

Numerical investigation of a counter measure to control local scour around a bridge pier: A new source of bridge vibration

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ABSTRACT: Bridge scour causes wearing away of the earth around and underneath the bridge piers or abutments by the water-flow. A reliable prediction of local scour depth for the designed life time of a bridge still remains a big challenge to the practicing engineers. When the local scour around the bridge pier exceeds the design scour depth, the unsupported free length of the bridge pier may exceed the allowable free length. This has the potential to reduce confinement around the foundation system below the streambed level. As a result, even the operational traffic loads may cause the bridge to vibrate. The vibration, so generated, may significantly reduce the traffic thoroughfare. A minor and localized vibration resulting from the local scour may also lead to bridge catastrophe due to resonance from secondary factors. This study was carried out in July 2012 when the bridge over the Meghna river in Bangladesh was suffering from excessive vibration only under traffic load. In this paper, a counter measure to provide underwater confinement using sand and sand-filled geobags is conceived to control the bridge vibration by regaining the confinement around the piers. An extensive numerical investigation with possible parametric variations was carried out to investigate the effectiveness of the proposed counter measure. In this respect, the numerical model was developed using a finite element method based advanced geotechnical software. The numerical data presenting the lateral support was theoretically achieved around the group of piers that lost confinement due to scour. The present study outcome provides an approach to the bridge designers while designing the counter measure not only at the design stage but also at the vibration mitigation stage of an in-service bridge.

1 INTRODUCTION

Local scour causes wearing away the earth around and underneath the bridge piers or abutments by the water-flow. As a result, the confinement around the pier is reduced putting the whole bridge into risk. Bridge scour is considered to be one of the major causes of highway bridge failures, as it significantly affects the integrity of the structure (Murillo, 1987). To overcome such risks, the embedded pier length is designed either with or without scour protection condition. The embedded pier design length is greater in case of without-scour protection than that of with-scour protection. Prediction of local scour depth in design, however, still remains a big challenge to the practicing engineers. In literature, several prediction methods (mostly empirical and semi-empirical) are available for estimating local scour depth. However, the application of those formulae is limited to some extent of hydraulic and geometric condition that is often exceeded by the variability of natural rivers, particularly for Bangladesh, a deltaic land covered by recent geological deposits from the Ganges, the Brahmaputra, and the Meghna (Alam et al. 1990). Sobhan and Amin (2010) mentions about this river system that generally carries excessive monsoon sediment-laden discharge and very little dry season flow. The ratio of the maximum and the minimum discharges of the Bangladesh Rivers are high; generally greater than 10. The year round excessive variation of flows charged with excessive sediment load beyond the river's dominant transportation capacity, generates unstable geomorphology of the river. One of the major approaches to mitigate the situation is to lower the number of pier obstructions in the river by increasing the bridge span length. Wider spans are also required for navigational clearance. However, to increase the bridge

span, the designer needs to reduce the number of pile caps supporting the piers. This, on other turn, usually increases the foundation size due to increased capacity requirement for longer spans. However, increased foundation size at flow level finally yields foundations to be more exposed to the threat of local scours. The design enters into a vicious cycle leaving a narrow band of solution for the designer to decide about the bridge span and foundation size.

In the past, most of the large rail bridges (including the Hardinge bridge) constructed before 1947 used caisson foundations. Hardinge Bridge boasts to have 20 m x 11 m size and 48 m deep caissons to achieve the 105 m span (Gales 1918). The east-west electricity transmission interconnection, also known as Jamuna River 230 kV Crossing (Hinch et al. 1984, Chandler et al. 1984), was the deepest river bed caisson in the world, when constructed. To alleviate the situation, UK-Bangladesh Friendship Bridge and Dapdapia Bridge (Project Builders Limited 2010) opted to lower the pile cap at the river bed to reduce the design scour depth. Bangabandhu Jamuna Bridge (Hyundai 1997) constructed in 1998 and the under-construction Padma Bridge (Sham 2015) are designed to rest on groups of battered deep steel piles to reduce the pile cap size at flow level to achieve 100 m and 150 m river spans, respectively. The piles of these bridges are about 70 m and 120 m deep, respectively to ensure the bridge safety against local scour. Nevertheless, construction of large diameter battered steel piles to such depths evolves as a great construction challenge to overcome. Therefore, an optimized design together with the available construction technique is important to solve this vital design issue. Nevertheless, a large number of parameters governing the design local scour depth for a particular site require the designers to remain equipped with different design options to mitigate the local scour not only at the design stage but also during the service life of a bridge.

