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For any query on submission the author(s) should contact: MIST, Mirpur Cantonment, Dhaka-1216, Bangladesh; Tel: 88 02 8034194, FAX: 88 02 9011311, email: *mijst@mist.ac.bd*. For detailed information on submission of articles, the author(s) should refer to the Call for Papers and About MIJST at the back cover of the MIJST Journal. Authors must browse MIJST website through the journal link (*https://mijst.mist.ac.bd/mijst*) for electronic submission of their manuscripts.

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FOREWORD

Bismillahir Rahmanir Rahim

It gives me immense pleasure that MIJST is going to publish a Special Issue on the Padma Multipurpose Bridge on the eve of the 51st Victory Day of Bangladesh. Our Honorable Prime Minister Sheikh Hasina has turned the aspiration of Bangabandhu Sheikh Mujibur Rahman - the Father of the Nation - into reality by constructing the largest bridge in Bangladesh over a span of 6.15 km across the great river – Padma, connecting the southwestern part of the country to the Capital city Dhaka. The Bridge symbolizes the country's extraordinary economic potential and its achievements in nationwide infrastructure and communication link development in recent years. It is a matter of pride for all Bangladeshis that this challenging megastructure was built using the country's own financial resources and local expertise.

I'm pleased to note that the eight invited papers of this special issue on structural analysis, geotechnical consideration, environmental, transportation, construction, and management challenges of the Padma Multipurpose Bridge are contributed by practitioners and academics from Bangladesh, Singapore, and Norway who directly participated in the design and construction of the bridge under the leadership of the Panel of Bangladeshi Expert headed by late Professor Jamilur Reza Choudhury. My heartfelt thanks and gratitude are due to the authors of all these papers. I sincerely hope and trust that these papers will significantly advance academics' and professionals' comprehension of how this iconic Bridge was designed, developed, and finally put into place overcoming all design and construction obstacles.

I wish continued success of MIJST!

Major General Md Wahid-Uz-Zaman, BSP, ndc, aowc, psc, te
Commandant, MIST, Bangladesh
Chief Patron, MIJST, Bangladesh

EDITORIAL

Bangladesh as an emerging nation has been undergoing epoch making economic transformation under the visionary leadership of Prime Minister Sheikh Hasina. The rapid industrialisation aided by major infrastructure development (roads/highways, road and railway bridges, mass rail transit (metro) systems, underwater tunnel, deep seaport, bay terminal, new international and domestic airport terminals, thermal and nuclear power plants, high voltage power transmission, etc.) has created immense opportunities as well as technical and economic challenges for Bangladesh. For the first time in the history of Bangladesh, the nation's technical/engineering, scientific and policymaking communities are required to deal with mega projects for which they need firsthand experience, skills, and expertise. These-nation building mega projects have provided ground breaking opportunities, confidence and experience for future mega ventures to be undertaken by homegrown experts relinquishing the dependency on foreign consultants. The gained firsthand experience and innovations to overcome challenges in the recently completed mega projects are yet to be scientifically documented and disseminated. The innovations in problem solving for the mega project implementations in Bangladesh can be applied with local contextualisation anywhere in the world. It is very pleasing to inform that the MIST International Journal of Science and Technology has taken a bold initiative to publish research articles on challenges and difficulties that required innovative solutions for the execution of mega projects in Bangladesh through a series of Special Issues, and I am excited to present the of first such Special Issue on Padma Multipurpose Bridge project.

The inaugural Special Issue includes a distinct selection of eight research articles encompassing from construction challenges and management, benefits of connectivity and mobility, environmental safeguards in construction, bridge structural health monitoring, riverbed soil characterisation at bridge site, seismic study of bridge piers, dynamic response of moving vehicles and trains, and engineering unique features of Padma rail bridge. All eight articles are original, innovative and have notable implication in science, engineering, and technology. The research findings of each article are unique.

I cordially invite to submit articles on any mega projects including under construction Rooppur Nuclear Power Plant, Hazrat Shah Jalal International Airport Terminal 3, Chattogram-Cox's Bazar Railway project, Cox's Bazar Runway Extension Project, Bangabandhu Railway Bridge, Karnafuly River Tunnel, Materbari Deepsea Port, Patenga Seaport Bay Terminal, Matarbari Thermal Power Plant, and recently completed Payra Thermal Power Plant and Rampal Thermal Power for the next series of Special Issues. Articles on other mega projects anywhere in the world are also gladly welcome for Special and/or regular issues.

I express my profound gratitude and thanks to the chief patron, executive editor, associate editors, section editors, reviewers, other editors and proof-readers, editorial board members (national and international), and web production consultant for their extraordinary support for the Special Issue. Their commitment, enthusiasm and 'can do' attitude have made possible to publish the Special Issue on schedule. I fervently request you all to promote the Journal and its articles among your colleagues, research scholars and library databases.

As always, I warmly welcome your advice, suggestion, and feedback for the betterment of the Journal. Please feel free to contact me at firoz.alam@rmit.edu.au or mijst@mist.ac.bd with your queries or ideas.

Sincerely,

Prof. Dr. Firoz Alam
Editor in Chief

Tribute – Professor Jamilur Reza Choudhury

Professor Jamilur Reza Choudhury, the most eminent personality in the engineering community of Bangladesh who played a cardinal role in the development of the infrastructure system of Bangladesh, passed away on 28th April 2020 at the age of 76. Professor Choudhury had the highest professional credentials as a civil and structural engineer. He was a beehive of energy as well as an internationally recognized civil engineer, educationist, researcher, administrator, and leader. What struck us most was Prof Choudhury's highly strategic vision for the future development of new information-based communication technologies, which provided the platform for today's "Digital Bangladesh". His involvement in different sectors of our national development seemed to be limitless. Prof Choudhury's contribution to infrastructure development of Bangladesh cannot be overstated. Next to no significant development project in Bangladesh has been implemented without the involvement of Prof Choudhury. He acted as an expert consultant to many national and international projects related to expressways, bridges, buildings, industries, transmission towers, aircraft hangars, stadiums, ports and jetties, computerization of public and private sector organizations, etc. Prof Choudhury was the team leader for the Multipurpose Cyclone Shelter Program and prepared the master plan for the shelters constructed along the coastline of the Bay of Bengal that saved millions of lives. He was the chairman of the Panel of Experts (PoE) of the Bangabandhu (Jamuna) Bridge. In recognition of his contributions, he was awarded the 'Ekushey Padak' in Science and Technology in 2017 by the Government of Bangladesh, an 'Honoris Causa' from the University of Manchester in 2010 and the 'Order of the Rising Sun' in 2018 from the Government of Japan (the highest award conferred to a foreign national), etc. He was inducted as a National Professor by the Government of Bangladesh in 2018.

Professor Choudhury was selected as the chairman of the PoE of Padma Multipurpose Bridge Project (PMBP). While a complicated situation arose during the selection of Construction Supervision Consultant for the construction of the main bridge and river training works, Professor Choudhury assured the government that the Bangladeshi engineers have the capability to lead the design and construction of the challenging mega project. The Government of Bangladesh finally decided to build this largest infrastructure in the country using its own fund and expertise. This decision of the government placed enormous responsibilities on the local PoE members. In the meantime, several national and international experts also joined as members of the PoE of PMBP. The local experts under the leadership of Professor Choudhury solved the problem by introducing new technology and redesigning some piers of the bridge. This complex bridge adopted new and innovative technologies and established new records in the construction industry through local engineers.

Professor Choudhury's immense contribution in leading the PMBP has been recognized by the Honorable PM Sheikh Hasina at the eve of the opening of the bridge. She wished that Prof Choudhury was present to see the completion of the bridge.

Professor Jamilur Reza Chudhury's name will be immortalized in the country's development history as one of the great builders of Bangladesh. His unanticipated, premature, departure from our midst has not just left a void in his family and among all who knew him but also caused a colossal and irreparable loss for the nation.

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The Padma Multipurpose Bridge: A Link towards a Prosperous Future through Connectivity and Mobility

M. Y. Ali[1], S. A. Suma[2], M. R. Islam[3], and M. Hadiuzzaman[4*]

[1]Department of Civil Engineering, Ahsanullah University of Science and Technology (AUST), Dhaka, Bangladesh
[2,4]Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh
[3]Department of Civil Engineering, Military Institute of Science and Technology (MIST), Dhaka, Bangladesh

emails: [1]*yusuf.ce@aust.edu;* [2]*afrosesuma@ce.buet.ac.bd;* [3]*russed@ce.mist.ac.bd; and* [4*]*hadiuzza@ualberta.ca*

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ABSTRACT

This study describes the impact of the Padma Multipurpose Bridge in creating regional connectivity and mobility in traffic movement, thus contributing to the socioeconomic development of Bangladesh. It finds that the travel time between the Dhaka division and the southwestern region will be saved by about two hours for cars and buses and by over 10 hours for trucks due to new connectivity through the bridge. It will reduce the distance from Mongla Port to Dhaka by more than 100 km to 170 km and save a lot of working hours, which will further accelerate the growth of the country's economy. Additionally, a total of 212.05 km of the new railway line is being constructed for the Padma Multipurpose Bridge, which will connect Dhaka with the country's largest land port, Jessore. After the Padma Bridge Rail Link project is done, the travel time from Dhaka to Kolkata via Jessore will be cut in half, and it will take only 3 to 4 hours. Moreover, the bridge will also pave the way for putting in place a new route for the Trans-Asian Railway network. The Padma Multipurpose Bridge is estimated to boost the country's annual GDP by 1.23 percent and the southwestern region's GDP by 2.5 percent. Moreover, the Padma Multipurpose Bridge will reduce the poverty rate by 1.01 percent at the regional level and by 0.84 percent at the national level. This study finds that to take full advantage of the newly constructed bridge, the southern part of the outer ring road of Dhaka proposed in RSTP should be completed soon. Padma Multipurpose Bridge will work as a key component of Asian Highway-1, boosting economic growth in Asia and improving the country's standing on the continent.

1. INTRODUCTION

Bangladesh is a riverine country. According to Bangladesh Water Development Board (BWDB, 2022), about 230 rivers currently flow in Bangladesh (during summer and winter). Among them, Brahmaputra is the longest river and Padma is the swiftest whereas Jamuna is the widest river. These three rivers divided the land area of Bangladesh into three parts and created great barriers for movement of people and commodities among the regions. Construction of Bangabandhu bridge on the river Jamuna linked the north-western part of the country with the eastern part where the capital and the main seaport are located. The Hardinge bridge and Lalon Shah bridge established road and rail communication between north-western and south-western regions of the country. However, there was no direct road or rail connection for easy communication between eastern and south-western parts of country and the people of Bangladesh had a dream of having a bridge on the fiercely flowing Padma River. Hence, the Padma Multipurpose Bridge has been a dream project for millions of people in the southwestern region of Bangladesh. This bridge has made a connection of Louhajong, Munshiganj to Shariatpur, and Madaripur, linking the southwest of the country, to the northern and eastern regions.

The Pre-feasibility Study of the Padma Multipurpose Bridge Project was done from 1996 to 1999. Bangladesh Bridge Authority and a Japanese company named JICA finalized the study between 2003 and 2005. Later, between 2009 and 2011, the US, New Zealand, and Australia-based consultant organization Maunsell-Aecom concluded the design of the Padma Multipurpose Bridge. However, when there was a crisis over the bridge's funding, the

Bangladesh government announced the construction of the Padma bridge with its own fund in 2013. In 2014, a deal to construct the main bridge was struck with China Major Bridge Engineering Co. Ltd., and Sinohydro Corporation Limited got the contract for river training work. The construction began in December of that year. About six (6.15) km long structure of the main bridge was being erected on 42 pillars with the help of 41 spans, spanning 150 meters that are expected to withstand earthquakes of magnitude nine on the Richter scale. Moreover, it has the deepest piling in the world at 128 meters, is the 122nd longest bridge in the world, with piles that are 3 meters in diameter. Besides the four-lane road link at the top and a single line rail link at the bottom, the bridge will also take gas, electricity, and broadband internet through fiber optical cable to the country's south-west. The bridge's total length, including the main bridge and viaduct, is more than 9 kilometers. Moreover, it is the largest multipurpose road-rail bridge and the first fixed river crossing for road traffic across the Padma River.

Initially, the Padma Bridge megaproject cost was estimated at BDT 10,161 crore in 2006 and BDT 20,506 crore in 2011, which later increased to BDT 30,793 crore (Business Inspection, 2022). Although several mega projects, like the Rooppur Nuclear Power Plant, are financially much larger than the Padma Multipurpose Bridge project, however the socio-economic, historical, and geopolitical significance of the Padma is far greater than others. The Padma Multipurpose Bridge is no longer simply a steel structure; it has become the focal point of Bangladesh's ability, economic prosperity, and the emotions of the Bangladeshi people. The bridge was finally ceremonially inaugurated for road traffic by the Honorable Prime Minister on 25th June 2022.

2. SCENARIO OF CONNECTIVITY BEFORE THE PADMA BRIDGE

The southwest region is characterized by vast inland waterways utilizing many rivers and their tributaries. Prior to the opening of the bridge, there was no direct links by roads and passenger transport between Dhaka and the southwest districts were cut off from the country's major economic centre, the Dhaka-Chattogram economic corridor as shown in Figure 1. Moreover, the southwest region the only available rail connection of these southwest districts with Dhaka city is through Jamuna Bridge and Hardinge Bridge which takes approximately 10-12 hours.

Consequently, the southwest region relied heavily on inland waterways. There are 48 ghats in Barisal Port, 40 ghats in Khulna Port and 39 ghats in Patuakhali Port. Southwest region was connected to Dhaka city by two ghat namely Mawa-Kathabaria and Paturia-Goalundo. The Paturia site uses 22 ferries over 24 hours at 5 ghats while the Goalundo site has 3 ghats. The average time of crossing is approximately 40 minutes in the high-water level season and 30 minutes in the low-water level season. However, Mawa-Kathabaria site utilizes 11 ferries at 4 ghats over 24 hours. The average number of round trips per day for each ferry is 4, and the average crossing time is 2 hours 5 minutes in the high-water level season and 2 hours in the low-water level season.

Figure 1: Connectivity link missing between Southwestern side and Dhaka before the construction of Padma bridge. (Source: Railway Gazette International)

Approximately 62,500 passengers cross directly from the north-east Dhaka region to the south-west each day at the combined Mawa and Goalundo crossing points. In terms of vehicle numbers, 2,909 vehicles cross Padma River per day, comprising 1295 trucks (44%), 700 light vehicles (24%), and 914 car (32%) (Feasibility study, 2005). As trucks cross the river by ferry, no loading/unloading of cargo takes place. Trucks tend to have long waiting times. This increases their travel time by hours or even days. It took at least 2 to 3 days for a freight truck to travel from Barisal or Khulna to Dhaka or from Dhaka to these areas. This form of transport was not only uncertain but was also time-consuming.

According to the Asian Development Bank (ADB), 27% of the total population of Bangladesh lives in the south-west (Mustafizur Rahman, 2022). Due to poor connectivity, economic operations in the southwestern zone have not been too easy. Consequently, the districts did not seize much industrialization. As a result, poverty and under-employment constitute major problems in the region.

3. EXPECTED TRANSPORTATION BENEFITS

Padma Multipurpose Bridge will offer many advantages to the region. It connects the isolated 21 southwestern districts as well as the port of Mongla and the port of Payra, respectively the second and third-largest ports in the country, with the capital. According to Zahid Hossain, lead economist at the World Bank, with the opening of road and rail traffic to the Padma Bridge, people in the country's south-west will begin to benefit from the bridge immediately (Mustafizur Rahman, 2022). The following sections describe the transportation benefits of the bridge.

A. Roadway

According to ADB, the Padma Multipurpose Bridge will carry an average of 24,000 vehicles per day in 2024 and 67,000 by 2050. It is expected that the travel time between the Dhaka division and the southwestern region (SWR) will be saved by about two hours for cars and buses and over 10 hours for trucks. Moreover, according to ADB, the long-term (31 years) road user benefit of the Padma Bridge in the traffic model stood at 18.512 billion dollars, and according to the Social Accounting Matrix (SAM), the total project benefit was estimated at $25 billion (24.993) at the same time.

B. Railway

A total of 212.05 km of the new railway line is being constructed for the Padma Multipurpose Bridge with the sponsorship of the Bangladesh Railway Ministry, which will connect Dhaka with the country's largest land port, Jessore shown in Figure 2. The Chinese government will provide 85 percent of the financing of the 40,000-crore project through China Exim Bank, and the Bangladesh government will provide the rest.

Figure 2: Padma bridge rail link
(Source: The Daily Gonokantho)

After the Padma Bridge Rail Link project is done, the travel time from Dhaka to Kolkata via Jessore will be cut in half, and it will take only 3 to 4 hours which will boost the country's foreign trade. By doing so, Bangladesh will be able to maintain a railway network with Bhutan, Nepal, and India.

C. Waterway

As mentioned in the previous section, the southwest region is characterized by vast inland waterways utilizing many rivers and their tributaries. Considering the importance of navigation on the Padma River throughout the year, a vertical navigation clearance of 18.3m is maintained above high flood level for free movement of all types of vessels using the river. However, the vehicle crossing by ferry is reduced after the opening of the Padma bridge.

4. EXPECTED ECONOMIC BENEFITS

The total production of the transport, trade, and local industrialization focused on the Padma Bridge, as well as GDP growth, will influence the country's entire economy. The Padma Multipurpose Bridge is estimated to boost the country's annual GDP by 1.23 percent. Similarly, the southwestern region's GDP is projected to increase by 2.5 percent as shown in Figure 3. Additionally, the bridge will be linked to the Padma Rail Link Project, which is expected to turn Bangladesh into a sub-route of the trans-Asian rail network and accelerate GDP growth by approximately 1 percent.

