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Dynamic behaviour of the Jamuna Multi-purpose bridge considering different scour depth

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ABSTRACT: System identification of structures depends on the accuracy of modeling both the superstructure and the substructure. For bridge structures, scour depth of riverbed is an important factor that may influence the identified parameters while comparing with the recorded data. In this paper, the effect of scour depth on dynamic behavior of the Jamuna Multipurpose Bridge, the longest bridge in Bangladesh, is studied. The effect of scour depth on the substructure dynamic stiffness is analyzed. Complex stiffness of the underlying batter piles is determined considering the semi-infinite extent of layered soil profile of the riverbed. A three-dimensional finite element model of the super-structure on one module of the bridge has been developed considering all critical parameters of the bridge. The variation of modal periods and response of the bridge to a 2008 earthquake record is studied for different scour depth. Almost linear increase of first three modes is observed with the increase of scour depth. Peak accelerations of the responses in the longitudinal and vertical directions to the 2008 earthquake are reduced due to increase in scour depth.

1 INTRODUCTION

Dynamic response during earthquake is a very important factor for both the serviceability and safety of bridge structures. The Jamuna Multi-Purpose 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**.** A sophisticated model of the Jamuna Bridge has been developed using the finite element method (Rahman, 2008). The riverbed level of the Jamuna varies throughout the length of the bridge and the top of pile-cap level is the same. Moreover, there are seasonal changes in riverbed profile. Therefore, the scour depths at different pier locations are different. The objectives of the present study are to include the effect of scour depth of river in the finite element model and to examine the modal parameters.

2 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 two end spans of about 64.687 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 approach road 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.

3 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, 1996) 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. Figure 1 shows that shear wave velocity profiles at different pier locations do not vary significantly.

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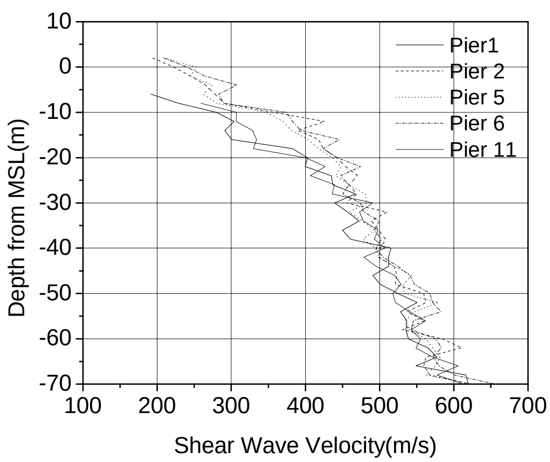


Figure 1. Shear wave velocity and pile thickness data under different piers.

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. Piles of the second module of the bridge have been considered in the study, where soil level is over the pile-cap bottom level. However, to study the effect of scour depth the soil level has been assumed to exist at different depths.

4 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 considering zero scour depth, shown in Figures 2 and 3, have been calculated by the TLEM. The damping has been found to be relatively small. Since, the change of stiffness with frequency is small, static stiffness of pile head can be used for further analyses. The static stiffness of piles at different scour level are given in Tables 1 and 2.

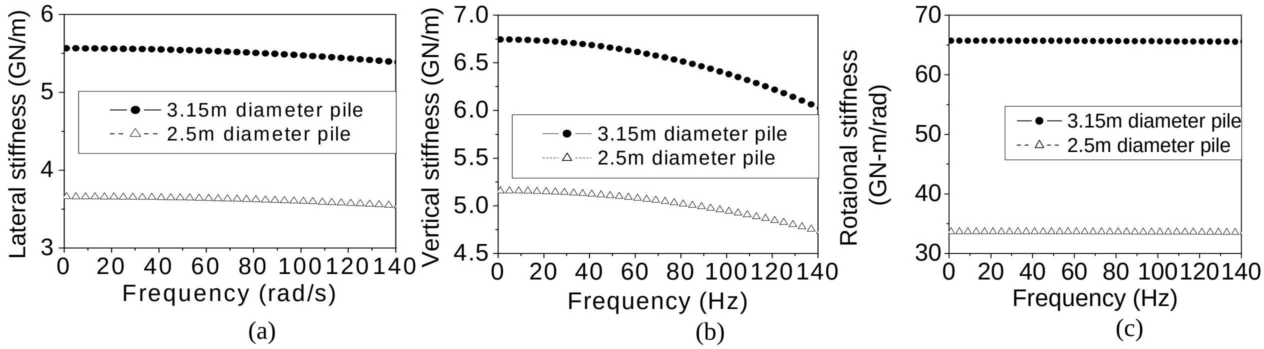


Figure 2. Stiffness of pile-head, (a) lateral, (b) vertical and (c) rotational.