To this end, the numerical study reported in this paper was undertaken when significant vibration was experienced in the Meghna Bridge, Bangladesh (also known as the Japan-Bangladesh Friendship Bridge-I) in July 2012. The local scour exposed the pile below the streambed level and the affected piers were suffering from the loss of essential confinement. Due to local scour, the unsupported free length of the bridge pier increased largely and only the traffic loads was enough to contribute additional vibration in the bridge (Choudhury et al. 2015). The increased free length of piers due to large local scours, particularly around Piers 7 and 8 together with non-functional hinges, caused excessive vibrations that reduced the throughput of this most important national corridor. The vibration of that bridge was noted not to show any relevance to wind, cable or seismic vibration. The observed scour around the bridge piers did not exceed the design scour depth. However, the vibration was getting enhanced with traffic load. This paper identifies the local scour as source contributing to bridge vibration and proposes a counter measure. A parametric study using finite element method was conducted to investigate the influence of different factors on the effectiveness of the proposed measure.

2 PAST SCOUR EVENTS IN THE MEGHNA BRIDGE

The Meghna Bridge (Figures 1 and 2) is a prestressed concrete balanced cantilever bridge with a central hinge at each of the mid-spans. The bridge is founded on groups of 1.5 m to 2.0 m diameter cast-in-situ concrete piles for achieving 87 m span (PCI and Nippon Koei 1986). The 100 year scour depth was calculated based on the design condition that piers shall have to be protected using pitched rocks to prevent local scours around the pile caps. Such an approach allows considering lower design scour depth but requires periodic monitoring to ensure the design conditions are effectively met during its service life. However, during the construction of the bridge, it experienced a very large flood of Bangladesh history. This required further attention in preventing local scour at Piers 6-8 (JICA 1990; Hoque et al. 2004). Periodic maintenance for local scour was also conducted in 2005 by rock pitching. However, further unattended scour together with non-functional central hinges caused substantial worries and warranted to initiate emergency measures in July 2012 to protect the N1 National Highway, the lifeline of the country connecting Dhaka, the capital and Chittagong, the major port city (see also Choudhury et al. 2015), when the study reported in this paper was undertaken.

3 SOURCE OF VIBRATION AND THE PROPOSED COUNTER MEASURE

All the bridges (like the one across the Meghna) that was vibrating under traffic load only, required immediate measures to reduce the vibration to safe level. In order to propose a counter measure in minimizing the bridge vibration, the source/cause of vibration needs to be identified. A sophisticated field exploration program employing vibration sensors at different locations of the bridge in a few combinations was carried out. The vibration monitoring system recorded the maximum vibration of the bridge near the Pier 8 (Figure 3, see also Choudhury et al. 2015).

Extensive bathymetric survey conducted at the river-bed level identified scoured zones around Piers 7, 8 and 9. The maximum observed scouring was about 7 m deep and took place around Pier 8 (Figure 3) where a hard strata was seen to be missing in the geological formation. Due to the significant scouring of the river-bed level, the unsupported length of the Pier 8 increased significantly. In the literature, 15 m of the unsupported length is marked as a crucial point, where the lateral resistance is difficult to achieve (Ferrito 1997). Yet, the 7 m scour depth as recorded for the Meghna Bridge also showed significance with respect to contributing vibrations indicating the loss of confinement around the piers resulting increased effective unsupported lengths in the affected piers.

Based on the above field observations, a two-step counter measure was conceived, as illustrated in Figure 4. In Step I, the scoured zone has to be filled with a suitable gradation of sand. Further, in Step II, the sand filled zone surrounding the pile cap up to a certain radial distance (H_x) has to be put under surcharge pressure not only to generate a confining pressure around the pile group but also to protect from future scouring by dumping sand-filled geobags of up to a certain height. Of course, the applied surcharge pressure has to be such that it overcomes the hydrostatic head to ensure generation of adequate effective stress at the design level. Unless this is ensured, the whole protection system is likely to wash away due to inadequate shear strength of the silty-sand type of soil at the scour level.