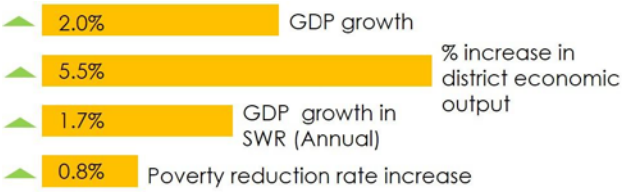

Figure 3: Economic Improvement of regional and national level after Padma Bridge construction
(Source: Light Castle Partners)

Moreover, new industrial units will be established, creating many job possibilities. All the southwestern districts will be covered in these areas. There will be increased hiring, re-skilling, or up-skilling of the labor force in accordance with industry needs, and maybe a hike in the minimum wage as the demand for labor rises. Hence, more economic opportunities will ultimately improve living conditions and thus reduce poverty. The following sections describe the economic impacts of Padma Bridge.

A. Effect on the economy

The bridge's development will have a significant economic effect on the country. In 2010, Aecom-Maunsell, reported that the bridge's Reward Ratio (BCR) was 1.6% and the Economic Rate of Return (ERR) was 18%. The BCR will be 2.1 and the ERR will be 22%.

In addition to the design experts, the World Bank's independent consultants and the Bridges Team's consulting firm assessed the bridge's economic effect and found that the bridge's building will be financially profitable. In addition, economic activity in the south-west has already increased around the bridge, with mass-level industrialization underway. In this context, the rate of land sale in Barisal is doubled in 2022 compared to 2021. Lands near highways are also being sold at three-four times higher prices than before. So, there will be rapid growth of mega factories, hospitals, universities, housing industries, and small businesses around the Padma Bridge.

B. Trade and commerce

The direct connection to the capital will aid in the expansion of trade and commerce, as well as the supply of raw materials and industrialization. Moreover, the bridge will reduce the freight transportation time to a maximum of one day, which increases the trading of the regions by several times. According to a report by the Khulna Chamber of Commerce, the region will play a groundbreaking role in regional connectivity in South Asia and connect Dhaka with Mongla and Payra ports once the bridge is launched. The bridge will reduce the distance from Mongla Port to Dhaka by more than 100 km to 170 km, whereas the current distance between Chittagong Port and Dhaka is about 264 km. As a result, the distance between Dhaka's Mongla seaport and Chittagong port will be reduced. Increasing the importance of the Mongla port in the transportation of goods and facilitating communication between Dhaka and the south will save a lot of working hours, which will further accelerate the growth of the country's economy.

At present, more than 90 percent of the country's international trade is done through the Chittagong Port. In 2021, the trade volume of this port was about 90 billion dollars. Initially, the port of Chittagong could handle 2 million TEU (Twenty-Foot Equivalent Unit) containers per year, but in 2021 it increased to more than 3.2 million TEU. Increased cargo movement between Dhaka and the Mongla Port will reduce congestion in the port of Chattogram. Until December 2021, less than 20 (19,224) thousand containers were handled from Mongla, which is even less in the case of Payra port. In addition, after the launch of the bridge, besides easy commute, it will also reduce the cost of gas, electricity, and internet services, which will expand the existing trade in the region.

C. Regional industrial revolution

Experts estimate an industrial revolution in 21 districts in the southwest, especially within a year of the double-decker bridge's launch. Moreover, the bridge will significantly improve the economy of the country's south-west region, an evident proof of which is the Bangabandhu Bridge, around which an industrial revolution has taken place in North Bengal. The changes in the economy of North Bengal because of this bridge have contributed about 2% to the GDP growth of Bangladesh. Such contribution has also been estimated in the case of Padma Multipurpose Bridge. According to many experts, the contribution will be more than the Jamuna. Experts believe that many small and big industries will be growing in the south-western part of the country along the bridge route, including manufacturing businesses, RMG, assembling plants, storage facilities. According to ADB estimates, the direct investment made around this bridge will boost the regional economy. According to JICA estimates, a 10 percent reduction in travel time from Dhaka would increase the district economy to 5.5 percent, which would increase the region's annual GDP growth by 1.7 percent. Furthermore, after the bridge is completed, it will cut the cost of gasoline, power, and online services, thereby expanding the region's current trade.

Additionally, the shipbreaking industry, RMG, assembling plant, and storage facilities will be set up in this region. According to a BSIC source, 500 to 1000 factories of the different sectors will be set up in 6 districts of the Barisal division in the next ten years. According to a report by Dhaka Tribune, if demand for gas, electricity, internet, and infrastructure in the south-west can be met, trade between India, Nepal, and Bhutan with Bangladesh through the region will increase. As a result, the economic landscape of the south-west may change. The Bangladesh Economic Zones Authority (BEZA) is developing 17 economic zones in the region to accelerate industrialization and economic growth.

D. GDP Growth

The road distance between Dhaka and most of the south-western districts will be reduced to at least 100 km. In addition to reducing the time and cost of transporting passengers and goods, vehicle maintenance and fuel costs will be much lower. As a result, people from all sectors, including business and agriculture, will be benefited, impacting the country's GDP.

Moreover, the economic output of the transportation, trading, and regional industrial revolution centered on the Padma Multipurpose Bridge, along with the GDP growth, will impact the overall economy of the country. According to a Dhaka Tribune report, the bridge is expected to contribute about 1.3 to 2 percent per annum to the country's GDP. At the same time, with the completion of the Padma Bridge Rail Link project, GDP will grow by another 1 percent. According to the current base year, a BRAC study estimates a 5 percent contribution to GDP in 31 years (Rahman, A. and Khondker, B.H., 2016). However, once the bridge is fully completed, it will contribute 1.2 percent to the country's GDP. According to the IMF forecast, Bangladesh ranks 20th in the world in ranking GDP growth in 2022. In 2026, Bangladesh will reach the 3rd position in this ranking, one of the contributors of which will be this bridge.

E. Tourism

The tourism sector will thrive, and domestic and international tourists will flock to new and old tourist spots such as Kuakata beach in the southern area, the Sundarbans, Bangabandhu Mazar in Tungipara, and old and new resorts at Mawa and Jazira.

5. EXPECTED SOCIO-ECONOMIC BENEFITS

According to a CPD source, the poverty rate in the Khulna-Barisal region is at least 10 percent higher than the national average (Mustafizur Rahman, 2022). The construction of the Padma Multipurpose Bridge will reduce the poverty rate by 1.01 percent at the regional level and by 0.84 percent at the national level as shown in Figure 3. Agriculture will be significantly improve. Farmers will be benefited from higher commodities prices. Farmers in these areas are not getting a fair price for their crops due to expensive and time-consuming transportation systems. Once the bridge is completed, jute and fish from Khulna division of Faridpur, along with agricultural products from Barisal, can be transported in the country and abroad quickly. As a result, farmers and producers get better prices for their products, which increase their quality of life.

As a result of communication, transportation, agriculture, industrialization, and employment progress, the living standards of the people of this region will be improved. The country's real estate sector in the south-west has also boosted around the Padma Bridge. As a result, it is expected that in the future people in this region will have access to gas, electricity and internet services at a lower cost than before. With the availability of broadband internet facilities, digitalization will be easier in these areas. There is a possibility of creating more jobs through freelancing, which will help to enhance the socio-economic status of the people of the region. Being financially prosperous the education system will be improved of the area as well as increase the cultural integration among the people on both sides of the Padma. According to a TBS source, employers will increase by about 1 million within the upcoming five years of the bridge's opening, reaching 30 to 40 million in the next ten years. In addition, at the regional level, the government has taken several steps to create a skilled workforce. In addition to this, for a long time, the people of this region were almost deprived of the advanced medical services of Dhaka due to the poor transportation system. After the construction of the Padma Bridge and the development of communication systems, people from this region can travel to Dhaka and receive advanced medical care quickly.

6. FUTURE CHALLENGES & OPPORTUNITY

The Padma Multipurpose Bridge is a dream bridge which will not only establish the long-awaited direct road and rail communications between the capital and south-western parts of Bangladesh but also contribute to greater connectivity and trade among Asian countries. The following sections describe the future opportunities of the national and international connectivity.

A. Improvement of backward and forward linkage

The forward link of the Padma Multipurpose Bridge is achieved by the Bhanga Expressway. However, the backward link is still not properly achieved. However, there is a scope of achieving the full efficiency of this bridge once the backward link is well established. In the RSTP (2015), three kinds of ring roads were proposed for Dhaka City. The alignment of inner ring road is along the Balu River and the Buriganga River, located inside current urban area, while the alignment of middle ring road shares with the Dhaka Bypass Road and the outer ring road is a newly proposed alignment which falls along the boundary of RAJUK area shown in Figure 4 while Table 1 shows the construction status of these three ring roads.

Table 1
Construction status of the ring roads

	Inner Ring Road	Middle Ring Road	Outer Ring Road
Completed	4.0 (5.5%)	0.0 (0.0%)	0.0 (0.0%)
Widening/Improvement	38.2 (52.2%)	59.9 (55.5%)	0.0 (0.0%)
New Road	31.0 (42.3%)	48.1 (44.5%)	129.0 (100.0%)
Total	73.2 (100.0%)	108.0 (100.0%)	129.0 (100.0%)

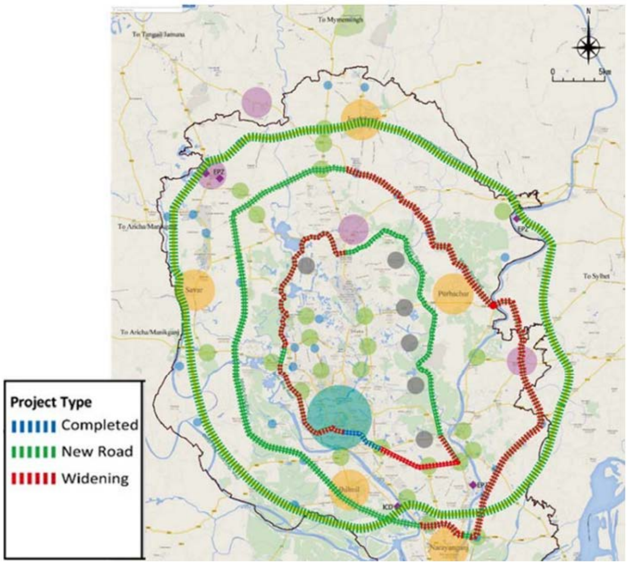

Figure 4: Current construction status of the three ring roads (Source: JICA Study Team)

Middle road is total 108.0 km whereas outer ring road is 129.0 km. The location of middle road passes through as shown in Figure 5, specifically, Autpara, Dhaka bypass, Bhulta, Kanchpur, Narayanganj, Jhilmil and Western bypass.

On the other hand, the outer ring road passes through Hemayetpur, Kalakandi, Madanpur, Danga, Bypail, Gazipur (RSTP, 2015). Southern part of the outer ring road, which is shown in Figure 6, is considered as high priority project to connect with Padma Multipurpose Bridge. It will connect Louhajong, Munshiganj to Shariatpur and Madaripur, linking the south-west of the country to northern and eastern regions. Huge number of vehicles from Padma Multipurpose Bridge will flow from southern-west side to Jatrabari area which is also known for congestion prone area. So, to mitigate the congestion and get full advantage of the newly constructed bridge, the southern part of the outer ring road should be completed soon.

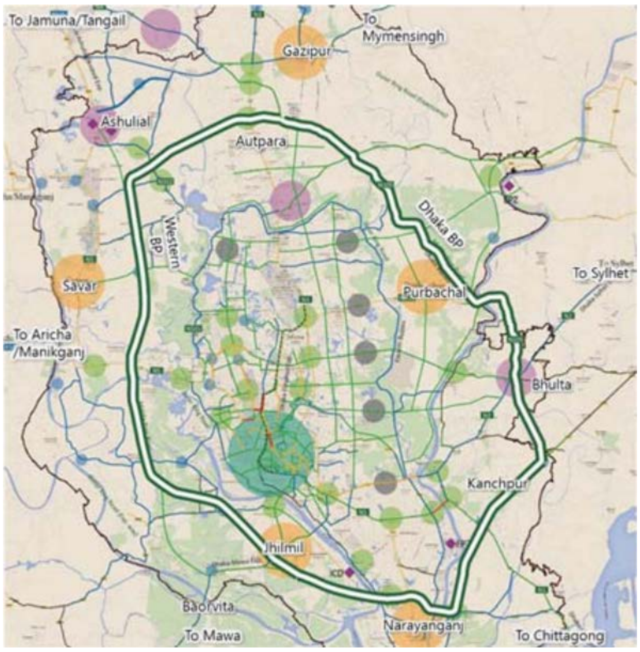

Figure 5: The location of middle ring road (Source: JICA Study Team**)**

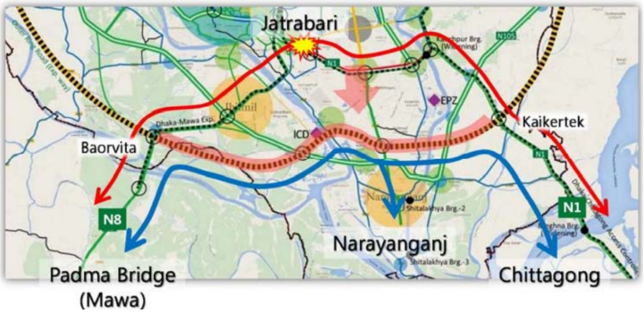

Figure 6: The high priority projects
(Source: JICA Study Team)

B. *Establishment of international connectivity*

In August 2009, Bangladesh joined the network conceived by the United Nations with a view to setting up regional connectivity among Asian countries via a highway system of over 145,000km roads passing through 32 countries. Bangladesh is connected to three Asian Highway routes named AH-1, AH-2, and AH-41 with a total length of 1,771km (Figure 7).

The route of AH-1 is Guwahati in Assam-Tamabil-Sylhet-Shaistaganj-Narsingdi-Kanchpur-Dhaka-Mawa-harjanajat-Bhanga-Bhatiapara-Kalna Ferry Ghat-Narail-Jashore-Benapole-Petrapole in West Bengal. Its length is 492km. It had two missing links: one is the Padma Bridge and another Kalna Bridge in Narail. One of the two, the 690m bridge construction in Kalna was comparatively easier, but the 6.150km bridge over the mighty Padma was always a massive task in terms of the magnitude of the work. With the opening of Padma Bridge and Kalna Bridge, these two missing links has disappeared. Padma Multipurpose Bridge will now work as a key component of the Asian Highway-1, boosting economic growth of Asia and improving the country's standing in the continent.

Moreover, the most portion of the AH-1 route is two-lane and it has four-lane stretches in urban areas and marketplaces. The RHD is implementing two projects involving Tk 20,500 crore to turn Kanchpur-Sylhet and Sylhet-Tamabil portions into four-lane keeping two additional lanes for slow-moving vehicles. Of the route, the portion from Kanchpur to Dhaka is now an eight-lane highway and Dhaka-Mawa-Bhanga a four-lane expressway. The RHD is going to take up a project to turn the 135km road from Bhanga to Benapole via Kalna, Narail and Jashore into a four-lane highway with Indian lines of credit. Meanwhile, the department has completed construction of the 690m bridge over the Madhumati River at Kalna point with a cost of Tk 959 crore. Once all the projects are completed, the entire AH-1 route would be elevated to either primary access-controlled motorway or Class-I (four or more lanes) highway.

Moreover, the bridge will also pave the way for putting in place a new route for the Trans-Asian Railway (TAR) network, another UN initiative aimed at creating an integrated railway network across Asia. It would be the fourth and the shortest TAR route, which would link India and Myanmar via the country and ultimately become a part of a network comprising 125,500km of railway lines serving 28 countries. The TAR network is aimed at enhancing the efficiency and development of the railway infrastructure in Asia, according to the UNESCAP website. At the beginning, three routes of TAR had passed through Bangladesh. The route of TAR-1 is Gede in West Bengal-Darshana-Ishwardi-Bangabandhu Bridge-Joydevepur-Tongi-Akhaura-Chattogram-Cox's Bazar-Ghundhum-Myanmar. It has two sub-routes -- Tongi-Dhaka and Akhaura-Kulaura-Shahbazpur-Mahisasan of India. The route of TAR-2 runs through Singabad in West Bengal-Rohanpur-Abdulpur-Ishwardi to meet TAR-1. The route of TAR-3 runs through Radhikapur in West Bengal-Birol-Dinajpur-Parbatipur-Abdulpur to meet TAR-1.

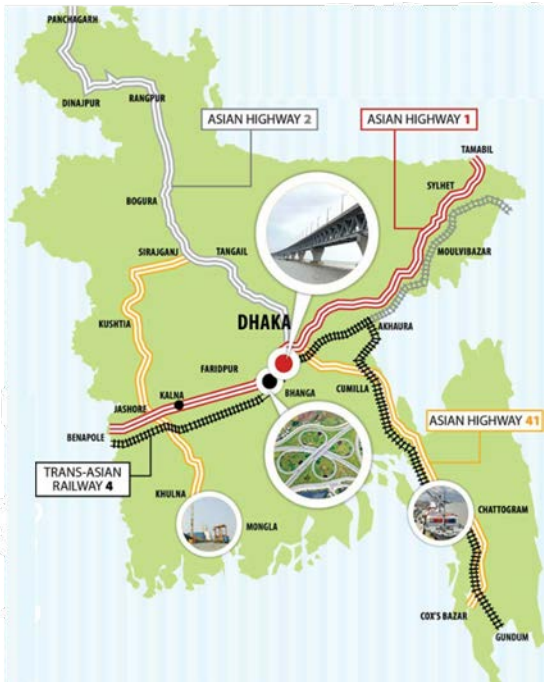

Figure 7: Asian highway and TAR project
(Source: The Daily Star)

With the building of a double-decker bridge roadway on the top and railway on the bottom over the Padma River, the country enters a new era of railway connectivity. Following Bangladesh Railway's request, UNESCAP agreed to incorporate Dhaka-Bhanga-Jashore track as a fourth route of the TAR network in Bangladesh (Figure 7). The route would run through Petrapole-Benapole-Jashore-Narail-Bhanga-Mawa-Narayanganj-Dhaka-Tongi before meeting TAR-1. However, Bangladesh Railway has to do a lot of things, including gauge conversions, to establish effective connectivity with TAR.

