a) 3D view of mode shape 11, (b) 3D view of mode shape 7.

The actual response of bridge excites these mode shapes causing a predominant frequency around 1 Hz. Since the modal amplitudes of these frequencies are less compared to that of 2 Hz., the recorded PGA is less than the simulated one. Thus, consideration of non-simultaneous loading along with rigorous modeling of super-structure and support condition is important for proper simulation of seismic response of a bridge.

Conclusions

In this study, dynamic analyses have been performed with a sophisticated finite element model of the second module of the Jamuna Multipurpose Bridge considering soil- structure interaction. Damping of the huge steel piles has been found negligible compared to the stiffness. Soil-structure interaction introduces modes with long periods, which are vulnerable to distant earthquakes with high magnitude. Time history analyses have been conducted for the ground motions of the earthquake of 26 July 2008, and the responses have been compared with the actual response of the bridge deck at Pier 10. In this study, it has been assumed that ground motion at all piers of the bridge module is the same. However, in actual condition ground motion varies along the length of the bridge. Thus simulated response deviated from the actual response both in magnitude and frequency. Consideration of non-simultaneous and attenuated input ground motion at piers is important for simulation of seismic behavior of a bridge.

References

Bolt, B. A., "Site Specific Seismicity Study of Seismic Intensity and Ground Motion Parameter for Proposed Jamuna Bridge, Bangladesh," Report of Jamuna Multipurpose Bridge Authority, 1987.

Bowles, J. E. " Foundation Analysis And Design (5th edition)", McGraw-Hill, 1996.

BUET, "Invitation for Proposals for Supply and Installation of Seismic Instruments for Bangabandhu (Jamuna Multipurpose) Bridg," Report of Jamuna Multipurpose Bridge Authority, 2001.

BUET, "Final Report: Installation Phase, Jamuna Multipurpose Bridge Seismic Instrumentation Projec," Report of Jamuna Multipurpose Bridge Authority, 2003.

Kramer, S. L., " Geotechnical Earthquake Engineering", Prentice-Hall, Inc, 1996.

Rahman, A. Z. M. M. "Study on dynamic parameters of the Jamuna Multipurpose Bridge" M.Sc.thesis, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka, 2008.

Tajimi H. and Shimomura Y., "Dynamic analysis of soil-structure interaction by the thin layered element method", Transactions of Architecture Institute of Japan (1976), 243, 51, 1976.

Tamura, I. And F. Yamazaki, Estimation of S-wave velocity based on geological survey data for K-NET and Yokohama seismometer network. Journal of Structural Mechanics and Earthquake Engineering No. 696, Vol. I-58, 237-248, 2002.