Figure 1. A general view of the Meghna Bridge



Figure 2. Meghna Bridge showing central hinge at the mid-span between Pier 9 and Pier 8 (marked in red)

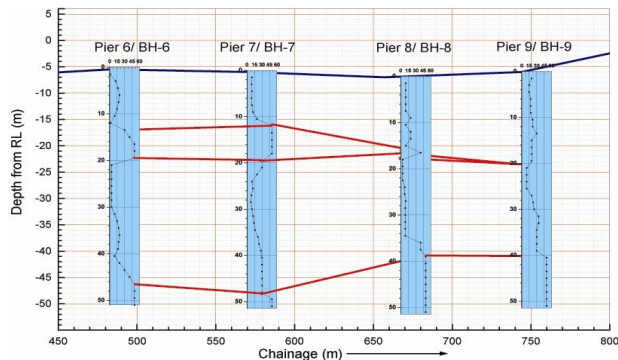
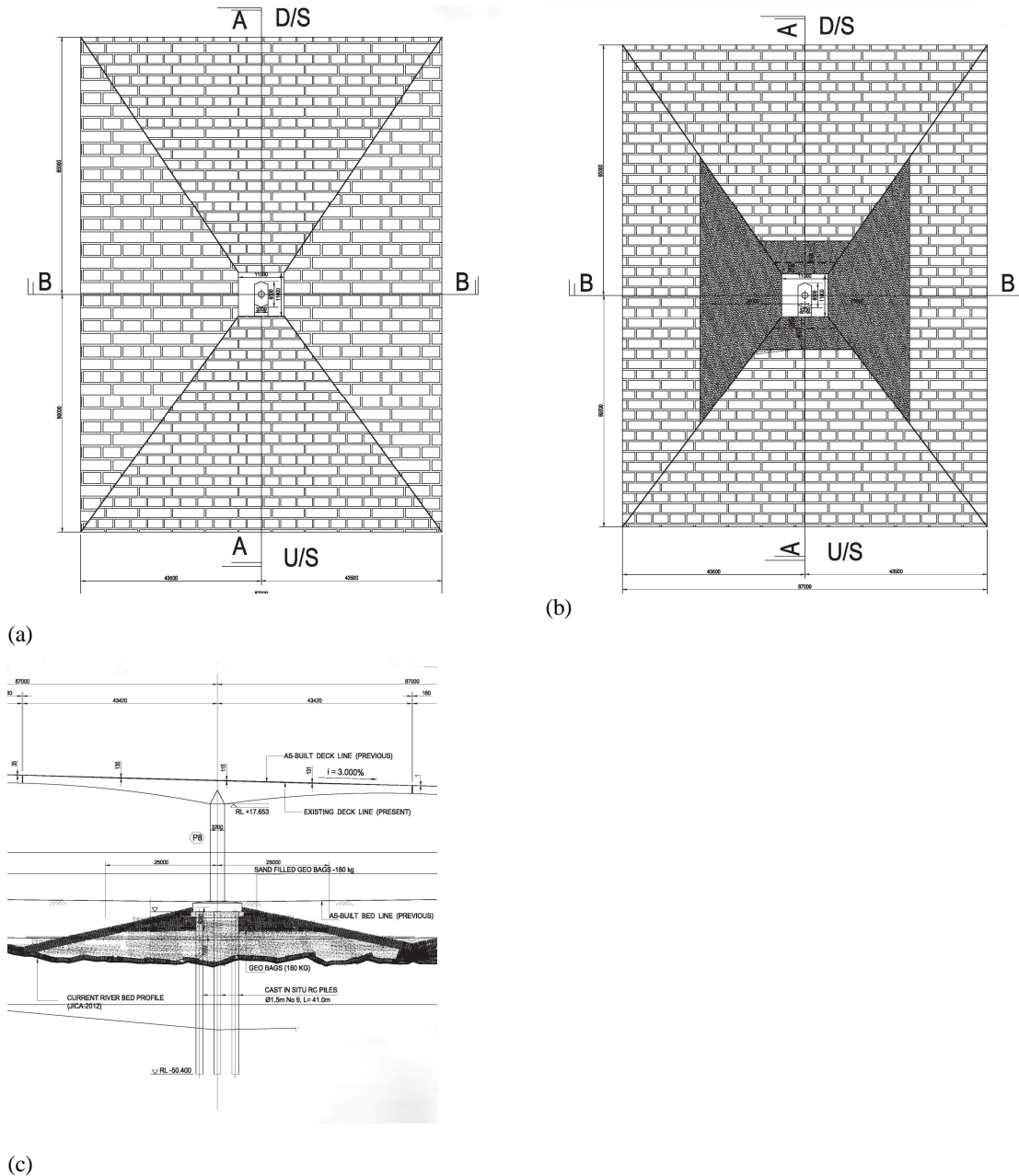