7. CONCLUSIONS

Padma Bridge is strategically located on the Asian Highway route AH-1 and Trans-Asian Railway Route. In the country context, it will provide a vital link in the transport network of Bangladesh by connecting Mongla sea port and Benapole land port in southwestern region with eastern region of the country and Chittagong Sea port. Padma Bridge will significantly boost economic and social uplift of the country, especially in the south-western part and function as a catalyst for poverty reduction. The construction of Padma Multipurpose Bridge will increase national GDP by 1.23 percent and southwest regional GDP by 2.30 percent and reduce poverty by 0.84 percent. The construction of Padma Bridge has added a new dimension in construction industry by establishing records in the use of high-capacity technologies exceeding the existing limits and developing innovative technologies. Bangladesh is proud to show its ability to construct the largest and most difficult project using its own professional and financial resources. The travel time for southwestern bound traffic from capital city will be reduced 2-3 times than before. But Jatrabari is currently famous for the traffic congestion and after the opening of Padma Bridge, traffic situation is come to worst. Therefore, southern part of the middle or outer ring road should be constructed as soon as possible to achieve the full capacity of Padma Multipurpose Bridge.

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The Padma Multipurpose Bridge: Construction Challenges and Sustainable Management

Md. Tauhid Ur Rahman[1*], and Sadib Bin Kabir[2]

Department of Civil Engineering, Military Institute of Science and Technology (MIST), Dhaka 1216, Bangladesh

emails: *[1*]tauhid@ce.mist.ac.bd; and [2]sadib.11165.sk1@gmail.com*

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ABSTRACT

An iconic building linking Bangladesh's southwest to its northern and eastern areas is the Padma bridge, which spans the third-largest river in the world with a complicated topology. By boosting production, employment, transportation, and the national and regional economy, this multipurpose bridge is projected to boost GDP growth by 1.2%. This study's primary goal is to pinpoint the greatest challenges encountered during Padma Bridge's construction and explain how sustainable management procedures might be put in place to address such difficulties. The most challenging tasks included finding a suitable site, dealing with complex river morphology, overcoming geotechnical barriers, controlling unfavorable environmental conditions, assembling massive construction equipment and materials, maintaining the construction schedule, and dealing with the COVID epidemic. To resolve these construction challenges, massive river training works and a unique pile foundation design that consists of six floating heaps and one center pile with the largest raking pile in the center were both utilized. To get around the difficulties in superstructural design, longer pre-assembled steel truss girders, pre-tensioned Super-T girders in viaducts, seismic isolation devices, and the largest friction pendulum bearings in the world were all made. Only a small number of people experienced COVID-19 without any fatalities or causing delays in the construction schedule since the Project was kept operational during the COVID-19 period by tightly enforcing the COVID laws and limits on people's mobility. The field of construction management would undergo a paradigm shift with this sustainable management of construction-related difficulties, which might later be used to design more intricate bridges.

1. INTRODUCTION

The Padma Bridge, which links Bangladesh's southwest with its northern and eastern areas, is a representation of the country's dignity, honor, and distinction. The greatest mangrove forest in the nation is located in the south and is a designated Cultural UNESCO World Heritage Site. It is currently in danger owing to natural disasters and a lack of connectivity and communication (Mukul *et al.*, 2020). Through her vision and strategic planning, the Honorable Prime Minister of Bangladesh, Sheikh Hasina has made a brave decision to restore the country's dignity and connectedness in this situation (Aditya, 2021).

The third-largest river in the world, the Padma has a complicated morphology that tends to move west. Traveling through the 6.15-km broad river is difficult since there are few and inconsistent boat connections, which limit mobility and economic opportunities (Figure 1).

As a result, the percentage of people living in poverty is around 5% higher than the national average. The government began construction of the Padma Bridge with financial support from the World Bank, JICA, Islamic Development Bank, and Asian Development Bank in order to improve connectivity and increase trade prospects (E. Hossain *et al.*, 2018). But afterwards, the Padma Bridge project was wholly supported by the Bangladeshi government, and both Bangladeshi and foreign construction companies worked on its completion (Du & Weng, 2021).

The bridge would create the gap connecting the Trans Asian Railway and Asian Highway, improving regional communication between the southwest region and the seaports of Mongla and Payra. To facilitate freight movement between India and the container ports at

Chittagong on the south coast of Bangladesh, a multimodal international transportation network would need to be developed. This would help Bangladesh's economy thrive (Islam *et al.*, 2020).

The bridge is expected to boost the nation's GDP by 1.2% and the south-GDP West by 2.3%, which is plagued by poverty (Blankespoor *et al.*, 2022). In total, there were two tiers of the Padma Bridge, which cost about US$2.97 billion and were used for both rail and roads. During the planning and construction phases, the project encountered several obstinate issues, mostly as a result of the Padma River's ingrained characteristics. Significant changes in the riverbed level are brought on by the Padma River's yearly flow variance, endangering the stability of the bridge's foundations. Given that the Padma River transports the most sediment (1×10^9 t/year on average), extensive river training works (RTW) were also necessary to safeguard the bridge against disasters (Islam *et al.*, 2022). With a 100-year return period, the predicted riverbed scour depth is around 62 m. (Wang *et al.*, 2018). Due to Bangladesh's proximity to the Himalayan tectonic plate contact zones, the bridge building location is also vulnerable to seismic activity. Consequently, the pile foundation design was made difficult by deep scour and seismicity.

To design the Main Bridge and RTW, the Bangladesh Bridge Authority (BBA) hired AECOM, Hong Kong, NHS, Canada, and SMEC, Australia. Before carefully considering a variety of bridge shapes, AECOM conducted a thorough evaluation of the prior works designed for the project (Hossain *et al.*, 2018). The COVID pandemic's harsh working circumstances were made easier by the workers' zeal (Figure 3). This project has set four new world records to build the magnificent structure. The design evolved into a two-level steel truss bridge with a concrete top slab operating as a composite element based on the development of a number of workable schemes. This plan, which places the highway on the top deck and the railway on the lower deck, was determined to be the most suitable kind of structure for the project. The detailed design, which was finished in 2010, used this two-level combined railroad bridge scheme. Figure 2 depicts how these multipurpose structure transporting utilities in addition to the highway-railway, such as a gas pipeline and telephone cables (Kabir *et al.*, 2022). The two-level bridge makes it possible to arrange utilities rationally, safely separate the highway from the railroad, and provide easy access for maintenance and inspection (Robin Sham, 2015). The bridge is also provided with emergency access points to facilitate safe and efficient evacuation from a train on the lower deck (Muhaimin *et al.*, 2021). This study critically examined the sustainable management approaches that were applied to resolve the significant construction challenges encountered during the construction of the multipurpose bridge. This project's successful completion demonstrated that any difficulties could be solved by following a strategic process, and it would encourage a nation to carry out more challenging projects in the future.

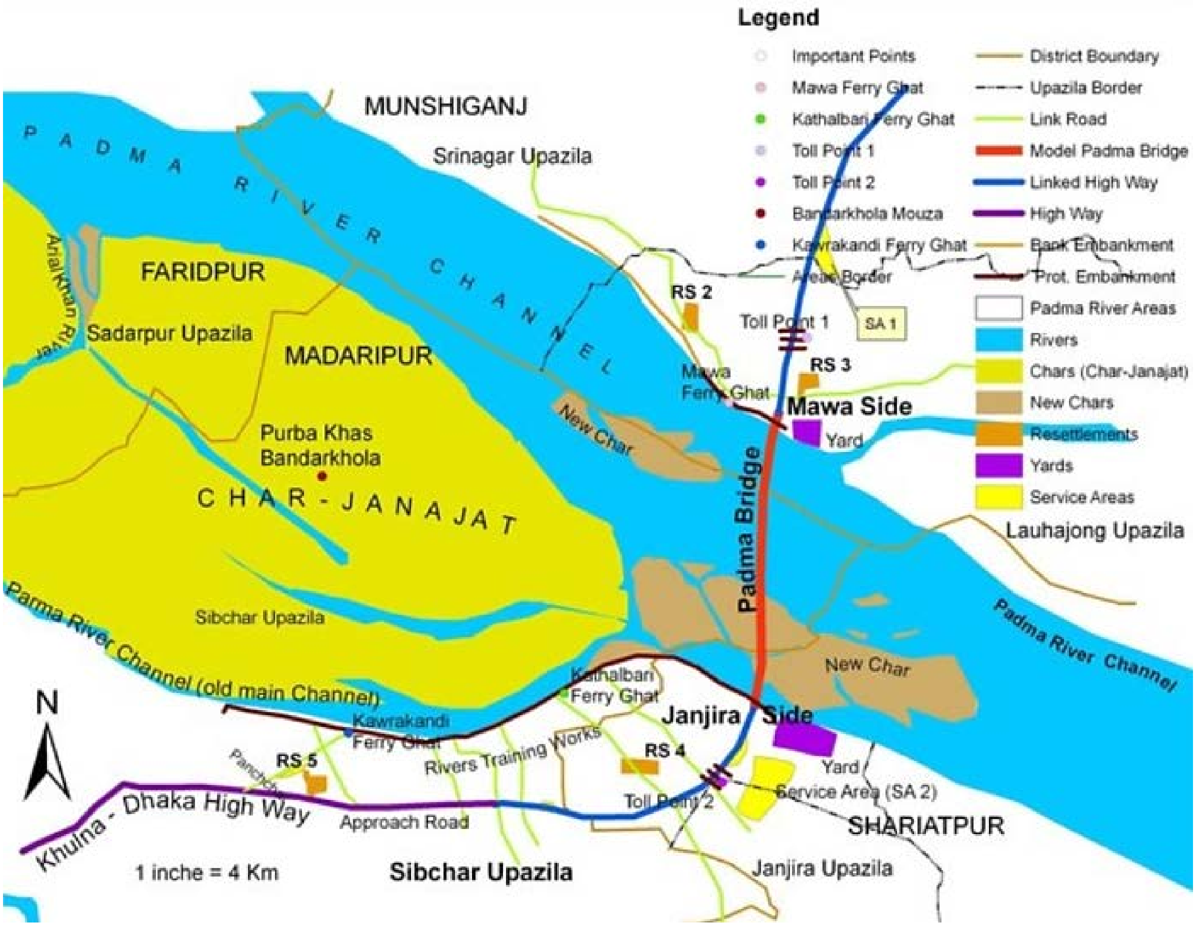

Figure 1: Location of Padma Bridge adopted from Islam *et al.*, (2011)

Figure 2: Gas pipeline and telecommunications cables in Padma Bridge (*Padma multipurpose bridge project*, 2022)

Figure 3: Record-breaking works of Padma Bridge Project (*Padma Multipurpose Bridge Project*, 2022)

2. TECHNICAL DETAILS

With a length of 6.15 kilometres, the Padma Bridge is both the longest railroad and roadway bridge in Bangladesh. The bridge is being built between Janzira in Shariatpur and Mawa in Munshiganj. The construction of the multipurpose bridge, connecting northern and eastern regions to the south-west of the country, created communication between Louhajong in Munshiganj and Shariatpur and Madaripur districts (Blankespoor *et al.*, 2022). There are 42 piers and 41 total spans in the bridge (Figure 4). Of these, two are in approach roads for linking the bridge, and 40 are in the river.

Steel tube driven piles stacked inclined at 1H:1V will be driven beneath the river for each pier. The main bridge has a total of 262 piles, with 6 in each of 18 piers, 7 in each of 11 piers, and 7 in each of 11 piers with skin grouting. Using TAM Duct Technology, Microfine Cement was used to apply the skin grouting (Nur, 2014). The 22-pier structure had to be redone with these unique layouts since TAM Duct technology was being used for the first time in this project.

The Padma Bridge's superstructural loads are supported by 294 piles in total. There are 365 bored piles altogether among the 1.2 m diameter vertical bored piles in viaducts, with 172 in Mawa and 193 in Janjira. The piles are 150 meters long, making them the deepest piles ever used in a bridge (Sham *et al.*, 2010). German engineers employed the largest hydraulic hammer in the world, with a 3,000-kilojoule capacity, to drive those piles (De Silva *et al.*, 2013). The piers are covered with steel spans. In total, the bridge has 41 spans. Upper deck and lower deck are the two decks that make up the spans. The bottom deck features a single-track dual gauge rail, and the upper deck is made up of a 21.65 m wide concrete deck slab with a four-lane roadway. The deck has a 13.6 m height and 18.3 m of clearance was maintained for navigation. The speed restriction for cars on the route is 60 km/h, whereas it will be 160 km/h for trains. The bridge is anticipated to last for about 100 years in total.

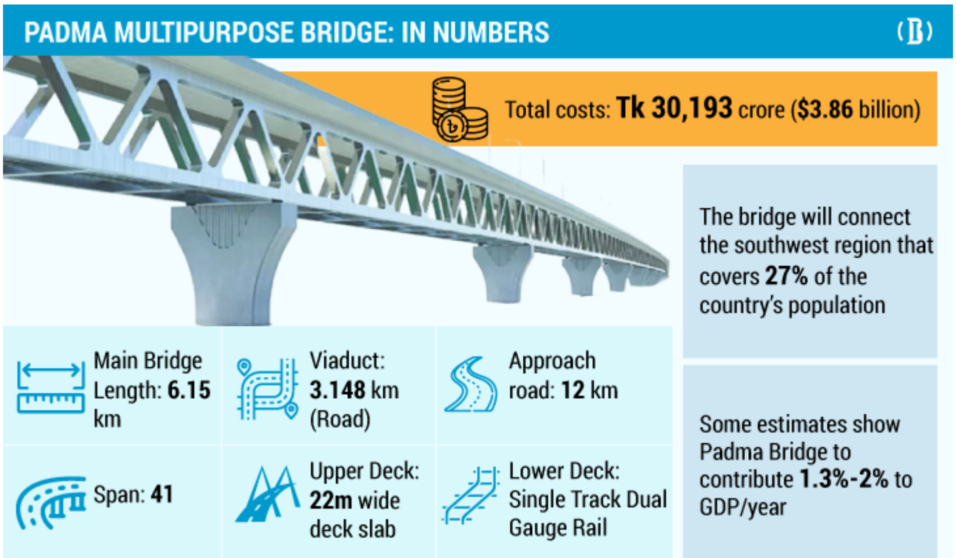

Figure 4: Technical details of Padma Bridge (Business Insider Bangladesh, 2022)

As shown in Figure 5, technical aspects were delegated to a few knowledgeable foreign and domestic organizations through various contract packages. BBA carried out the pre-feasibility study for the Padma Bridge Project between 1998 and 2000. Later, the Japan International Cooperation Agency (JICA) completed the Padma Bridge feasibility study at the request of the Government of Bangladesh (GOB) to the Government of Japan in 2005. The feasibility study proposed that building the bridge will boost regional development through the installation of public services (electric power line, gas pipeline, telecom line), reduce regional poverty, and encourage international trade between neighbouring nations (Zaman *et al.*, 2006).