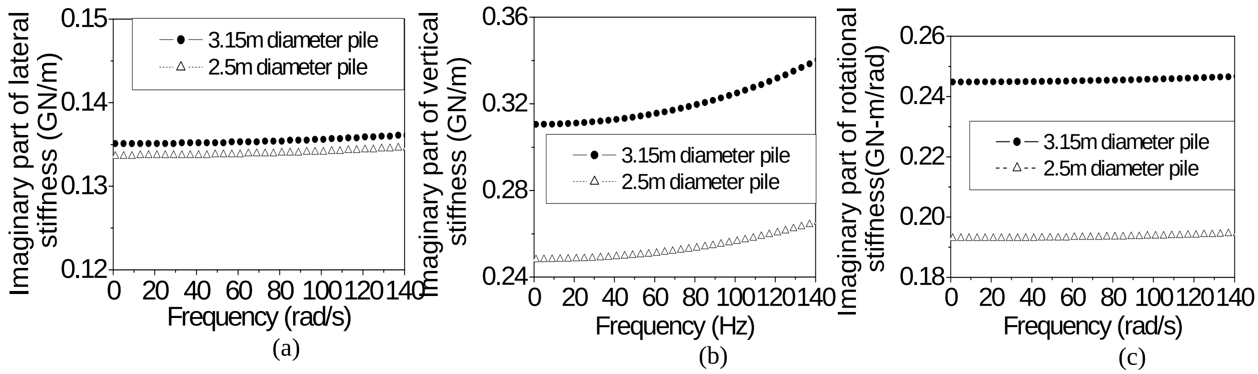


Figure 3. Imaginary part of stiffness of pile-head, (a) lateral, (b) vertical and (c) rotational.

Table 1. Properties of pile-head for 3.15 m diameter single pile.

	Stiffness and damping of a 3.15 m diameter pile-head					
Scour depth	Lateral stiffness (N/m)	Rotational stiffness (N-m/rad)	Vertical stiffness (N/m)	Lateral damping (N-s/m)	Rotational damping (N-m-s/rad)	Vertical Damping (N-s/m)
0 m	5.56e+09	6.57e+10	6.75e+09	6331	11057	173333
3 m	6.86e+09	6.69e+10	6.72e+09	3736	3866	169827
6 m	5.47e+09	6.52e+10	6.75e+09	6674	12424	173333
9 m	6.85e+09	6.43e+10	7.30e+09	4861	5234	161075
12 m	6.21e+09	6.22e+10	7.71e+09	9620	16172	157181
15 m	7.47e+09	6.33e+10	7.77e+09	6320	6814	154016

Table 2. Properties of pile-head for 2.5 m diameter single pile.

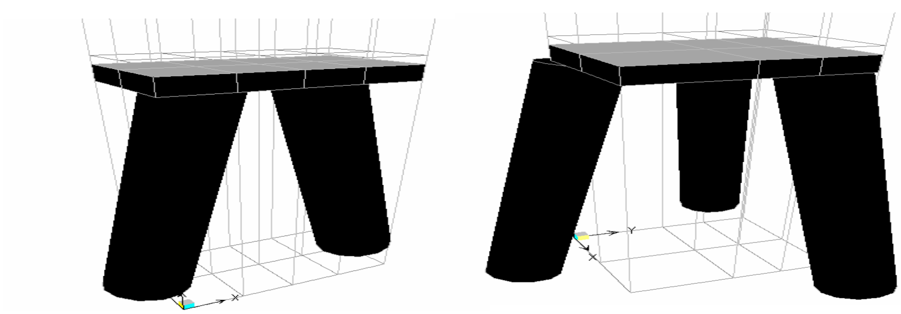
	Stiffness and damping of a 2.5 m diameter pile-head at pier 5					
Scour depth	Lateral stiffness (N/m)	Rotational stiffness (N-m/rad)	Vertical stiffness (N/m)	Lateral damping (N-s/m)	Rotational damping (N-m-s/rad)	Vertical Damping (N-s/m)
0 m	3.66e+09	3.37e+10	5.16e+09	5869	9640	101311
3 m	4.23e+09	3.36e+10	5.00e+09	3356	3308	97218
6 m	3.38e+09	3.31e+10	5.21e+09	5428	10035	92817
9 m	4.12e+09	3.20e+10	5.35e+09	3676	3975	90538
12 m	3.83e+09	3.12e+10	5.69e+09	6790	11239	88926
15 m	4.56e+09	3.11e+10	5.79e+09	5869	9640	101311