Figure 3. Soil Profile near the Bridge Pier-8 in Meghna river. The red lines shows a missing hard strata between Piers 7 and 9.

4 NUMERICAL MODELLING

Numerical investigation is required to optimize the proposed control measure, as the radial distance (H_x) of the protected zone and the height of the geo-bag layer imposing a surcharge load over the scour prone zone cannot be obtained otherwise. In this context, an axisymmetric finite element model is developed in “PLAXIS”, (2D version 8.6) platform to study the lateral confinement attained after implementing the proposed measure. The centerline of the mesh coincides with the centre of the soil column enclosed by the piles arranged in a group. The outer vertical boundary of the mesh was placed at 50 times the horizontal dimension of the soil column from the centre line. The horizontal boundary is placed at 1.7 times the pile length from the ground surface. The vertical boundaries were restrained in the horizontal direction, but free to

move in the vertical direction. The bottom of the mesh is restrained in both the horizontal and the vertical directions. The 15 nodes triangular element, giving a fourth order interpolation for displacements, is used for both the soil and the pile clusters. Five-node line elements are used at the pile (outermost one)-soil interface (i.e., the interface between soil column and the surrounding to account for the relative pile-soil movement (Noor et al. 2013).



(b)

(a)

(c)

Figure 4. Counter measure scheme using granular confinement with surcharge pressure from geobags. (a) Plan view at top, (b) Plan view at bottom, (c) Elevation.

In simulating the proposed counter measure (as shown in Figure 4), the computation was performed in two steps (Steps I and II) after generating the initial soil condition. Initial soil condition is generated by giving input to the respective soil material properties to all clusters according to their initial states. Initial soil effective stresses and pore-water pressures were generated from the input of coefficient of earth pressure at rest (K_0) and the given phreatic level, respectively. Step I is for the filling the scoured zone, and Step II is for the application of surcharge at the river-bed level surrounding the piers. After numerical computation, the effective normal stress distribution and the lateral confinement, F_H (Figure 6) gathered from computation

around the outer periphery (5.5 m from the centerline) of the group piers with 7 m fill are studied in each of the cases.

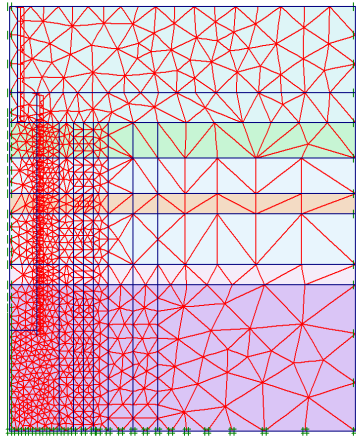


Figure 5. Generated Mesh (Axi-symmetric Model)

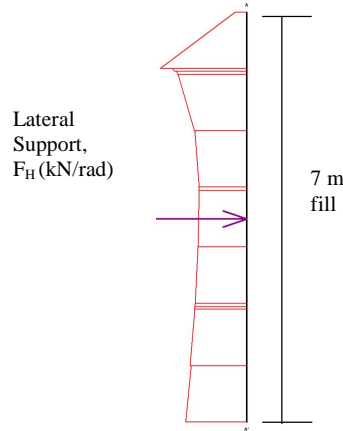


Figure 6. A typical effective normal stress distribution along the outer pile interface (at 5.5 m from the centre of the pile group) with 7 m fill.