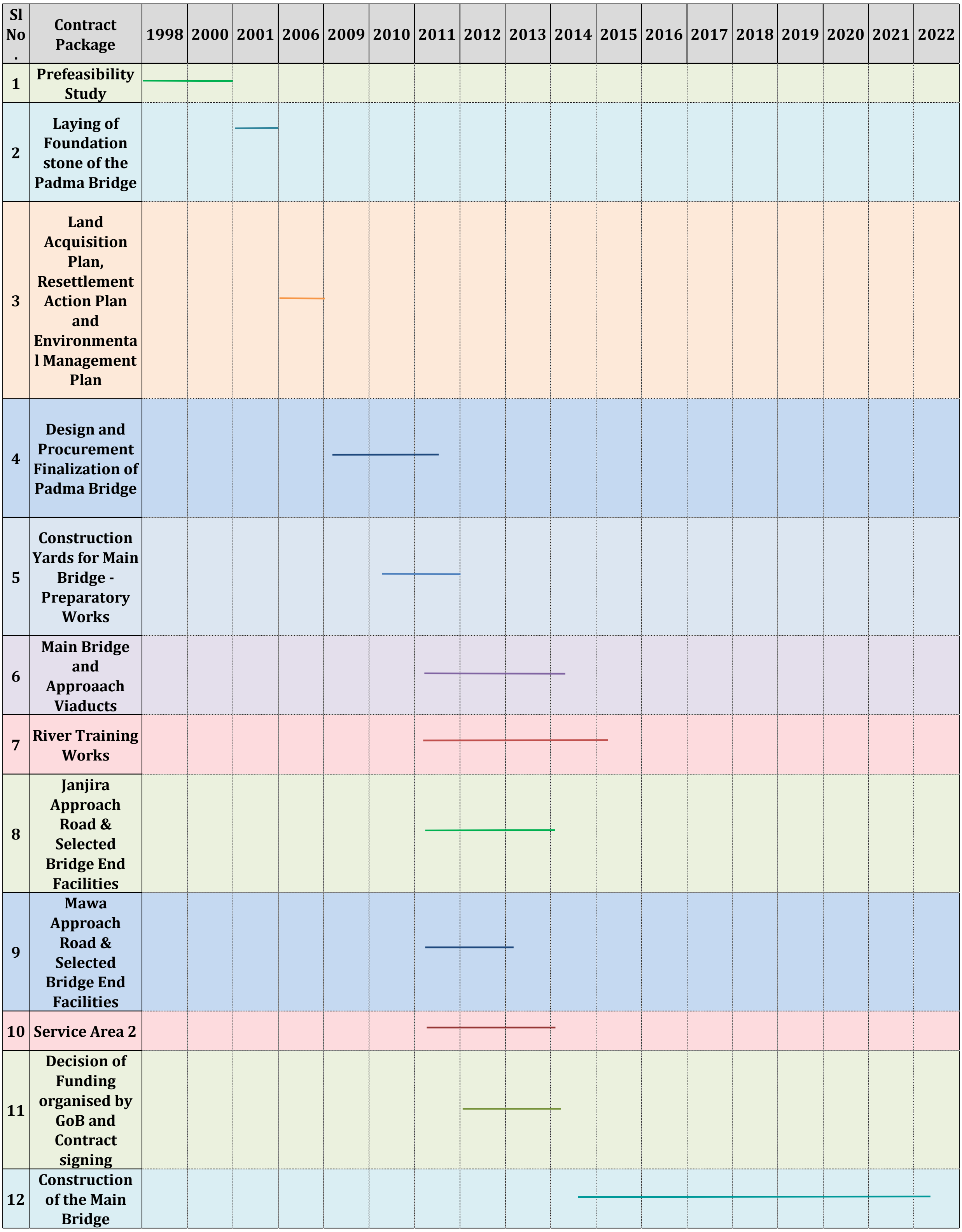

Figure 5: Implementation Schedule of the Padma Bridge Project

3. METHODOLOGY

The Bangladesh Bridge Authority's publications and earlier literature were used to gather secondary data for this study. In order to determine the significant technical originality of Padma Bridge construction, the acquired data were thoroughly examined. The review was carried out by looking into the important conclusions of earlier studies, implementing unique processes in Padma Bridge, and contrasting the benefits and downsides with earlier project management procedures (Campos *et al.*, 2018). Research design, bibliometric data collection, identifying difficulties encountered during the construction of the Padma Bridge, and lastly analysis and interpretation of construction management processes make up the majority of critical review study methods (Qi *et al.*, 2015). The stages for critically examining considerable engineering complexity during the project and management processes of the Padma Bridge are all summarized in Figure 6.

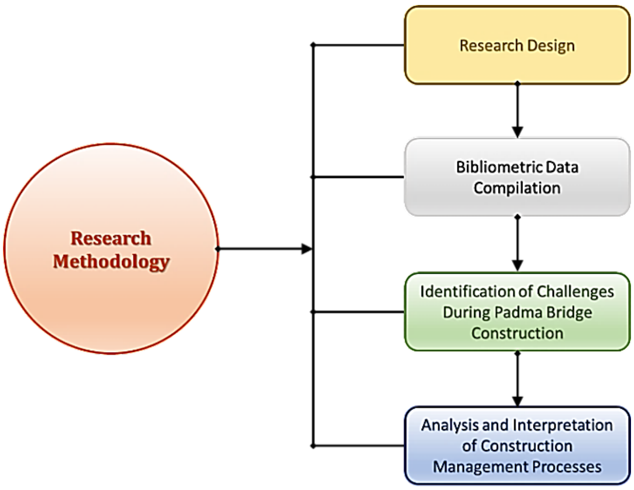

Figure 6: Research methodology of this critical review study

4. MAJOR CONSTRUCTION CHALLENGES

Every work of the Padma Bridge's construction was carried out in accordance with international standards to guarantee that it has a minimum lifespan of 100 years. Additionally, the Bangladeshi government sought to guarantee that the bridge was constructed in accordance with the highest standards (He *et al.*, 2021). During the design and construction phases, a number of critical components of the Main Bridge Contract's works met considerable technical difficulties. The main building obstacles that were faced when putting the bridge's work into actuality are briefly described in the following sections.

A. Site Selection

Four crossing sites—namely, (i) Paturia-Goalundo, (ii) Dohar-Charbhardrasan, (iii) Mawa-Janjira, and (iv) Chandpur-Bhedarganj—were selected for consideration based on a plan-form of the Padma River. After the first assessment of all four sites, two suggested sites, Paturia-Goalundo and Mawa-Janjira, were chosen based on comparison studies from physical, technical, economic, local infrastructural, and social/environmental aspects. However, choosing the ideal location for this historic project was exceedingly challenging.

B. Unfavourable Environmental Condition

The Bridge construction was particularly difficult due to the unfavourable Environmental conditions year-round, which included high sand content in river water, year-round silt in the construction channel, repeated erosion and slips in the construction yard, and frequent tornadoes (wind speeds above strong gale, up to 46 m/s). Due to pile drive, tremendous underwater noise and vibration generated near Hilsa fish sanctuary made the project a challenging one. These conditions have never been seen in conventional bridge construction conditions.

C. Complex River Morphology

For decades, the Padma River has been meandered, twisted, and weaved in different shapes through central Bangladesh. Each zigzag and turn has a geologic story of the region, such as a large flood event or the opening of a nearby dam (Titlee *et al.*, 2020). These events had led to intense erosion along the bank of the river, displacing farms, homes, and even lives. Every year, hundreds and thousands of hectares of land erode and are swallowed by the Padma River (Mondal, 2022). Making a bridge in such a terrible river is a great challenge.

The Padma River, which is thought to have the fastest flow, moves at a speed of 4 to 4.6 meters per second. Approximately 1 billion tons of sediment are transported to the Bay of Bengal annually by the maximum flow, which is 140,000 m3/s (Gani *et al.*, 2022). Since there was so much sediment, the entire construction channel had to be dredged twice a year, which added time and cost to the process. Sometimes the depth of the sedimentation exceeds 10 meters. In 2020 Mawa Construction Yard was the victim of severe river erosion when 125 Roadway slabs and 68 railway stringers were lost into the river and could not be salvaged (Vasquez *et al.*, 2012).

2015 saw considerable erosion on Mawa Construction Yard following the task's award and during the contractor's preparations to begin construction. One batching plant was among the Mawa Construction Yard components lost by the contractor. At the Mawa Construction Yard, the strong river currents during the rainy season of 2020 resulted in significant bank erosion. A sizable portion of the Mawa Construction Yard's eroding area was where slabs for the Roadway Deck, railway stringers, and various items of equipment were piled. A total of 192 railway stringers, 126 roadway deck slabs, and contractor's equipment sank into the riverbed and were no longer retrievable. Rebuilding the deck slabs and importing Railway Stringers from Luxembourg took a lot of time. Projects' work was consequently hampered.

D. Geotechnical Challenges

The construction of steel tubular piles and pile driving posed geotechnical difficulties. Building steel tubular piles with base and skin grouting for the Main Bridge piers to dependable confirm that they can carry the necessary design loads under very deep riverbed scour conditions (up to 62 m depth), as well as very substantial railway loads, wind loads, earthquake loads, and potential ship impact loads (Islam, 2021). The Main Bridge piers' working piles, which are the largest of their kind in the world, measure 3 meters in diameter and up to 125 meters in length. Confirming the construction of RC bored piles for the Janjira and Mawa Approach viaducts, as well as Transition piers P1 and P42, posed a significant problem. On the Mawa side along the Approach Viaducts position, the natural subsoils had a depth of up to 27 m, and they may liquefy after a strong earthquake. Bridge piers. Unexpectedly, as the piling was being completed, the location of the soft soil beneath a few piers was discovered. While bedrock is believed to be located around 6 km downward, the soil at the bottom of the Padma is of the soft mud variety. Flow Slide occurred frequently during precise dredging for the preparation of a slope with just a 250 mm tolerance due to the soil conditions throughout the whole working period, which was a significant difficulty (Oberhagemann *et al.*, 2020). It took a lot of time and money to reconstruct in accordance with the specifications of the design.

E. Funding by own resources

Raising fund for the Padma bridge's construction at that crucial time for the country was a significant task. The World Bank delayed making its decision, therefore the government decided to build the bridge on its own. Prime Minister Sheikh Hasina declared that the Padma Bridge will be built using national funds (Liton & Hasan, 2012). The historic brave choice that was made pushed the construction of the Padma Bridge, which was opened in 2015 (Hossain *et al.*, 2018).

F. Fabrication and Assembly of Structutal Components

In roughly one and a half years, the design and testing work for the new pilings was completed. Steel trusses were still being produced in China at this time. At the Mawa Construction Yard, the steel trusses started to assemble as they came one by one. The steel truss is not being put in any shape because the pile and pier construction there is taking longer than expected. In the event that there is a pressing requirement for storage space, each steel truss is 150 meters long and 3200 tons in weight. The steel truss, which is of the Warren type, is made from steel plates with a thickness range of 40 to 110 mm. After being transported to the Mawa site, the nodes and chords were assembled there using welding to create a whole truss. The nodes and chords were made in China. Each truss has a self-weight of 3200t. The truss had to be moved by a floating crane and put on top of the piers, which was a significant difficulty. The 3600t capacity of the Tyan Yee floating crane was customized (Du & Weng, 2021). The steel truss had to be launched in a certain order for erection since some parts of the bridge are straight and other parts feature horizontal and vertical curves. The nodes and chords of the truss were manufactured in China and put together at Mawa, in accordance with the authorized Program Rev-4B, but pile driving for those piers had to wait a while because the contractor had to wait for the 22 piers' pile working plans to be sent to him. The site's truss storage experienced major issues as a result of the construction delay.

5. SUSTAINABLE MANAGEMENT

A. Site finalization

Based on a plan-form of the Padma River, four crossing sites—namely, Paturia-Goalundo, Dohar-Charbhardrasan, Mawa-Janjira, and Chandpur-Bhedarganj—were chosen for consideration. Two recommended sites, Paturia-Goalundo and Mawa-Janjira, were chosen based on comparison studies from physical, technical, economic, local infrastructural, and social/environmental viewpoints after the initial screening of all four sites. Further comparisons between the two preferred locations were made while taking into account (i) economic viability (economic internal rate of return, benefit/cost ratio, net present value); (ii) economic costs (direct investment costs, operation/maintenance); (iii) regional development (increase in gross regional domestic product)/poverty reduction; and (iv) social/resettlement issues. Last but not least, the Mawa-Janjira site was selected as the best location for the construction of the proposed bridge despite having significantly worse social effects than Paturia-Goalundo due to, among other things, higher bankline stability, higher traffic forecast, lower project construction costs, better EIRR (economic internal rate of return), and other indirect benefits like improved accessibility to the southwest and creation of an international road network. In addition, the government had to spend Tk 4,700 crore on land acquisition, while Tk 3,000 crore in value-added tax was paid on consulting fees.

B. Management for Environmental Protection

According to a study done as a part of the biodiversity baseline survey, the mother Hilsha migrates in deep water. Therefore, it was decided to stop all construction works in the Padma River during Hilsha's breeding and migration season if the depth was greater than 7 meters, and this decision was carefully followed. All activities were prohibited in the Padma River's main channel due to the fast-moving water. Around the bridge, a wildlife sanctuary was developed that comprised a Charland area for the conservation of biodiversity, including the unhindered breeding of turtles. A rise in Hilsha production was observed during the bridge construction phase according to the biodiversity monitoring program.

It was noted that the sound level decreased little as the pile was driven, and the rate at which the sound decreased with distance was very slow. The sound pressure level was less than the injury threshold for fish, which is 206 dB peak, and for pinnipeds, which is 190 dB RMS. The fact that fish were not harmed by the sound of piling was further validated by fishermen who fished within 100 meters of the piling site.

The bridge has a 100-year lifespan. As a result, the design of the bridge takes into account the expected changes in sea level rise, rainfall, temperature, and wind speed in the next 100 years owing to climate change. The bridge is located around 240 kilometers upstream of the Bay of Bengal coast. The maximum range, mid-range, and lower ranges of the expected sea level increase are 0.98 meters, 0.60 meters, and 0.26 meters, respectively, according to

IPCC, where the estimated ice sheet contribution was taken into account. Water levels at the bridge site were predicted to rise by 0.47, 0.42, 0.27, and 0.09 meters, respectively, as a result of the net sea-level rise in the four scenarios: 1.00, 0.88, 0.60, and 0.26 meters.

C. Advanced Materials and Equipment

In addition to purchasing resources from China, such as steel plates and other items, more for the construction of the Padma Bridge, more than 20 new bridge materials from other nations had to be purchased in addition to the steel plates, etc., that were already present in China (Islam *et al.*, 2020). These materials included waterproofing supplies from GCP in the UK, steel stringer beams from Arcelor Mittal in Luxembourg, microfine cement from Singapore, polymer slurry from Australia, skin grouting TAM ducts (customized in China), and American PPG Paints made in as seen in Table 1, anodized aluminum parapet rail is available from V & G in the UK. It gathered more than 100 pieces of cutting-edge equipment, including the largest piling hammer in the world (3500KJ), a self-boring pressure meter from the University of Cambridge, a sonicaliper echo sounder from the United States, and chemgrout grouting equipment (Germany).

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As seen in Table 4, anodized aluminum parapet rail is available from V & G in the UK.

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D. Advanced design of the superstructure

After weighing the benefits and drawbacks of the extradosed concrete truss, concrete girder, and steel truss bridges, the design of the superstructure for the bridge was decided upon. After weighing the benefits and drawbacks of the extradosed concrete truss, concrete girder, and steel truss bridges, the superstructure bridge concept design was decided upon. A two-level structure was suggested in each scenario because it has several advantages over a single-level structure. All welded joints undergo selective non-destructive testing, such as visual inspection, UT testing, and MPI testing, as well as destructive testing, such as tensile and bend tests. In accordance with the terms of the contract, all welded joint surfaces are prepared for painting by grinding and sandblasting. The entire truss is painted using a three-coat method under humidity- and dust-controlled conditions. The trusses were moved from the assembly yard and put onto the piers using a floating crane (Tyan Yi) with a capacity of 4,000 tons (Robin Sham, 2015). Seven continuous structural modules are formed by connecting steel trusses every 150 meters. Each of the six modules has six spans, and one module has five spans. Warren-type two-level continuous steel trusses are used to create composite superstructures that have pre-cast rail slabs on the lower deck and longitudinally post-tensioned deck slabs on the upper deck.The upper deck has a precast concrete deck slab that is 21.65 meters wide and acts as a four-lane roadway with a breakdown lane that is 2.5 meters wide on each side and concrete barriers along the sides and midway (Figure 7). The match-cast portions that made up the deck slab. Each segment is 2 and 2.15 meters long. Segment units are post-tensioned longitudinally and adhered together. The roadway deck slab rises 13.6 meters above the base of the lower chord.

A steel truss bridge with a concrete top slab can have steel weights of up to 3,200t per truss, and when the concrete decks are added, the weight increases to 8,600 t. Nodes and chords of each truss were constructed in China using steel plates that ranged in thickness from 40mm to 120mm (Tian *et al.*, 2021). The nodes and chords were combined and welded into the final 3D shape at the Mawa construction yard.

Figure 7: Provision for a dual gauge double-stack container freight rail line along the lower deck.

At the end of the bridge, the road viaducts are constructed with Super-T girders (Figure 7). A type of pre-cast post-tensioned concrete bridge beam is called a super-T girder. These Super-T girders make up 83 of the bridge's spans, 39 of which are on the Mawa side and 44 of which are on the Janjira side. 438 Super-T Girders in all, comprising 204 on the Mawa side and 234 on the Janjira side, were pre-cast. These five to seven girders, each between 34 and 38 meters long and 1,800 mm deep, make up the single viaduct roadway cross-section (Figure 7). Over the girders is a 180 mm deck slab that has a 50 mm asphalt concrete surface. At each end of the railway approach viaduct, there are seven spans. Six PSC l-girders, each 2200 mm deep, support each span, and the deck slab is 250 mm thick. Three profiled tendons of 29 x 15.7mm dia high-strength and low relaxation steel strands are included with each PSC I-girder. C60 is the concrete grade. The PSC l-girder decks are supported by pot bearings, which also provide seismic protection.