5 PILE CAP STIFFNESS

To determine pile cap properties from single pile properties at different scour levels, finite element models have been developed considering the batter angle of the piles. These models consist of a pile cap of very high stiffness, which has been connected to the free lengths of piles over the soil bed. The pile-head to pile-cap joint has been considered to be fixed. The piles are supported by the spring equivalent to the portion of pile embedded in the soil. 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 3 and 4, taking x as longitudinal direction and y as transverse direction of the bridge.

Table 3. Uncoupled stiffness components of pile-cap containing 2-3.15 m diameter piles.

Scour depth	Pier 2 pile cap stiffness					
	K_x (N/m)	K_y (N/m)	K_z (N/m)	K_{thetax} (N-m/rad)	K_{thetay} (N-m/rad)	K_{thetaz} (N-m/rad)
0 m	1.12e+10	1.12e+10	1.34e+10	1.88e+11	1.27e+11	5.07e+10
3 m	6.33e+09	6.49e+09	1.13e+10	1.40e+11	8.06e+10	3.87e+10
6 m	2.93e+09	3.15e+09	9.80e+09	1.25e+11	7.40e+10	2.25e+10
9 m	1.62e+09	1.85e+09	9.10e+09	1.16e+11	6.94e+10	1.51e+10
12 m	9.01e+08	1.13e+09	8.36e+09	1.03e+11	6.11e+10	1.01e+10
15 m	5.55e+08	7.73e+08	7.55e+09	9.10e+10	5.42e+10	7.36e+09



(a) (b)

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

Table 4: Uncoupled stiffness components of pile-cap containing 3-2.5 m diameter piles.

Scour depth	Pier 5 pile cap stiffness					
	K_x (N/m)	K_y (N/m)	K_z (N/m)	K_{thetax} (N-m/rad)	K_{thetay} (N-m/rad)	K_{thetaz} (N-m/rad)
0 m	1.11e+10	1.11e+10	1.53e+10	1.93e+11	1.93e+11	1.37e+11
3 m	5.86e+09	5.86e+09	1.23e+10	1.43e+11	1.43e+11	8.64e+10
6 m	2.58e+09	2.58e+09	1.09e+10	1.27e+11	1.27e+11	4.26e+10
9 m	1.36e+09	1.36e+09	9.61e+09	1.12e+11	1.12e+11	2.45e+10
12 m	7.84e+08	7.84e+08	8.79e+09	9.88e+10	9.88e+10	1.48e+10
15 m	5.06e+08	5.06e+08	7.93e+09	8.72e+10	8.72e+10	9.82e+09

6 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 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.

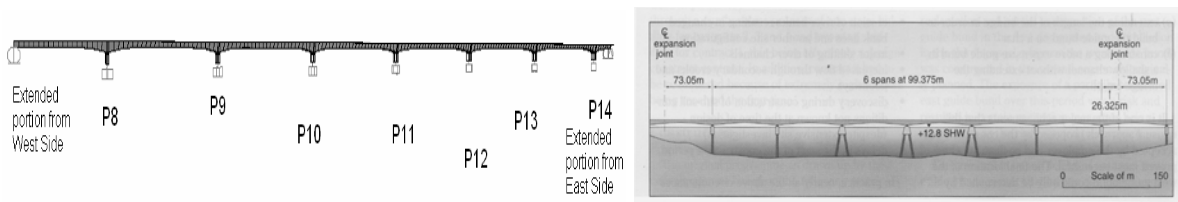


Figure 5. (a) longitudinal profile of the model, (b) pile arrangement.

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.