5 RESULTS FROM NUMERICAL ANALYSIS

The effects of different parameters, including the properties of fill material, dimensions of the scour-protection zone around the piers and the surcharge load (imposed by the height of the geo-bag layer), are examined on the lateral support attained at the top 7 m of the piers after taking the proposed control measures. Seasonal variations in water level in the Meghna river are also considered. Table 1 presents the list of parameters studied using the numerical model developed.

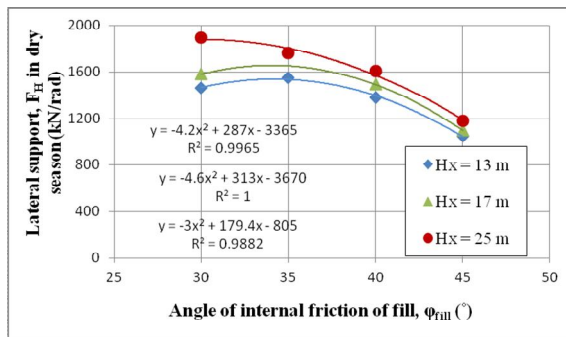


Figure 7. Lateral support (lateral force) F_H vs angle of internal friction of fill ϕ_{fill} in dry season (45 kPa)

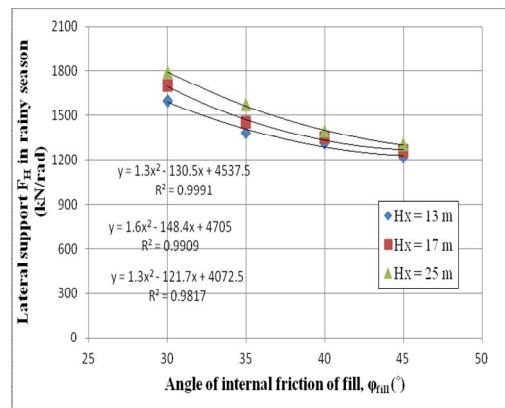


Figure 8. Lateral support (lateral force) F_H vs angle of internal friction of fill ϕ_{fill} in rainy season (45 kPa)

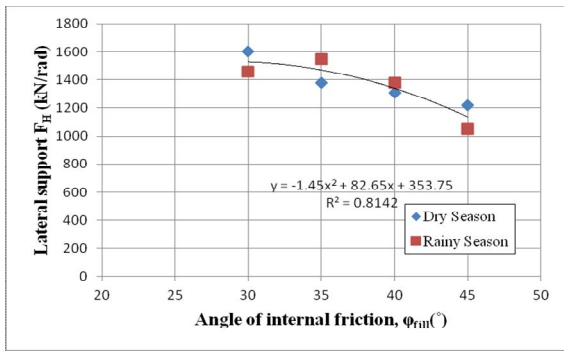


Figure 9. Lateral support (lateral force) F_H vs angle of internal friction of fill ϕ_{fill} : Common trend line for both seasons ($H_X = 13$ m) (45 kPa)

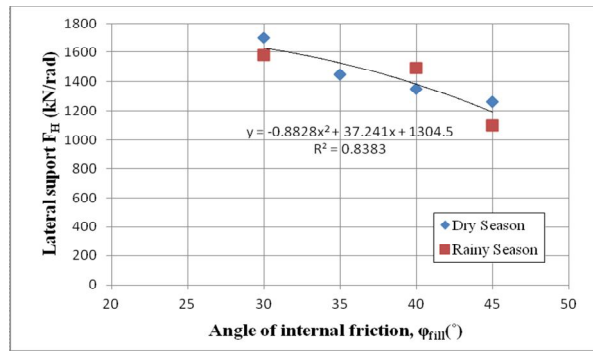


Figure 10. Lateral support (lateral force) F_H vs angle of internal friction of fill ϕ_{fill} : Common trend line for both seasons ($H_X = 17$ m) (45 kPa)