Table 1
Materials used for the construction of Padma Bridge

Major Materials	Quantity	Specification	Source of Supply
Deformed Bar/Rod	108264 tons	It took 92 thousand 286 people for the main bridge. The rest is used for connecting roads.	Domestics
Steel plates	289,000 tons	Pilling and other purposes	China
Steel Span-41	1 lakh 26 thousand tons	steel plates are attached to the spans.	China
Bearing Plate	96 sets	Friction pendulum bearing. The largest bearing weighs about 25 tons. One set of bearings is capable of carrying a load of about 10,000 tons.	
	3556 Sets	Apart from bearings, 3 thousand 556 sets of other types of bearings have been used in Padma Bridge. These bearings help to connect the different parts of the bridge	
	28 Set	All bridges have expansion joints (expansion joints) to accommodate expansion and contraction under heat and pressure. These bearings have been installed in this work.	
Cement	2.25 lakh tonnes 0.25 lakh tonnes	Main Structure Others Structure Padma Rail Link Project	Domestics Domestics Domestics
Microfine Cement	2 thousand tons		Singapore
Sand	64 lakh 58 thousand 115 cubic meters	Sand has been used in the project. 52 lakh 97 thousand 736 cubic meters is taken by river administration.	Coarse sand has been brought from Sylhet and Sunamganj
Stone	15,50,260	Main Structure & Link Road	India & UAE
Bricks	1,22,97,914	Bricks have been used in connection road work. No brick was used in the original bridge.	Domestics
Rock	18,86,000	Used for river management	Jharkhand, India
Concrete Block	8 million	Concrete blocks are needed for river management.	Domestics
Geo Bag	1 crore 90 lakh 90 thousand 521	Geo bags of 125 and 800 kg are used in the river basin of Padma Bridge. 800 kg geo bags and solid rock were thrown into the river to form the foundation in the pile area of the bridge. The sack of 125 kg is thrown to prevent the erosion of the river bank to do the work of river management. Around 24 lakhs of 250 kg geo bags have been installed.	Domestics
Bitumen	2,100 tons		Domestics
Cables	3 Lakh Meter	High-voltage electric line supply	Domestics
Pipe	1 Lakh 20 thousand meter	760 mm dia Gas transmission line through Padma bridge, Fiber optic and Telephone duck which dia is 150 mm	Domestics
	264 each	Pipe-like (hollow inside) steel piles of a three-meter radius are placed on the main bridge i.e., the river section. Their weight was about 1 lakh 62 thousand tons	China
Static load pipe	27	10 steel pipes, 17 board pipe	China
Lamps	415 lamps	328 lampposts have been set up on the main bridge, 46 on the viaduct at the Jajira side, and 41 on the viaduct at the Mawa side. Besides, another 200 electric lights are located on the connecting road on both sides.	Domestics
Diesel	4.15 Crore Litter		Domestics
Waterproof Membrane	560 tons		UK
Rail Girder (Stinger)	9000 tonnes		Luxemburg
Water Disposal Pipe	39000 Meter		Australia
Polymer (For seating Pipe)	249 tonnes		Australia
Hydraulic Hammer	25 thousand Metric tonnes	The world's largest and strongest hammer is being used in the Padma Bridge.	Germany
Floating crane	3,600 metric tonnes	lifting capacity of span carrying crane 3600 tons	China

E. Overcoming Geotechnical challenges

A unique pile foundation design that consists of six floating heaps and one center pile with the largest raking pile in the center were both utilized to resolve the geotechnical challenges. Raking steel tube-driven piles with a 1:6 inclination were used as the Main Bridge Piles. There are 6 piles on 18 piers and 7 piles on 22 piers. Out of 22 piers, 7 piles on 11 piers have skin grouting, and the remaining 7 piles on the other 11 piers don't have that. Pile lengths range from 98 to 125 meters, with the longest-driven tubular pile in the world measuring 125 meters. 124.6MN is the maximum pile capacity (Islam, 2016). The 3m exterior diameter steel tube piles are made from a 60mm thick steel plate (Figure 7). A 70-meter-long bottom part and a roughly 50-meter-long top section were created for each pile by combining 3.2-meter-long pile components. Full penetration welding was used to link each pile segment. After welding, a non-destructive test (NDT) was performed on the pile's inside and exterior. Visual inspection and ultrasound testing were used for NDT testing. Some samples of the welded plates were taken for laboratory tensile tests, bending tests, and impact tests (De Silva *et al.*, 2013). Pile was propelled by MENK hammers with 1,900, 2,400, and 3,500 kJ capabilities. The manufacture of the 262 piles required a total of 155,779 mt of steel plate (Muhaimin *et al.*, 2021).

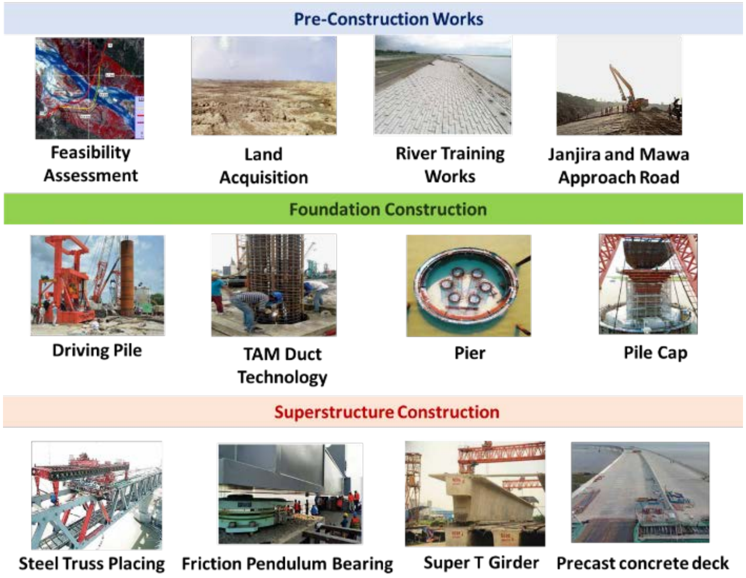

Figure 8: Padma Bridge Project Construction Processes

Through the use of TAM nozzles, microfine cement grout was injected into the skin-grouted pile to fortify the surrounding soil. There are ten 137mm x 130mm TAM ducts that are welded all the way around the pile (Figure 8). On all three of its exterior faces, each TAM duct includes eight 8mm grouting nozzles spaced one meter apart. After the sand was removed from the TAM ducts and before base grouting, the skin grouting operation was completed. "Microfine Cement" grout is poured into the TAM duct from the top with a pressure of up to 3 MPa after driving the pile and cleaning the dirt inside. The skin friction of the pile is considerably increased by the microfine cement grout that travels via the nozzles, penetrates the surrounding soil, and passes through. 11 piers were constructed using skin-grouted piles, with 7 piles under each pier. The TAM duct mechanism is being employed for the first time ever in the world to increase skin friction in the silty sands of the foundation.

F. Overcoming Complex River challenges

Keeping such a turbulent river under control was a big challenge. Since there was so much sediment, the entire construction channel had to be dredged twice a year, which added time and cost to the process. Sometimes the depth of the sedimentation exceeds 10 meters.

The complex river morphological challenges of this bridge project were resolved by introducing massive river training works, employing protection works of lower slope, applying dredging works and placing geobags to treat scour holes and introducing unique pile design along with advanced geotechnical solution including TAM duct mechanism.

(i) ***River training works:*** The river training works were performed to protect the riverbanks from erosion and to ensure that the river will flow under the bridge for its entire lifespan. The river training system consists of a guiding revetment along both banks of the river. Revetment and Slope Protection are layered systems placed on a sloping surface as protection against hydraulic forces and scouring (Figure 9). Revetment constructed by stripping of topsoil with a crest at an elevation of + 9.5m PWD. Dredging was performed from elevation +2.4m to between -12m-25m to develop a uniform slope of 1:6 as per design. The Upper and lower slope maintained at 1:6 (Oberhagemann *et al.*, 2020). This extends from an elevation of +2.5m to +9.0m PWD and is covered by 400 x 400 x 400/300mm CC blocks over the geotextile (Neill *et al.*, 2010). At elevation +5.6m PWD there is a 3m wide berm which is similarly paved. An Anchor Beam has been placed in between the upper slope and the river-side boundary at +2.5m PWD. The Anchor Beam provides a stable reference for the placement of the concrete block pitching. This beam is of 1000mm x 400mm cast in situ reinforced concrete wall (segmental) partially buried in the excavated surface with geotextile material underneath.

(ii) ***Protection of Lower Slope:*** The embankment slope protection was covered by placing CC blocks over the geotextile (Figure 8). Blocks were laid parallel to the direction of the river flow over the geotextile filter. Blocks are placed in a manner to have gaps of 10mm that are filled with pea gravel. Geotextiles were required to be provided as an under-layer filter for the various slope protection systems (Kamal *et al.*, 2019). Concrete blocks were laid on a 400 g/m² non-woven geotextile underlayer. 3 layers of 125 kg bags were dumped on the lower slope (Figure 9). 125 kg geobags were transported by barge equipped with an adjustable guiding frame/chute up to 22m long for precision dumping onto the river bed. Geo bags were filled with sand with a size $\geq$1.0mm. Geo bags were dumped at different stages from -25m/-20m/-15m/-12m up to -2.4m PWD (Hossain & Hasan, 2016). Post-dumping survey conducted by multibeam eco-sounder. Pre-survey and post-survey results were compared to confirm the design thickness of 0.45m or dumping density of 6.27/m².

(iii) ***Dreging to remove silt and sediment:*** Developing a suitable method using dredging equipment to build and trim underwater slopes to the tolerances required to allow placement of the revetment bank protection materials (in water depths up to 25 m) (Oberhagemann *et al.*, 2020).

(iv) ***Protection of Scour with geobags:*** Creating appropriate methods and specially designed machinery or equipment to reliably and precisely insert geo-bags in water depths of up to 25 meters (on the trimmed underwater slope and in the launching apron). 600 kg of rice bags, 125 kg, and 800 kg of geo-bags were placed within the scour holes (Figure 9).

Figure 9: Dumping of Geobags on the lower slope

G. *Construction Scheduling and Contract Management*

Under the guidance of the Consultants of Bangladesh Bridge Authority (BBA), the land acquisition, resettlement, and environmental protection projects of the Padma Multipurpose Bridge started in January, 2009, and completed in June, 2022 (Figure 10 and 11). The Jajira Approach Road was started under the supervision of Bangladesh Army, (Construction Supervision Consultant), and it was completed in 2016. Mawa Approach Road construction began in January 2014 and was completed in July 2017 (Jalil & Mia, 2021). China Major Bridge started the main Bridge's construction in November 2014 and completed in June 2022.

River construction was initiated by Sinohydro Corporation Limited and it began in November 2014 and finished in June 2022. The completion of the Padma Bridge was on schedule despite the global COVID 19 pandemic because of the maintenance of the extremely stringent construction timetable and superb management.

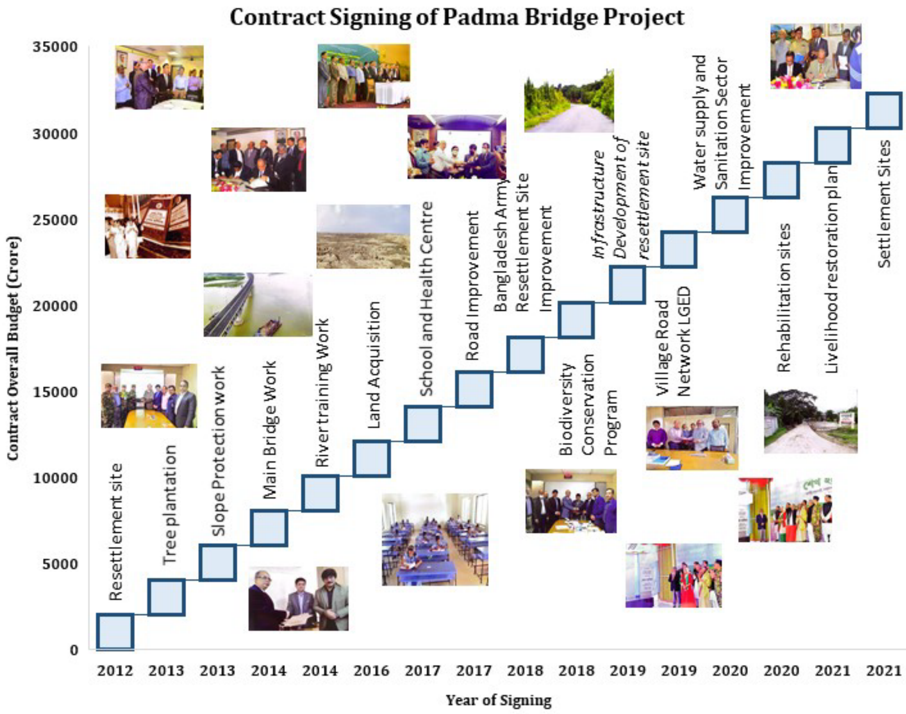

Figure 10: Contract management of Padma Bridge Project

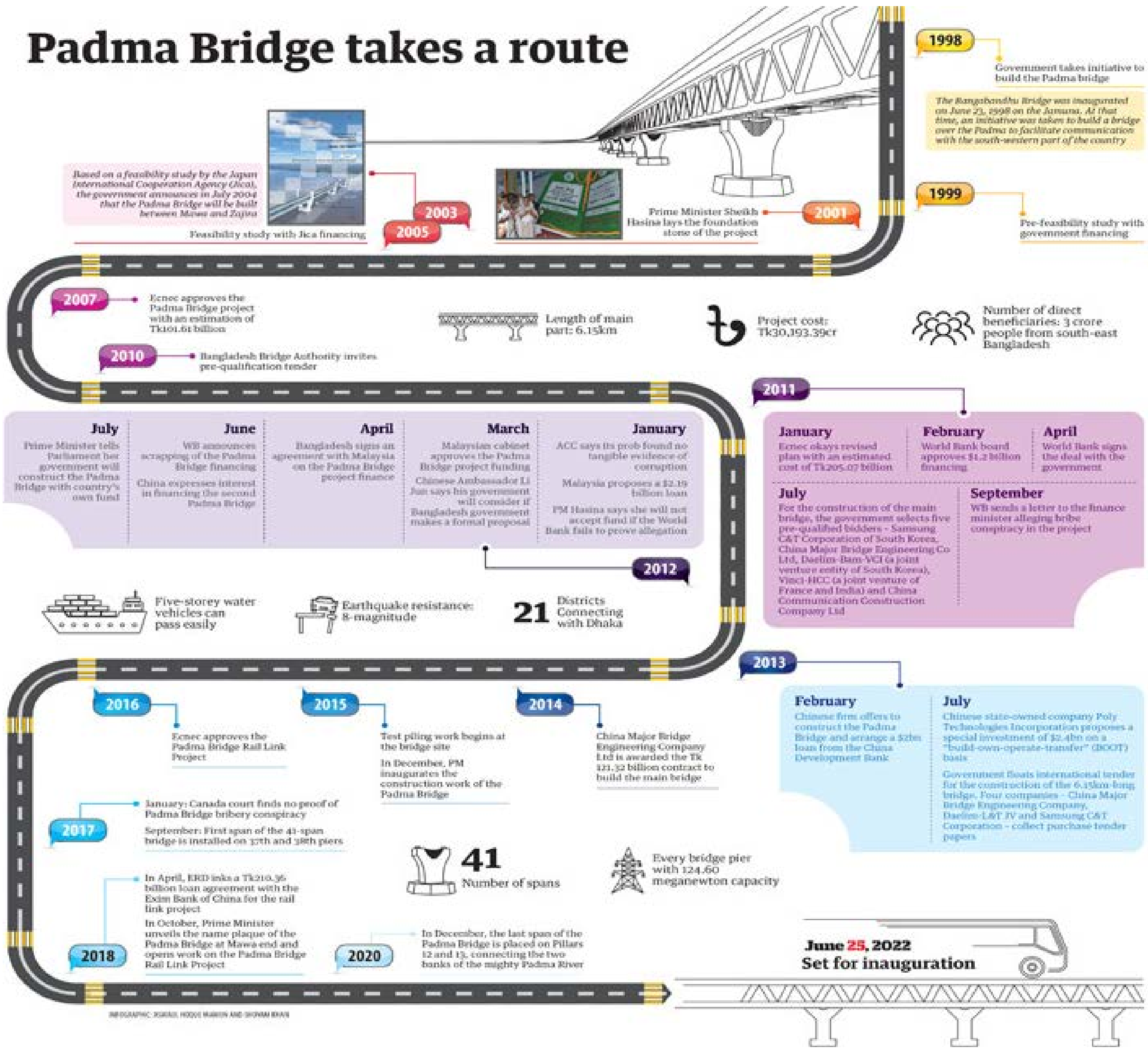

Figure 11: Construction schedule of Padma Bridge Project (Dhaka Tribune, 2022)

Figure 12: A few young members of the ACE engineers working on the bridge project

H. Construction Safety Measures

Local workers have improved their ability to defend themselves at the construction site due to the continuous training on construction safety (Figure 10). The project's vulnerability to extreme weather events like heatwaves, cyclones, and floods was constantly checked by construction safety monitoring team.

I. Management of COVID-19 Pandemic

The project works of the Padma Bridge did not even stop for a single day due to the COVID 19 epidemic. During the epidemic, the bridge contractor from China was severely impacted. BBA declared that the Chinese consultants and Contractors could not return to Wuhan, China, which was thought to be the heart of the COVID-19 pandemic. No one other than the Contractor, Consultant, and BBA is permitted to leave the Project site, and no one is permitted to enter from the outside. In the Project sites Service Areas-1 and 2, a full medical team with the necessary tools and medications was established. Few people were suffered from COVID-19, and there were no injuries because of rigorous adherence to the COVID guidelines and restrictions on people's movement (Lotfi *et al.*, 2022). This made it easier for the project to continue operating. Figure 12 shows specifics of COVID safety precautions taken during Padma Bridge building. However, the project work advanced somewhat slowly since the material supply chain was hampered.