7 MODAL ANALYSIS CONSIDERING DIFFERENT SCOUR DEPTH

A considerable change of stiffness of pile has been observed due to the scouring of the river bed, which causes change of the overall change in the stiffness of the pile cap. The support conditions of the FEM have been modified for different scouring depths and modal analysis of the FEM models of the Jamuna Multipurpose Bridge has been performed. Figure 6 shows the modal periods corresponding to different scour depths of the Model-IV of the Jamuna Multipurpose Bridge. The modal periods corresponding to the modes related to SSI (Mode 1 to 3) have been increased with the increase of scour depth. In contrast, the other modal periods do not vary with the change of scour depth. The period of Mode 1 changes most significantly, from 9.77 sec for zero scour depth to 14.65 sec for 15 m scour depth. The period increases almost linearly from 3 meter to 15 meter scour depth, however the slope is little more steeper for 0 meter to 3 meter scour depth. In case of Mode 2 and Mode 3 the increase of period is lesser than that of Mode 1. It is 5.003 sec to 6.878 sec for Mode 2 and 4.278 sec to 5.895 sec for Mode 3 at the range of 0 meter to 15 meter scour depth of pile.

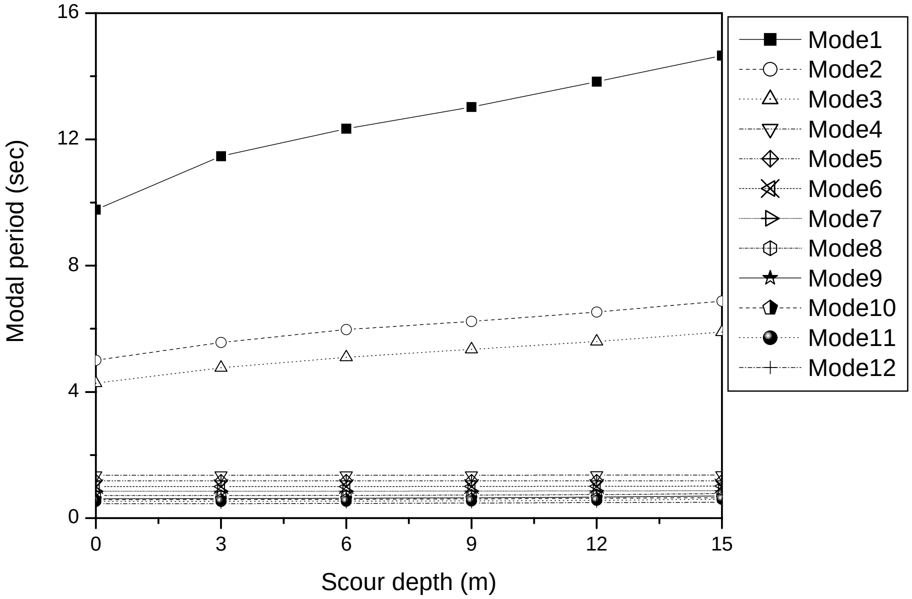


Figure 6. Change of modal periods with scour depths for the model IV.

8 GROUND MOTION OF THE EARTHQUAKE ON 26TH JULY 2008

Figs. 7, 8 and 9 shows the time history and Fast Fourier Transform (FFT) of the ground motion of the Mymenshingh earthquake on 26 July 2008 at the west and east ends of the Jamuna Multipurpose 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.

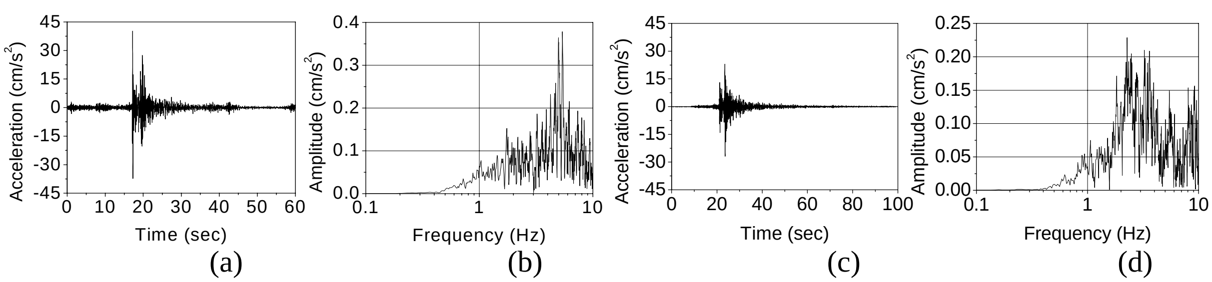


Figure 7. Ground motion along the longitudinal direction of the Mymensingh earthquake 2008, *at the west end* of the bridge (a) acceleration, (b) FFT; *at the east end* of the bridge (c) acceleration, (d) FFT.