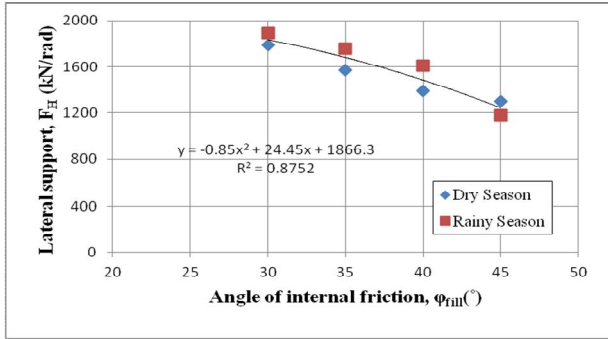


Figure 11. Lateral support (lateral force) F_H vs. angle of internal friction of fill ϕ_{fill} : Common trendline for both seasons ($H_X = 25$ m) (45 kPa)

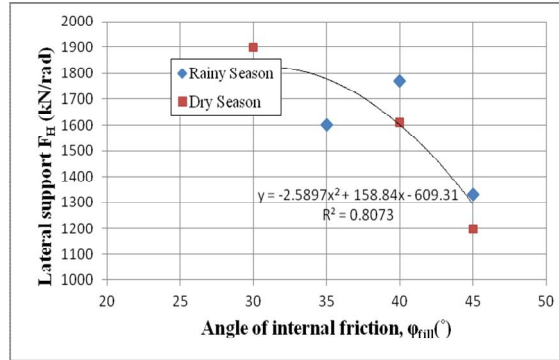


Figure 12. Lateral support (lateral force) F_H vs. angle of internal friction of fill ϕ_{fill} : Common trendline for both seasons ($H_X = 13$ m) (90 kPa)

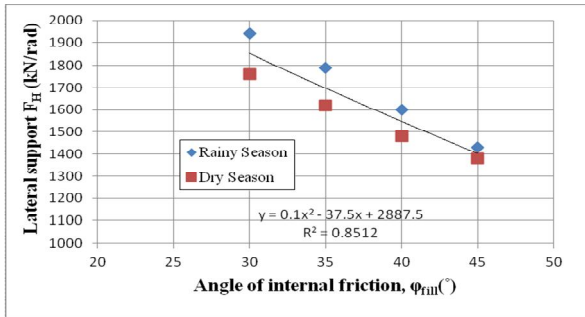


Figure 13. Lateral support (lateral force) F_H vs. angle of internal friction of fill ϕ_{fill} : Common trendline for both seasons ($H_X = 17$ m) (90 kPa)

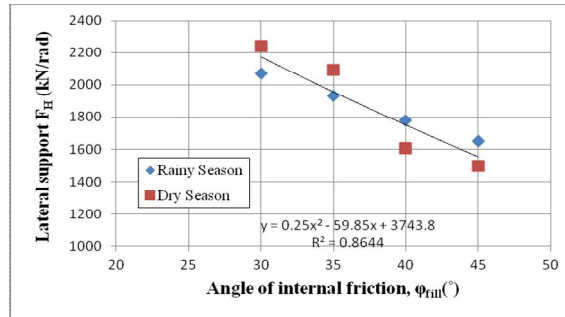


Figure 14. Lateral support (lateral force) F_H vs. angle of internal friction of fill ϕ_{fill} : Common trendline for both seasons ($H_X = 25$ m) (90 kPa)

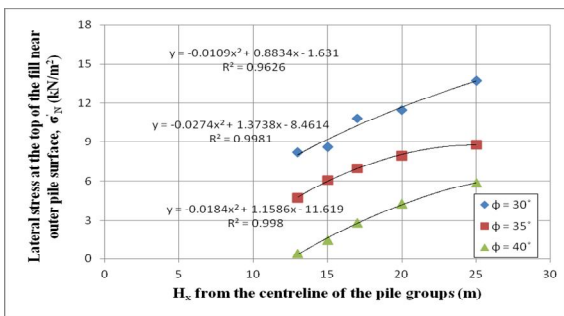


Figure 15. Lateral stress at the top of the fill near outer pile surface, σ_N (kN/m^2) vs. H_X in dry season (45 kPa).