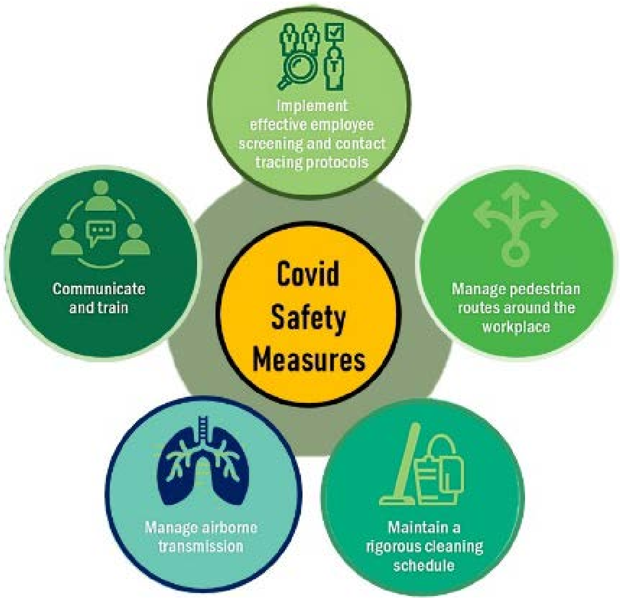

Figure 13: COVID Protocol issued during Padma Bridge Construction

6. CONCLUSION

The Padma Bridge's key construction challenges were examined extensively in this study, as well as the sustainable management strategies used to address them, leading to the establishment of four new world records. Introducing the longest-driven steel tube piling, building the longest steel truss bridge, building the largest double curvature friction pendulum bearing, and building the largest single contract for river training works are the four world records. Only a few people suffered from COVID-19, and there were no injuries since the construction throughout the COVID period was handled by tightly enforcing the COVID rules & limits on the mobility of people. Thus, this sustainable construction management approaches created the groundwork for the completion of the Padma Bridge. Padma Bridge ultimately stands as a miracle above the mighty river Padma, connecting districts and ensuring steady economic growth for the next 100 years, after successfully overcoming a sea of man-made obstacles and engineering difficulties. The building of the Padma Bridge has significantly increased the confidence of the civil engineers of Bangladesh.

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Environmental Safeguards in the Construction of Padma Bridge

M. Feroze Ahmed[1*], Tanvir Ahmed[2], and Md Tauhid Ur Rahman[3]

[1]Department of Civil Engineering, Stamford University Bangladesh, Dhaka, Bangladesh
[1]Member, Panel of Expert, Padma Multipurpose Bridge Project
[2]Department of Civil Engineering, Bangladesh University of Engineering & Technology (BUET), Dhaka, Bangladesh
[3]Department of Civil and Environmental Engineering, Military Institute of Science and Technology (MIST), Dhaka, Bangladesh

emails: *[1*]ferozeahmed@gmail.com; [2]tanvir@ce.buet.ac.bd; and [3]tauhid@ce.mist.ac.bd*

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Wildlife Sanctuary

ABSTRACT

The Padma Bridge, being the largest infrastructure development project of Bangladesh, required extensive environmental safeguards to make the dream project of Bangladesh environmentally sound. Threat to biodiversity particularly breeding and migration of HIlsha (Tenualosa ilisha) fish, safe disposal of 50 million m3 of dredging spoils, disturbances and displacement of wildlife, conservation of biodiversity, plantation of trees lost to the project, control of construction related noise, air and water pollution, occupational health and safety of the workers were the main environmental impacts of the project. An Environmental Action Plan (EAP) with effective protective measures was successfully implemented. Environmental monitoring of quality of both surface and drinking water, ambient noise level, concentration of PM10, PM2.5, CO, ozone, oxides of nitrogen and sulfur in ambient air, disposal of domestic, construction and hazardous wastes, disposal of dredged spoils, use of personal protective equipment (PPE) and safety at work sites were conducted regularly by a team constituted for this purpose throughout the project period and protective measures were adopted as and when required. Increased flow, water level and temperature in Padma River due to climate change were considered in the design of the Bridge. A wildlife sanctuary has been established in the project area for flourishing of flora and fauna in the protected environment.

1. INTRODUCTION

In the regional context, Padma bridge is strategically located on the Asian Highway route AH-1 and Trans-Asian Railway Route. In the country context, it will provide a vital link in the transport network of Bangladesh by connecting southwestern region of Bangladesh, Mongla sea port and Beanpole land port located in this region with eastern region of the country and Chittagong Sea port. Padma Bridge will significantly boost economic and social uplift of the country, especially in the southwestern region of the country and function as a catalyst for poverty reduction. The construction of Padma Multipurpose Bridge will increase national GDP by 1.23 percent and southwest regional GDP by 2.30 percent and reduce poverty by 0.84 percent.

The people of Bangladesh had a long dream of having a bridge on the fiercely flowing Padma River for easy communication between eastern and south-western parts of country. But construction of Padma Multipurpose Bridge was the most complex and difficult project on the mighty river Padma, the second largest river of the world next to Amazon in respect of flow. The river Padma carries the combined flow of the two mighty rivers, the Ganges and the Brahmaputra with a peak discharge of 140,000 m^3/s and a peak velocity of 4 to 4.5 m/s and transport an estimated 1 billion ton of sediment to the Bay of Bengal (GoB, 2022a). Construction of Padma Bridge by taming such a turbulent river having enormous capacity of erosion of riverbank and bed was a big challenge.

Padma Bridge is the largest Infrastructure Development project in Bangladesh. The implementation of such a megaproject requires comprehensive Environmental

Impact Assessment (EIA) of the project, identification and quantification of environment impacts, development and implementation of environment management plan, and monitoring of environmental impacts of project activities and effectiveness of remedial measures adopted by the project. The environmental activities in the construction of Padma Bridge were planned to meet the co-financiers' requirements, Environmental Conservation Rules, 1997 of the Government of Bangladesh (Gob, 1997) and environmental compliance requirement of the contractors as mentioned in their contract specification. Although the co-financiers, the World Bank (WB), Asian Development Bank (ADB) Japan International Cooperation Agency (JICA) and Islamic Development Bank (IDB) withdrew their commitments to finance the project, the planned environmental activities were fully implemented. This paper describes the environmental safeguards adopted by BBA in the construction of Padma Multipurpose Project to make the project environmentally sound.

2. ENVIRONMENTAL IMPACT ASSESSMENT.

Bangladesh Bridge Authority (BBA) prepared the Environmental Impact Assessment (EIA) report and Environmental Action Plan (EAP) at the design stage of the project in 2009-2010 (Maunsell/AECOM,2010a). Based on the recommendation of the EIA report BBA carried out a follow-up study in 2015-2016 to enhance the baseline information covering seasonal variations, prepare a monitoring plan for the construction and operation stages.

A. Physical and Biological Resources

The project boundary for environmental impact assessment included 15km upstream, 7 Km downstream, and laterally 6km from riverbank at Mawa towards Dhaka and 4km from riverbank at Janjira side. The project site has a rich physical and biological resources that are mutually dependent and belong to a unique ecological system. The physical resources including homestead, agricultural and commercial lands, char land and water bodies as observed during the baseline survey in 2015-2017 (Agroconsulting S.p.A, and Sodev, 2017). These features change with the change of the flow of the mainstream of the Padma River and associated erosion and accretion of the bank and bed of the river. The main flow of the river moves from north bank to south bank at an interval of around 12-15 years causing enormous bank and bed erosion. The River Training Works (RTWs) were located along relatively stable bank lines allowing the river to continue its usual movement. Hence, no obstruction to natural flow of the river was made to induce additional change of physical environment within the Padma River influence area.

An inventory of biological resources in the project area was made by conducting a baseline survey in 2015 (Agoconsulting S.p.A, and Sodev, 2017). A total of 311 species of Flora under 247 genera and 90 families was found in the PMBP area. Among the floral species 95 (31%) species were trees, 33 (11%) species were shrubs, 173 (56%) species were herbs and 10 (3%) species were climber. The study also revealed that 56 plant species were used as medicine in primary health care, 41 used as food and fruit, 57 as vegetables, 29 as fodder, 52 as construction material, 22 as timber, 11 as fuel wood, 9 as cash crop, 10 as culinary and 10 as decorative plants. The habitat-wise distribution of flora is shown in Figure 1. The wildlife recorded in the areas include 112 species of birds (86 resident and 26 migratory), 16 Amphibians, 35 reptile and 25 mammals. 89 species of fish were identified in the project area where Hilsha was the most dominant and important fish in the project area.

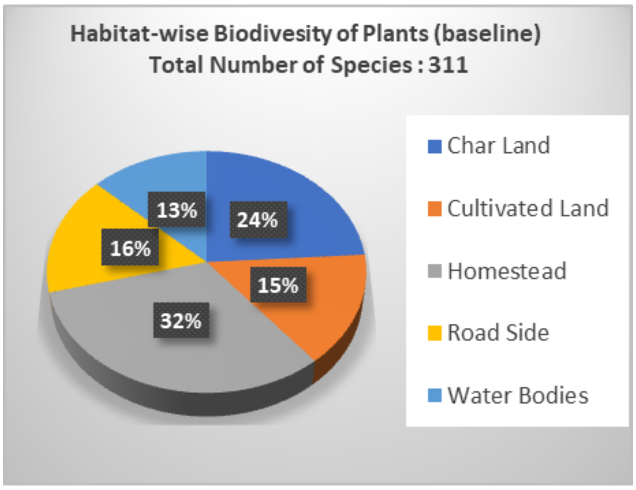

Figure 1: Habitat-wise Baseline Biodiversity in PMBP Area in 2015

B. Environmental Impacts

Comprehensive Environmental Impact Assessment was carried out for identification and quantification of major environmental impacts for mitigation. The major environmental impacts identified by comprehensive EIA of the project are given below:

- The Padma River is the migration route of Hilsha (*Tenualosa ilisha)* fish to upstream of the river and the bridge site is breeding ground for Hilsha and many fishes. The massive construction work in the river is likely to have adverse effect on breeding and migration and breeding of Hilsha and other fishes of Padma River.
- Construction work will disturb and displace wildlife and biodiversity in the project area may be adversely affected by massive construction work.
- Dredging of char land for construction work will destroy the breeding ground turtles.
- Disposal of huge quantity of dredging spoil on land or in water will affect the quality of land and river water. Presence of toxic substance in dredge spoils may pollute the environment.
- Disposal of wastewater and hazardous waste will also cause deterioration of river water quality.

- Destruction of trees from the areas acquired for the project will reduce tree cover in the project area.
- High noise level in water and ambient air due to driving of 3m diameter pile may have adverse impact on aquatic lives and hearing of workers and population around project site.
- Inadequate sanitation, solid and construction waste disposal will create a filthy environment.
- Construction related air, water, soil and noise pollution may create an unhealthy environment in the project site.
- Occupational health and safety of large number work force are of great concern.

C. Environmental Management Plan and Mitigation

Environmental management plans were made for all and components of the project to eliminate, reduce, compensate all adverse environmental impacts as well as enhancement of positive impacts of the project. The mitigation measures implemented by the project for adverse impacts are stated below.

i. Protection of Hilsha Fish

A study conducted under biodiversity baseline survey reported that the mother Hilsha migrate in deep water. So, a decision was taken to suspend all construction activities in the Padma River having depth greater than 7m in Hilsha breeding and migration season and the decision was implemented strictly. The high velocity of water prevented all activities in the main channel of the Padma River. Biodiversity monitoring program recorded an increase in Hilsha production in the construction period.

ii. Biodiversity Conservation

A biodiversity conservation program was conducted throughout the whole project period. An awareness of importance of biodiversity was raised among the workers, fishermen, local people and school children. All people around the project area were instructed not to disturb wildlife and destroy their breeding spots and nests. A wildlife sanctuary was established for conservation of biodiversity.

iii. Breeding of Hard Roofed Turtle

Construction of bridge and maintenance of channels for ferries and other watercrafts required dredging of char land used for breeding of turtles. An alternative char land was required to be protected for breeding of turtle. A wildlife sanctuary was established around the bridge which included char land for undisturbed breeding of turtles.

iv. Disposal of Dredging Spoils and hazardous wastes

Samples of soils to be dredged for RTW works were collected and tested in BUET Environmental Engineering Laboratories for concentration of lead (Pb), Cadmium (Cd), Chromium (Cr), Copper (Cu), Zinc (Zn), Manganese (Mn), Arsenic (As), Selenium (Se) and Mercury (Hg). Since, acceptable concentrations of these heavy metals in soil are not available in BDS, the results were compared with USEPA standards 2000. Trace amounts of Cr, Cu, Zn, Mn, As, Se, and Hg were found while concentrations of Pb and Cd were below minimum detection level (MDL). It was confirmed from the test results that no heavy metal accumulated in the bed of Padma River in bridge influenced area. But still disposal of dredging materials in water bodies having low dilution factor can deteriorate water quality (increased turbidity and total solids) and create artificial chars to obstruct water flow. On the other hand, disposal on agricultural lands reduces soil fertility. In the absence of lowlands or ditches for filling on both sides of river, some char lands were acquired by BBA for disposal of dredged soil. Discharge of dredged materials or effluent from deposits of dredged materials in agricultural land was strictly prohibited. The flow in the main channel of the Padma River is very high, about $140{,}000\ m^3/s$ in the monsoon period. The water becomes highly turbid and carries more than 1 billion tons of sediment per year. In this period, the discharge of some dredging materials was allowed in high flowing turbulent river in the monsoon, but no dredging material was discharged in river in dry season. In some locations, polythene bag and other materials were found that interfered with dredging operations.

v. Tree Plantation

The inventory of environmental resources in EIA report indicated that about 366,886 trees from acquired land for the project were cleared during construction of the project in which 101,319 were bamboo trees and 109,095 were banana and the rest were wood and fruit trees. On the other hand, a lot of scope for plantation of trees was created in 7 resettlement sites, 2 service areas, roadsides and vacant areas acquired by BBA. About 1,73,200 trees have been planted so far in 100 hectares in resettlement sites, service areas and on sides of approach roads. Different varieties of sapling consisting of 80% timber, 10% fruit, 5% medicinal and 5% ornamental plants have been planted with assistance from the Department of Forest. PMBP has already received Prime Minister’s National Award for tree plantation twice in recognition of best performance in tree plantation (GoB, 2022b). The ultimate target is to plant 3 trees against destruction of 1 tree by the project.

vi. Sound Level

The piers of bridge were constructed on 3m diameters steel piles driven to a maximum depth of 122m. The Menk hammers of 3500 kilojoules, 2400 kilojoule and 1900 kilojoule capacities, specially designed in Germany for this project were used for pile driving. The project made world records both in respect of depth of driven piles and capacity of hammer used for driving these piles. But it produced high sound in ambient air and higher sound in water that may be injurious for workers as well as aquatic lives.

The typical sound level in ambient air close to piling was found to be 115dB, which is not acceptable in any standard for humans. The workers engaged in pile driving were instructed to use air plug during pile driving. The sound intensity in water was measured at distances of 25m, 50m, 100m, 500m and 1000m from the piling locations at piers. The pattern of sound level in water is shown in Figure 2. The sound pressure level as shown in Figure 2 was very high and varied between the starting and ending of every stroke of the hammer. The sound generated during driving of the top and bottom sections of the pile no.1 of pier No. 9 is recorded at distances from 50m to 1000m and shown in dB RMS in Figure 3. It is observed that the sound level reduced a little bit from beginning to end of driving of the pile and the rate reduction of sound with distance is very low. However, the sound level was lower than the injury threshold of peak 206 dB for fish and 190 dB RMS for pinnipeds. The fishermen fishing within 100m from piling location further confirmed that the sound of piling did not cause any harm to fishes (Nizam Uddin, 2018).

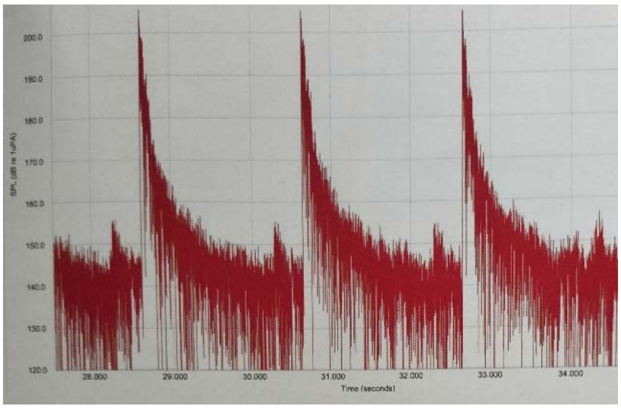

Figure 2: Pattern of Sound Level in Water

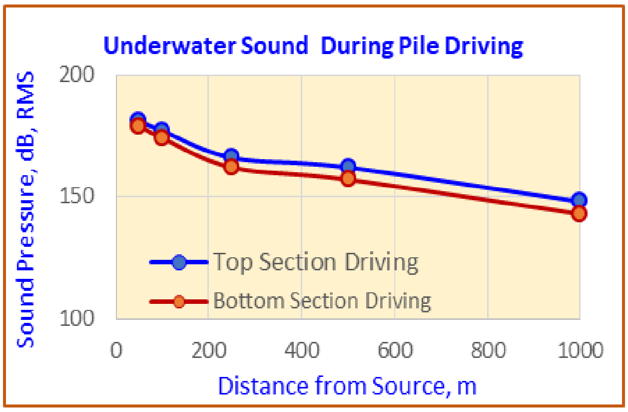

Figure 3: Variation of Sound with Distance

vii. Sanitation, solid and hazardous Waste

Safe sanitation and disposal of the solid waste, construction and hazardous waste was ensured in residential areas, accommodation of workers, construction yards and all workplaces by frequent monitoring. Safe sanitation was provided by installation of sanitary latrines for all. The solid waste was safely disposed in large concrete bins constructed in Mawa and Janjira sites. BBA has a plan to recycle the nutrient in solid waste by composting. Fuel, lubricant and chemicals used for construction were stored in safe containers at designated locations/warehouse as recommended monitoring team. Any leakage of fuel or chemicals was immediately reported, and remedial measures were adopted.

viii. Health and Safety

Occupational health and safety of the workers were given top priority in the construction of Padma Bridge. Safety at the workplaces and use of Personal Protective Equipment (PPE) were regularly inspected by the Environmental Team (ET) of Consultant Supervision Consultant-2 (CSC-2). Health centres, one in Service Area-1(SA-1) at Mawa and one in Service Area-2 at Janjira with doctors, nurses and word boy were established with all facilities and lifesaving medicines. Covid-19 isolated units were also established at health centres to monitor health condition and provide Corona related emergency health services. Speed boat and field ambulance were kept ready for transfer and transport of injured workers.