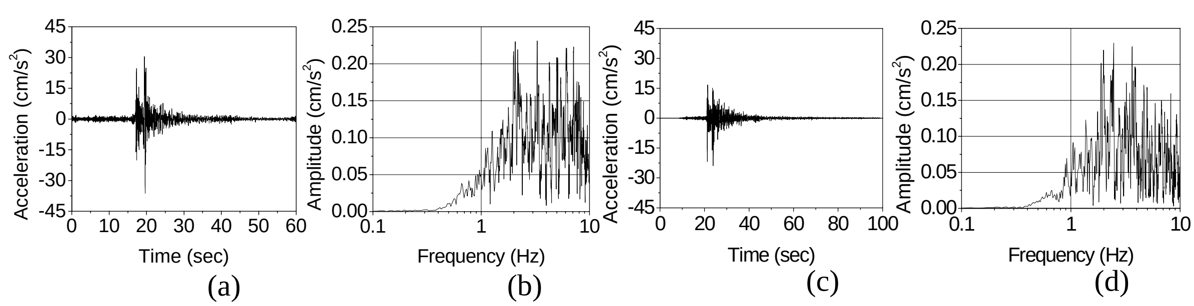


Figure 8. Ground motion along the transverse direction of the Mymensingh earthquake 2008, *at the west end* of the bridge (a) acceleration, (b) FFT; *at the east end* of the bridge (c) acceleration, (d) FFT.

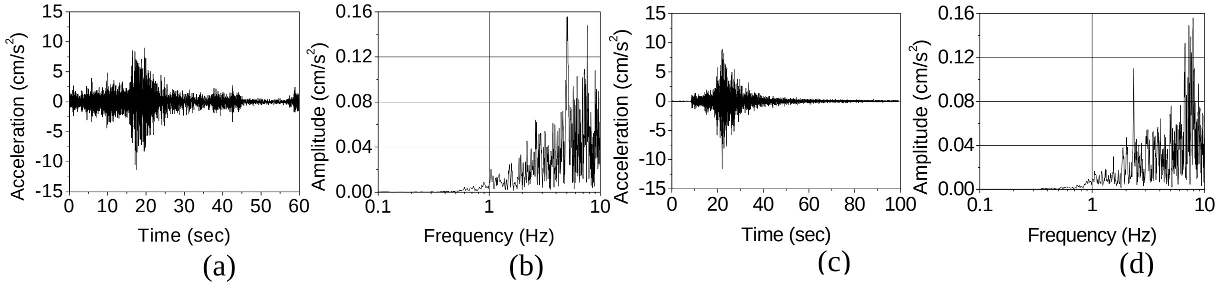


Figure 9. Ground motion along the up-down direction of the Mymensingh earthquake 2008, *at the west end* of the bridge (a) acceleration, (b) FFT; *at the east end* of the bridge (c) acceleration, (d) FFT.

9 TIME HISTORY ANALYSIS

Responses of the finite element model of the Jamuna Multipurpose Bridge have been determined for the earthquake of 2008 considering different scour depths using time history analysis. Table 5 shows the peak accelerations at deck of the FEM found from time history analyses. The peak gets reduced with the increase of the scour depth in the east-west direction (longitudinal direction of the bridge. However, peak acceleration at deck has found constant for all scour levels along transverse direction and a little change has been observed in the peaks along up-down direction; changes of stiffness of supports do not have any effect in the response along transverse direction in this finite element model.

Table 5. The effect of scour depth on the response of deck of FEM of the Jamuna Multipurpose Bridge to the west end ground motion of the earthquake 2008.

Peak acceleration responses (cm/s^2) for different scour depths for earthquake 2008						
Scour depth	0 m	3 m	6 m	9 m	12 m	15 m
EW	31.09	30.06	27.47	24.05	20	18.44
NS	35.75	35.75	35.75	35.75	35.75	35.77
UD	13.19	13.06	12.87	12.92	12.81	11.7

10 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 different scour depth. 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. Significant increase in the modal periods corresponding to soil-structure interaction has been observed due to increase in scour depth. Peaks of acceleration of the responses in longitudinal and vertical direction are reduced due to increase in scour depth.

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