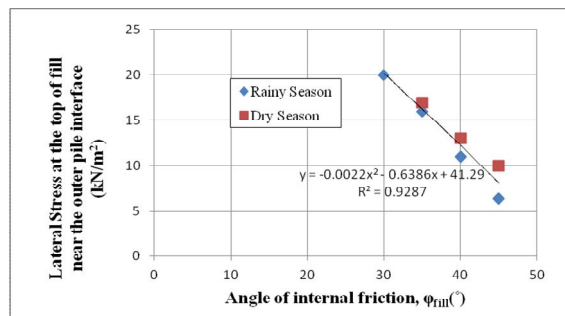


Figure 16. Lateral stress at the top of the fill near outer pile surface, σ_N (kN/m^2) vs. angle of internal friction of fill ϕ_{fill} : Common trendline for both seasons ($H_X = 17$ m) (90 kPa).

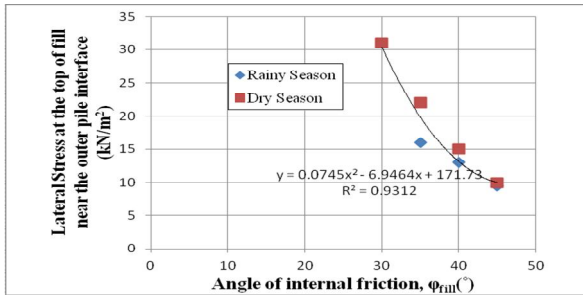


Table 1. List of parameter Variations

Parameters	Unit	Range
ϕ_{fill}	degree	30 - 45
H_x	m	13 - 25
Surcharge	kPa	45 and 90

Figure 17. Lateral stress at the top of the fill near outer pile surface, σ_N (kN/m²) vs. angle of internal friction of fill ϕ_{fill} : Common trendline for both seasons ($H_x = 25$ m) (90 kPa)

Figures 7 and 8 present the effects of angle of internal friction of the fill material on the lateral support attained by the top 7 m of the bridge piers during dry and rainy seasons, respectively. The radius of the scour protection zone was varied from 13 m to 25 m and the height of the geobags caused 45 kPa surcharge at the river-bed level. In both seasons, the greater radius of the scour-protection zone produces the greater confinement. It is to note that the influence of angle of internal friction of the fill material on the magnitude of F_H follow different pattern with seasonal variation.

Further, the effects of angle of internal friction of fill material, radius of scour protection zone and the surcharge load were examined on the development of lateral confinement for both the seasons (Figures 9-14). It can be noted that a common trend line, between F_H and ϕ_{fill} , is obtained for each set of H_x and surcharge load for both the seasons. The greater the surcharge, the higher the lateral confinement will be.

In order to study the effectiveness of the proposed measure, the influence of surcharge (related to the height of the geobags' layer) on the effective stress developed at the top level of the fill (riverbed level) near the outer pile interface are investigated, as shown in Figures 15-17. In Figure 15, it can be noted that the effective stress, developed at that level of interest, may become zero for fill materials having high values of ϕ in dry season if a value of 45 kPa surcharge is applied. The condition of zero effective stress at that level gives an indication for the proposed vibration control measure being ineffective. It has previously been noted that lateral support from the measures taken is less during rainy season than in dry season (Figures 7 and 8). Therefore, the proposed measure may be ineffective during rainy season under 45 kPa surcharge. Instead, if high surcharge (90 kPa) is applied over larger radius of sour protection zone, some values of effective stress at the river-bed level can be attained consistently in both the season with a minor variation, as shown in Figures 16-17. This implies, the height of the geobag layer is not only important to protect future scour but also to attain a minimum effective stress at the river-bed level.

6 CONCLUSIONS

This study identifies a cause of significant horizontal sway of the bridge that is observed with traffic load only and in absence of extreme wind or earthquake. When the unsupported length of the pier increases due to local scour around a group of piles, additional vibration is induced even only under traffic load. A two-step vibration counter measure has been proposed.