D. Environmental Monitoring

Environmental monitoring was conducted at regular intervals to observe the effectiveness of the environmental protection measures in reducing impacts and overall impact of the project activities on environmental quality of project area. Biodiversity within the project area was monitored by a consulting firm engaged for this purpose. Environmental monitoring was conducted by physical inspection, visual and instrumental methods. A team comprised of Environmental unit of PMBP, Environmental specialist of CSC, MSC and representatives of contractors was constituted to conduct monitoring. The main tasks of the team were to inspect environmental and occupational health aspects such dredging spoil disposal, solid and liquid waste management, dust and noise control, safety of water and sanitation provisions, as well as occupational health and safety related matters like safety at construction sites, use of appropriate personal protective equipment (PPE), fire safety etc. To comply with Environmental Quality Standards (EQS) as proposed in Environmental Management Plan (EMP) the following environmental quality parameters were monitored at prescribed interval:

- River water quality
- Drinking water quality
- Ambient air quality
- Effluent from dredging spoil
- Noise level

i. Surface water quality

Surface water quality was monitored at regular interval to observe the change in surface water quality during construction period. The water quality parameters monitored were pH, Turbidity, Total Dissolved Solids (TDS), Total suspended Solids (TSS), Electrical Conductivity (EC), Chloride (Cl), Ammonia Nitrogen (NH_3-N), Iron (Fe), Arsenic (As), Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD) and Oil and Grese. The surface water quality was measured quarterly from 6 strategically located points fixed by GPS around the work area. The water quality parameters measured in May 2018 are shown in Table 1. The test results on quality of water of Padma River is generally good. Pollution assimilation capacity of Padma River is very high due the high discharge and turbulent nature of the flow. High Dissolved Oxygen and Low Biochemical Oxygen Demand as compared to baseline values indicate an improvement of water quality during the period of study. Very low chloride content of water indicates that influence of salinity does not reach up to Padma Bridge.

Table 1
Surface Water Quality of Padma River Water at 5 locations

Sl. No.	WQ Para-meters, Unit	Sample ID						BDS	Baseline Value
		SW 1	SW 2	SW 3	SW 4	SW 5	SW 6		
1	pH	7.33	7.58	7.70	7.86	7.91	7.93	6.5-8.5	7.76
2	Turbidity, NTU	107	91.6	101	86.1	118	84.1	-	-
3	TDS, mg/L	93	82	97	89	102	101	-	93
4	TSS, mg/L	69	45	82	64	73	67	-	96
5	EC, µS/cm	148	139	148	140	179	115	-	131
6	Cl, mg/L	6	4	5	6	8	8	-	6
7	NH3-N, mg/L	0.18	0.12	0.18	0.95	0.23	0.22	-	0.58
8	Fe, mg/L	1.6	1.4	1.6	1.2	1.2	1.0	-	0.5
9	As, µg/L	1.5	2.0	<MDL	2.3	2.7	1.5	-	2.0
10	DO, mg/L	6.97	6.81	6.82	6.78	6.63	6.52	≥ 5	4.83
11	BOD, mg/L	0.2	0.4	0.4	0.2	0.2	0.2	≤ 6	1
12	COD, mg/L	3	7	7	4	4	3	-	6

ii. Drinking water

Safe water was ensured by regular monitoring of some essential parameter of drinking water quality. Deep tubewells were the main source of drinking water in residential areas, resettlement sites and works areas. Water samples collected from 9 deep tube wells used as source of drinking water in project site were tested quarterly in laboratory. Out of 9 water quality parameters shown in Table 2, Mn, As, TC and FC are related to health and others are related to aesthetic quality and taste. The test results of all 9 tubewell water samples in Table 2 show that the water supplied for drinking and other domestic purposes was very clear (low turbidity), contained very low hazardous chemicals (Mn and As) and free from microbial contamination. Close examination shows that 2 samples exceed Bangladesh standard for manganese but the allowable concentration of Mn in drinking water has been increased to 0.4 mg/L by World Health Organization (WHO 2011), whereas BDS maintained a strict standard of 0.1 mg/L set in 1991 and enforced by gazette notification in 1997. The Department of Environment (DoE) has recently taken an initiative to update EQS for drinking water. Although presence of microbial contamination was found in baseline samples, no such contamination is found in any of the samples examined later. The deep tube well water used as drinking water in the project area, as compared to acceptable levels in Bangladesh Standards (BDS), was of excellent quality.

Table 2
Quality of 9 Deep Tube wells (DW) Water Used as Source of Drinking Water

WQ Para-meters, Unit	Sample ID									BDS	Base-line Value
	DW1	DW2	DW3	DW 4	DW 5	DW 6	DW 7	DW 8	DW 9		
pH	6.64	6.60	6.68	7.34	7.05	6.45	7.23	8.12	6.47	6.5-8.5	7.76
Turbidity, NTU	1.73	0.87	2.85	0.88	3.14	0.66	7.67	0.71	0.59	10	-
TDS, mg/L	32	259	75	219	461	140	369	49	72	1000	-
Cl, mg/L	14	104	26	50	136	9	86	5	12	150-600	103
Fe, mg/ L	<MDL	<MDL	0.15	<MDL	0.18	<MDL	0.55	<MDL	<MDL	0.3-1.0	0.40
Mn, mg/L	<MDL	<MDL	<MDL	<MDL	0.25	<MDL	0.17	<MDL	<MDL	0.1	0.17
As, µg/L	<MDL	<MDL	<MDL	1.4	6	<MDL	4	<MDL	<MDL	50	2
TC, No./100ml	0	0	0	0	0	0	0	0	0	Nil	10
FC, No./100ml	0	0	0	0	0	0	0	0	0	Nil	2

iii. Dredging Effluent Quality

The dredging material, a mixture of water and soil, when deposited on land, the excess water after depositing solids comes out as effluent. The solid contents of the effluent often remain very high to silt up drainage channels, and khals carrying effluent and pollute receiving water. TDS, TSS, and Turbidity of the effluent from dredged soil were measured. In case of high solid content, the dredger was instructed to increase retention time within embanked area used for discharge of dredged materials. Long detention time in the embank area allows settling of more solid and clarify the effluent for disposal in natural water.

iv. Ambient noise level.

The main bridge contractor, Major Bridge Engineering Company (MBEC) of China, carried out regular ambient noise measurement at construction sites by digital sound level meter. Noise levels in ambient air were measured at different locations and distances from the sources. The results were reported in monthly, quarterly and annual reports of the Construction Supervision Consultants-2 throughout the project period of construction and protective measures were adopted as and when required (CSC-2, 2015-2022).

The baseline sound in Mawa roundabout was found to be 61.5 dB, which is the typical sound level in commercial areas of Bangladesh. The ferry ghat, river and road traffic were the main sources of sound. The main work stations were in the river, far away from residential and commercial areas. The noise from the construction hardly reached the populated areas. The noise level in the residential area varied from 53 dB to 68 dB. The maximum acceptable levels for residential and commercial areas are 55 dB and 70 dB respectively. However, the highest ambient sound of 115 dB was measured at 20m from pile driving and high sound was also measured in workshops exceeding Bangladesh standard of 75dB for industrial area. The contractors were instructed to provide air plug/air muffles to workers exposed to higher sound level and ensure its use.

v. V. Ambient air Quality

Deterioration of air quality at construction sites is common due to dust and burning fuel etc. The air quality parameters selected for monitoring include Particulate Matter PM10, and PM2.5, Oxides of Sulphur (SOx), Oxides of Nitrogen (NOx), Carbon Monoxide (CO) and Ozone (O3). Quality of air was quarterly monitored at Mawa and Janjira sides of the river and compared against Bangladesh Standards (BDS) and baseline values established in November 2009. It is observed that the air quality parameters measured during the period were well within the acceptable limits and the concentrations of most of the air pollutants were lower than the baseline values.

Table 3

Results of Air Quality Monitoring during 2nd Quarter of 2022 in the project Area

Sl. No.	Parameters	Unit	Concentrations at		BDS	Baseline Values	
			Mawa	Janjira		Mawa	Janjira
1	$PM_{2.5}$	μg/m³	3.11	2.85	65 for 24 hrs	<1	6.12
2	PM_{10}	μg/m³	5.39	8.26	150 for 24 hrs,	112.5	41.14
3	SOx	μg/m³	30.43	0.57	365 for 24 hrs	15.46	7.66
4	NOx	μg/m³	0.93	0.72	100 for 365 days	6.40	3.37
5	CO	ppm	0.52	0.38	10 for 8 hrs	-	-
6	O_3	μg/m³	47.70	48.57	157 for 8 hrs	-	-

vi. Corrosion of Steel Members of the Bridge

The steel members of the bridge are exposed to corrosion. The steel piles supporting the piers are exposed to water and soils have no protection against corrosion. It has been assumed that 10mm out of 60 mm total thickness of exposed steel pile will be lost due to corrosion and erosion in 100 years' lifespan of the bridge. The remaining thickness of the piles would be enough to carry the load of the bridge. Low salinity of water and soil as mentioned in section 2(i) will reduce the rate of corrosion of steel piles. Both inside and outside of the hollow members of steel truss of the bridge superstructure exposed to air are painted applying 3 coats of high quality paints. This will protect the members of steel truss against corrosion for long, but the paint will deteriorate with time. The outside of the truss members can be painted again but the inside of the truss member will remain inaccessible. It has been decided that dehumidifiers will be installed to dehumidify air inside the truss member to protect the inside of the truss members from corrosion.

vii. Biodiversity

Biodiversity is the most precious gift of nature, the value of which in the life of all organisms including humans is enormous. Biodiversity is globally recognized as a cornerstone of healthy ecosystem. Wildlife biodiversity in Bangladesh is under severe threat due to rapid development and related pressure like construction of infrastructure, industrialization, urbanization, deforestation, pollution, overexploitation of resources etc. Hence, biodiversity conservation was one of the important components of environmental management. Padma Multipurpose Bridge, being the largest infrastructure development project, biodiversity conservation has been given high priority. After preparing a comprehensive inventory of wildlife in the project area during project preparation, Sodev Consult International was given the responsibly of monitoring and conservation of biodiversity during construction phase of the project which will continue even after the construction of the project (Sodev, 2017-2022). Since all the species cannot be closely monitored 22 indicator species were selected for close monitoring along with quarterly monitoring of biodiversity of all flora and fauna in selected locations of the project area. The indicator species comprised of 11 wildlife species, 5 plant species and 6 species of fish are shown in Table 4.

Table 4
Fauna and Floral Indicator Species for Close Monitoring (Sodev, 2017-2022)

Wildlife Species, Local/English (*Scientific*) Name	Floral Species, Local/ English (*Scientific*) Name	Fish Species, Local (*Scientific*) Name
Amphibia 1. Sona Beng/Bull Frog (*Hoplobatrachus tigerinus* **Reptile** 2. Kori Kaittha/Roofed Turtle *(Pangshura tecta*) 3. Maita Guisap/Bengal Monitor (*Varanus bengalensis*) **Bird** 4. Katua Chil/Black-winged Kite (*Elanus caeruleus*) 5. Pakra Machranga/Pied Kingfisher (*Ceryle rudis*) 6. Hot-titi/Red-wattled Lapwing (*Venellus indicus*) 7. Choto Pankor/Little Cormorant (*Microcarbo niger*) 8. Gang Shalik/Bank Myna (*Acridotheris gingianus*) 9. Bhomra Soton/ Zitting Cisticola (*Cisticola juccidis*) **Mammal** 10. Shishu (shusuk)/ Ganges River Dolphin (*Platanista gangetica*) 11. Shial/Golden Jackal (*Canis aureus)*	1. Kash/Thatch Grass (*Saccharam spontanium L*) 2. Nal/Tropical Reed (*Phragmites karka(Rtz)Tnn*) 3. Hogla/Cat Trail (*Typha elephantina Roelephantina Roxb.*) 4. Panijoma/Indian Willow (*Salix tetrasperma Roxb.)* 5. Nona Jhau/Indian Tamarisk (*Tamarsik Indica L)*	1. Hilsha or Ilish (*Tenualosa ilisha*) 2. Rui (*Labio rohita*) 3. Aire (Mystusaor) 4. Chitol (*Chitala chitala)* 5. Baim (*Macrognathus - aculeatus*) 6. Baila (*Glosoglobius guris)*

The methods of monitoring followed for flora and fauna are (i) Field Diary Method (ii) Photo Documentation Method (iii) Transect Walk Method and (iv) Focused Group Discussion Method. A total of 324 plant species have been identified and recorded in Padma Bridge wildlife sanctuary area including landscape zone. Habitat-wise distribution of the plant species are shown in Figure 4 (Sodev, 2022). A total of 13 numbers of additional floral species is reported as compared to baseline species recorded in Biodiversity Baseline Survey conducted in 2015. A similar habitat-wise distribution of plant biodiversity shown in Figures 1 and Figure 4 indicates no significant change in plant biodiversity due to construction of Padma Bridge. The increase of 13 new species may be due to more intensive search for species during long monitoring period.

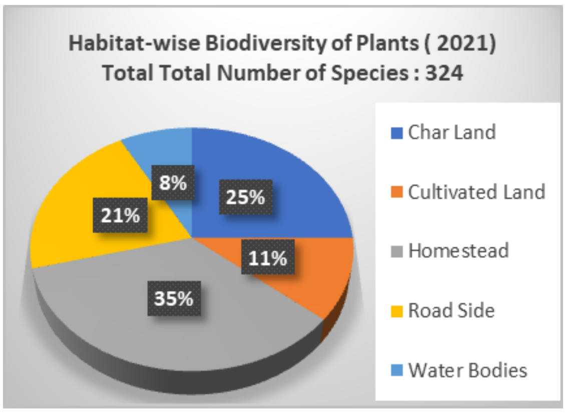

Figure 4: Habitat-wise Biodiversity of Plant in PMBP Area in 2021

Wildlife species diversity recorded in the Padma bridge influence area in 2019, 2020, and 2021 has been presented in Figure 5. A small variation in observed amphibians, reptiles, birds and mammals were recorded in the intensive construction period of the bridge, while total species variation shows decreasing trend. The observed decrease in biodiversity in 3 years of construction period is less than 4 percent. It is expected that the species diversity will be restored to normal after the construction of the bridge is over. The indicator species were visible almost every quarter indicating no disappearance of species from the Padma Bridge influence area.

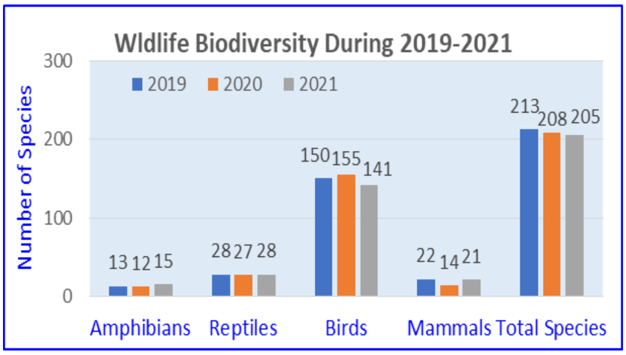

Figure 5: Variation of Wildlife Biodiversity in Last 3 Years

viii. Padma Bridge Wildlife Sanctuary

Padma Multipurpose Bridge Project for the first time in Bangladesh has ventured into a natural biological resources management through establishment of a wildlife sanctuary in an infrastructure development project area under biodiversity conservation program. The Government of Bangladesh established the Padma Bridge Wildlife Sanctuary (PBWS) by Gazette notification on 26 November 2020 under the Bangladesh Wildlife (Conservation and Security) Act 2012. Padma Bridge Wildlife Sanctuary (PBWS) is spread over 4 district, 5 Upazilas and 16 unions as shown in Figure 6. The total area of PBWS is 11,773 ha of which 8,143 ha is core area and 3,630 ha is buffer area, The sanctuary will be managed in compliance of the Protection and Conservation of Fish Rules, 1985 and Protected Area Management Rule 2017. The sanctuary when fully operational will enhance riverine and adjacent terrestrial biodiversity for the overall benefit of the local community in the project area.

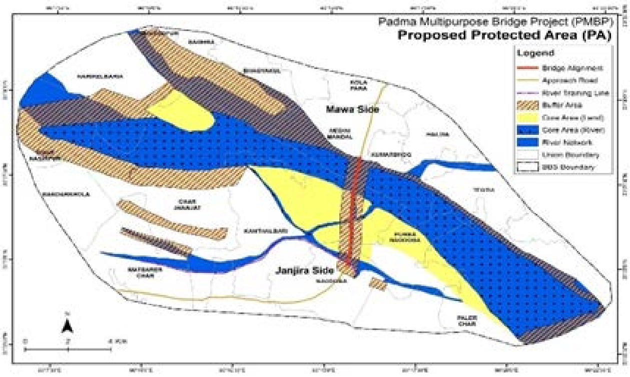

Figure 6: Padma Bridge Wildlife Sanctuary Area

ix. Wildlife Museum

BBA has established a wildlife museum in Service Area-1 (SA-1) with assistance from Department of Zoology, University of Dhaka. The primary objectives of establishing wildlife museum were to create people's awareness about wildlife biodiversity in the area, enhance knowledge of the students and researchers about animal diversity and conservation. The museum has collected and preserved 2353 wildlife specimen from Padma Bridge area up to May 2022 and arranged for public display. The museum has rich collection of amphibians, fishes, reptile, birds and mammals. In addition, replicas of several endangered species, fishing gears and bird nests have been collected and displayed. The museum is getting richer every month with more and more specimen. The wildlife museum has attracted many visitors and will continue to attract more visitors when the museum will be permanently located in the Padma Bridge Museum building under construction. The wildlife museum will be used for educational purpose for school children.