The numerical investigation presented in this paper confirms the effects of the properties of fill material and the dimension of the protected zone on the lateral confinement of the affected piers in both the seasons. A greater radius of the scour-protection zone can provide greater lateral confinement. In each of the cases of counter measure (defined by the dimension of the scour protection area and the surcharge height of geobags), there exists a common trend line between lateral support and angle of fill material for both the dry and the wet seasons. The height of the geobag layer is found not only important to protect future scour but also to attain a minimum effective stress at the river-bed level. When low surcharge over the scour protection zone is applied, the counter measure may not be effective in rainy season. Rainy season is found to be the most vulnerable period from the bridge vibration perspective, as it happens for the one across the Meghna.

REFERENCES

- Alam, M. K., Hasan, A. K. M. S., Khan, M. R., & Whitney, J. W. 1990. Geological map of Bangladesh: Dhaka. Geological Survey of Bangladesh, scale, 1(1), 000.
- Amin, A. F. M. S., Bhuiyan, A. R., Hossain, T., & Okui, Y. 2014. Nonlinear Viscosity Law in Finite-Element Analysis of High Damping Rubber Bearings and Expansion Joints. *Journal of Engineering Mechanics*, 141(6), 04014169.
- Chandler, J. A., Peraino, J., & Rowe, P. W. 1984. Jamuna River 230 kV Crossing, Bangladesh. Part III. Construction of Foundations. ICE Proceedings, Vol. 76, No. 4, pp. 965-984.
- Choudhury, M.S.I., Tobita, R., Amin, A.F.M.S. & Matsumto, Y. 2015. Experimental investigation on dynamic characteristics of Meghna Bridge at different structural conditions. Proceedings of IABSE–JSCE Conference on Advances in Bridge Engineering (Amin AFMS, Okui Y, Bhuiyan AR, Ueda T (eds)), Dhaka, Bangladesh.
- Gales, R. R. 1918. The Hardinge Bridge over the Lower Ganges River at Sara. In Minutes of the Proceedings of the Institution of Civil Engineers, Vol. 205, No. 1, pp. 18-99.
- Hinch, L. W., McDowell, D. M., & Rowe, P. W. 1984. Jamuna River 230 kV Crossing, Bangladesh. Part I. Design of Foundations. ICE Proceedings, Vol. 76, No. 4, pp. 927-949.
- Hoque, M.M., Rahman, M. M., Hossain, M. A. 2004. Morphological characteristics of the river Meghna: A collaborative study. The 2nd Asia Pacific Association of Hydrology and Water Resources (APHW) conference, Singapore, 5-8 July 2004.
- Hyundai 1997. Jamuna Bridge Design Report and As-built Drawings, Bangladesh Bridge Authority.
- Japan International Cooperation Agency 1990. Basic Design Study for Construction of the Meghna-Gumti Bridge, Roads and Highways Department, Bangladesh.
- Murrillo, J. A. 1987. The scour of scour. *Civil Engineering—ASCE*, 57(7), 66-69.
- Noor, S. T., Hanna, A., & Mashhour, I. 2013. Numerical modeling of piles in collapsible soil subjected to inundation. *International Journal of Geomechanics*, 13(5), 514-526.
- Pacific Consultants International and Nippon Koei Co. 1986. Detailed Design Report for Meghna Bridge Construction Project, Roads and Highways Department, Bangladesh.
- Project Builders Limited (2010). Construction of deepwater pile caps for Dapdapia Bridge over the Kirtonkhola river, Proceedings of IABSE–JSCE Conference on Advances in Bridge Engineering (Amin AFMS, Okui Y and Bhuiyan AR (eds)), Dhaka, Bangladesh, pp. 437-440.
- Sham, S. R. 2015. Design of the Padma road and rail bridge, Bangladesh, Paper 1400029, ICE Proceedings, <http://dx.doi.org/10.1680/bren.14.00029>
- Sobhan, M.A. & Amin, A.F.M.S. 2010. Foundation design methodology for Padma main bridge. Proceedings of IABSE–JSCE Conference on Advances in Bridge Engineering (Amin AFMS, Okui Y and Bhuiyan AR (eds)), Dhaka, Bangladesh, pp. 1-11.