Figure 7: Some Bird Species in Padma Bridge Wildlife Museum

x. (viii) Death on Road

The frequent death of wildlife on the Dhaka-Bhanga expressway due to vehicle-wildlife collision is a great concern for the wildlife conservation. The wildlife monitoring team of PMBP has found 6 Golden Jackal (Canis aureus) dead during April-June 2022 and 14 wildlife during July-September 2022 on the Padma Bridge approach road. It is now clear that large number of wildlife used to cross the Dhaka-Mawa road at night. The conversion of this road into expressway, the geometric design has been changed, the design speed has increased to 80km/hr but most of the drivers drive vehicles at a speed around 100 km/hr. The expressway has under pass for crossing local vehicles and pedestrians but it appears that the wildlife hardly uses the underpass. The wildlife as usual enter into the road through the opening under the side barrier for crossing but in most cases cannot cross the high median and get trapped in the road. Welding of 1 or 2 horizontal bar below the side barrier may prevent entry of wildlife into the expressway.

3. ADAPTATION TO CLIMATE CHANGE

Bangladesh is the one of worst affected countries of the world due to climate change. All major structures are required to be adapted to the impacts caused by climate change. The lifespan of the bridge is 100 years. So, the predicted changes in sea level rise, rainfall, temperature, wind speed in 100 years due to climate change are considered in the design of the bridge. The upper range, mid-range and lower range of sea level rise of 0.98m, 0.60m and 0.26m respectively as projected by IPCC 2007b where the estimated ice sheet contribution were considered in upper and mid-range projection of IPCC. The Padma bridge is located 240 km upstream of the Bay of Bengal coastline. The net sea-level rise of 4 scenarios, 1.00m, 0.88m, 0.60m, and 0.26m were projected to cause water level rise at bridge site by 0.47m, 0.42m, 0.27m, and 0.09m respectively as shown in Table 5.

Table 5
Water level rise at Padma Bridge site due to Sea-level Rise

Distance from Outer Boundary of SLR in Estuary, km	Sea Level Rise (SLR) in m			
	1.00	**0.88**	**0.60**	**0.26**
26	0.96	0.85	0.55	0.19
105	0.90	0.80	0.52	0.18
131	0.73	0.65	0.42	0.15
149	0.68	0.60	0.39	0.14
168 (Chandpur)	0.56	0.50	0.33	0.11
240 (Padma Bridge Site)	0.47	0.42	0.27	0.09

The global circulation model predicted that the rainfall in the catchment area of the Padma Bridge will increase by 26%, which may cause an increase of 16% water flow and 0.16m increase in water level in the Padma river. The total increase in water level would be 0.62m by adding 0.47m water level rise for 1.00m sea-level rise and 0.16m for excess rainfall. This was added to highest flood level in 100 years return period to arrive at the highest design flood level of 7.44m PWD. Since, Padma River is a busy waterway, a navigation clearance of 18.3m was added to highest design flood level to fix the bottom level of the bridge.

The design discharge of 151,100 m^3/s and design velocity of 5 m/s were estimated by considering additional flow caused by excess rainfall in the Padma Bridge catchment area due to climate change. The Maximum temperature of 46.6 0C and minimum temperature of 9.3 0C were considered in the design of the bridge (Maunsell/AECOM, 2010b). The change in temperature is important in the design of expansion joints provided between the modules of the bridge.

4. CONCLUSIONS

Padma Multipurpose Bridge Project is the most successful project having minimum impact on natural environment. The world's largest river training works have been erected to tame the river without affecting the natural flow of the river. Construction related impacts of such a megaproject such as disposal of 30 million m3 of dredging spoils, threat to Hilsha breeding and migration, disturbances and displacement wildlife, water, air and noise pollution have been managed successfully. The increased rainfall, water flow, water level and temperature due to climate change have been incorporated in the design of the bridge. A team comprised of environmental experts of BBA and Consultants and representative of contractors regularly monitored the implementation of EAP and compliance of environmental guidelines. All facilities developed for Implementation of the project are well planned and environment friendly. A wildlife museum has been established collecting and preserving wildlife from the Padma Bridge areas which will attract the visitors and be used for education of the school children. Padma Multipurpose Bridge Project for the first time in Bangladesh has ventured into a natural biological resources management initiative through establishment of a wildlife sanctuary in an infrastructure development project area under biodiversity conservation program. Government of Bangladesh supported the initiative of PMBP and declared 11,773 ha of char and wetland of Padma Bridge area as Padma Bridge Wildlife Sanctuary (PBWS) for breeding and preservation of wildlife and plant biodiversity.

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Soil Characteristics of Padma Multipurpose Bridge

Hossain Md. Shahin

Member, Panel of Experts (PoE), Padma Multipurpose Bridge Project
Department of Civil and Environmental Engineering, Islamic University of Technology (IUT), Gazipur, Bangladesh

emails: *shahin@iut-dhaka.edu; shahinnit@gmail.com*

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ABSTRACT

Padma Multipurpose Bridge is situated on a section of the Padma river where the soil condition is highly heterogeneous and intermixed with different soil layers, for which pile design was the critical part. This paper describes the soil properties and ground profiling of the Padma Multipurpose Bridge. Different types of field and laboratory tests were carried out to obtain accurate soil parameters and ground profiles along the whole alignment of the bridge. Standard Penetration Tests, Cone Penetration Tests, and grain size analyses were conducted for the soil classifications and ground profiling. Flat Plate Dilatometer Tests, High Pressure Dilatometer Tests, and Self-Boring Internal Friction Tests were performed to obtain the stiffness of the different soil layers and shear strength parameters in field conditions. Cross-hole and Seismic Tomography Geophysical tests were executed to obtain seismic waves and dynamic shear modulus of each soil layer. Gel Push Soil Sampling technique was used to collect undisturbed samples of sandy soils to get accurate stress–strength-dilatancy characteristics of sandy soils through different laboratory tests. The soil was classified into three Units and some sub-units based on grain size and SPT-N value. Soil parameters were finalized based on both laboratory and field test results. The pile design was possible for accurate measurement of soil parameters and ground profiling along the alignment of the bridge.

1. INTRODUCTION

Padma Multipurpose Bridge is located across Padma River in the central southern part of Bangladesh, at N23º24', E90º12' following UTM WGS 84 System. It is 6.15 km long, consisting of forty-one 150 m long-span steel trusses supported on 40 piers within the river and two transition piers on each riverbank. The river piers are supported by 3.0 m diameter steel tubular raked piles driven into the ground till the elevations of -98.0 m PWD (Public Works Department reference datum) to -122 m PWD depending on the locations. These large pile lengths resulted from a deep river bed scour from -20 m PWD to -62 m PWD in 100 year return period.

The pile design of the bridge was the critical part due to non-homogeneous intermixed soil stratifications along the length. Furthermore, the existence of stiff cohesive layers in some pile locations starting at an elevation of about -113 m PWD to -128 m PWD with a thickness ranging from about 3 m to more than 30 m made the pile design critical, which delayed the bridge construction by more than a year. To increase end bearing capacity, base grouting was employed below the pile tips. In addition, in some piles, skin grouting was employed to increase the skin friction capacity of the piles. Due to the existence of fine-grain soil, micro-fine cement was required in the grouting to avoid hydrofracture of the ground. The type of soil and soil characteristics are discussed in this paper based on different in-situ tests and laboratory tests.

2. IN-SITU TESTS

Many types of in-situ tests were carried out during feasibility studies and construction stages to classify the soil correctly and get appropriate soil parameters. The following in-situ tests were carried out along the alignment of the bridge:

- Standard Penetration Test (SPT),
- Cone Penetration Test (CPT),
- Self Boring Pressuremeter Test (SBPT),
- Flat Plate Dilatometer (DMT),
- High Pressure Dilatometer (HPD),
- Self Boring Internal Friction Test (SBIFT),
- Cross-hole Geophysical test,

- Seismic Tomography Geophysical Test, and Some field tests are illustrated in the subsequent sections.

A. *Standard Penetration Test (SPT)*

The depth of the Standard Penetration Test (SPT) was up to -150 m PWD from the river bed. SPT was executed at 1.5 m and 2 m intervals of depth to determine SPT-N value together with relative density, consistency, and classification of soil at different elevations collecting disturbed soil samples from each interval.

i. *Soil Classifications*

Soils were classified into Soil Units 1, 2, and 3 following the criteria stated in Table 1 and Table 3 based on the grain size. As described in Table 3, Units 1a and 1b are the fine soils dominated by clay and silt, and Units 2 and 3 are the granular soils dominated by sand. Grain size and identification is defined according to BS 5930. Here, fines mean the grain size is smaller than 0.06 mm, and coarse means the grain size is larger than 2 mm. Unit 1 is divided into 1a and 1b based on the amount of fine materials. Soil with 50% or more fine materials is classified as Unit 1a, and soil with 20% to less than 50% fine material is classified as Unit 1b.

Table 2 shows sub-units classification for Unit 2 and Unit 3 based on the SPT-N value, where Unit 2 is divided into 2a, 2b, 2c, 2d, 2e, and 2f; Unit 3 is divided into 3a, 3b, 3c, 3d, 3e, and 3f. In Table 2, the classification of coarse grained soils from very loose to extremely dense was based on U.S. Navy, 1982, and Lambe and Whitman, 1969. In the sub-units, a & b represent very loose to loose soil, c represents medium dense soil, d depicts dense soil, e represents very dense soil, and f depicts extremely dense soil.

Table 1
Soil Classifications

Geological Unit	Criteria	
	% of basic soil type of the geological unit	% of different particles size of the geological unit
Unit 1a	Fines ≥ 50%	Soil with 50% or more fine materials
Unit 1b	50% > Fines ≥ 20%	Soil with 20% to less than 50% fine materials
Unit 2	Fines < 20% and Coarse < 10%	Soil with less than 20% fine materials and less than 10% coarse materials
Unit 3	Fines < 20% and Coarse ≥ 10%	Soil with less than 20% fine materials and 10% or more coarse materials

Note: Fines = Particle size < 0.06 mm (clay and silt)
Coarse = Particle size > 2 mm (gravel)

Table 2
Sub-units classification for Unit 2 and Unit 3

Geological Sub-unit	Typical SPT N	Classification of soil
a & b	0 < N <10	Very loose to loose
c	10 < N<17	Medium dense
d	17 < N < 32	Dense
e	32 < N <50	Very dense
f	N > 50	Extremely dense

Table 3
Typical descriptions of the soils

Geological Unit	Descriptions of the Materials
Unit 1a and Unit 1b	Fine soil dominant by Clay and Silt. Commonly silty Clay, clayey Silt and slightly sandy Silt, with laminations or trace of Mica. Various colours including brownish Grey, dark grey, and grey
Unit 2	Granular soil dominant by Sand. Commonly silty Sand and slightly silty Sand with laminations or trace of Mica. Mainly grey but randomly brownish grey.
Unit 3	Granular soil dominant by Sand, commonly slightly silty Sand and gravelly Sand with much to some gravel & pebbles, and cobbles in places with laminations or trace of Mica. Mainly grey but randomly brownish grey.

B. *Cone Penetration Test (CPT)*

Cone Penetration Test was carried out up to a depth of -60 m PWD using 20 Ton hydraulic thrust equipment. The cone was saturated using silicon oil prior to the tests. The CPT was employed to get continuous soil data for profiling the ground. Soil parameters, such as Cone resistance, Sleeve Friction, Dynamic Pore Pressure, and Friction Ratio, are obtained from the CPT. Here, a typical plot of the effective angle of internal friction is presented in Figure 1, where the values were estimated based on Lunne et. al. (1997). The average effective frictional angle, ϕ', was obtained from the CPT was about 35^{o} for soil Unit 2, as seen in the figure.

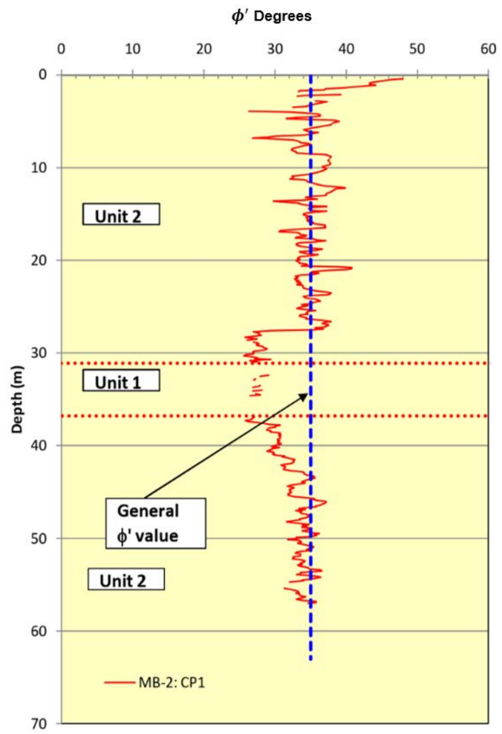

Figure 1: Angle of internal friction along depth (from CPT)

C. *High Pressure Dilatometer (HPD) Test*

Depth of the High Pressure Dilatometer Test (HPD) was up to -132 m PWD. The HPD measures the volume change under varying applied pressure on the drillhole wall. The pressuremeter membrane was 0.45 m long for a self boring probe, and 0.6 m long for the HPD. The shear moduli, angle of internal friction, and the coefficient of earth pressure at rest, K_0, of the ground are obtained from the applied pressure and the cavity strain during the tests. Figure 2 shows a typical result of the HPD test in soil Unit 2. It is seen a substantial plastic response of sandy soil in the figure. In the HPD tests, a wide range of variation with K_0 ranging from 0.31 to 0.86 is obtained for soil Unit 2 and Unit 3, having recommended values of 0.40 to 0.45 for these soil types. For soil Unit 1, K_0 is ranging from 0.8 to 1.09 with a recommended value of 0.80. Shear Modulus (G_{ur}) from the unload-reload cycle was obtained, and the recommended value of G_{ur} is 100 MPa for soil Unit 1.

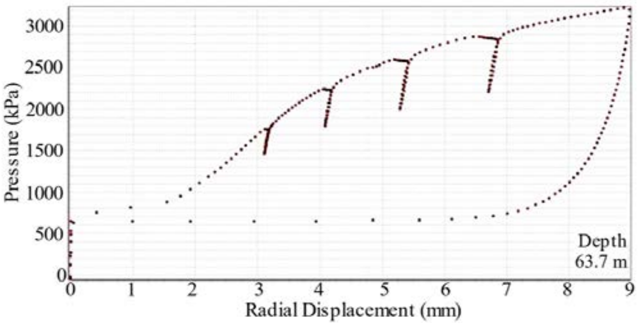

Figure 2: HPD test results in soil Unit 2

D. Self-Boring Internal Friction Test (SBIFT)

Self-Boring Internal Friction Tests (SBIFT) was conducted at three boreholes, GPS1B, GPS2B, and GPS3B, up to a depth of -75 m PWD. GPS1B was located in the middle of the alignment (Easting 220209, Northing 2594268), GPS2B was located near the Janjira area (Easting 220151, Northing 2592792), and GPS3B (Easting 220561, Northing 2598049) was located near the Mawa area. Soil stiffness was measured with the SBIFT. It also measures the internal angle of friction of the soil. The SBIFT probe is inserted into the ground, and different normal pressures and pull-up forces are applied, which generate shear stresses on the SBIFT probe wall. The cohesion (c') and effective angle of internal friction ϕ' were obtained by plotting the σ' and τ plot.

Shear strength parameters from the SBIFT are – (a) for soil Unit 1, c = 5 kPa, $\phi' = 28^o$, (b) for soil Unit 2, c' = 0 kPa and $\phi' = 34^0$, (c) for soil Unit 2, c' = 0 kPa and $\phi' = 35^0$. Pressuremeter modulus, E_p, corresponding to 1% strain is obtained from the SBIFT listed in Table 4. Here, the pressuremeter modulus increases with the depth having some exceptions due to a dense/stiff soil layer between the very dense soil layers.

E. Cross-hole Geophysical test

The seismic measurements were performed at three sites situated at the two river banks and in the center of the river up to a depth of -150 m PWD. Figure 3 shows typical P-wave and S-wave velocities along the depth. The p-wave velocities are found between 1600 and 1900 m/s. The range of s-wave velocity is between about 100 m/s at the surface and up to 500 m/s at a depth of about -150 m PWD. In general, the velocity, i.e., the soil stiffness, increased with the depth. Since the velocity of the s-wave (V_s) depends on the shear modulus G_0 and the density ρ, the shear modulus can be calculated from $G_0 = \rho V_s^2$. The density was obtained from the laboratory test as described in the laboratory test section. The dynamic shear modulus ranges from about 30 MPa at the surface to about 500 MPa at greater depths.

Table 4
Pressuremeter modulus with depth at three locations (GPS1B, GPS2B and GPS3B)

GPS1B		GPS2B		GPS1B	
Depth (m)	**E_p (kPa)**	**Depth (m)**	**E_p (kPa)**	**Depth (m)**	**E_p (kPa)**
5.10	23,990	6.50	24,460	8.03	17040
13.40	32,800	19.00	40,460	20.53	35600
20.90	29,200	31.50	45,510	33.03	45820
27.40	35,690	44.00	52,300	45.53	48670
35.90	23,180	56.50	48,340	58.03	62540
43.40	56,970	66.50	28,050	68.03	58640
50.90	54,060	71.50	97,740	73.03	81120
58.90	47,620	76.50	87,340	78.03	76620
65.90	53,080	81.50	106,960	83.03	70530
67.40	65,480	86.50	108,080	88.03	86150
68.40	69,530				
73.40	92,470				
80.90	92,330				

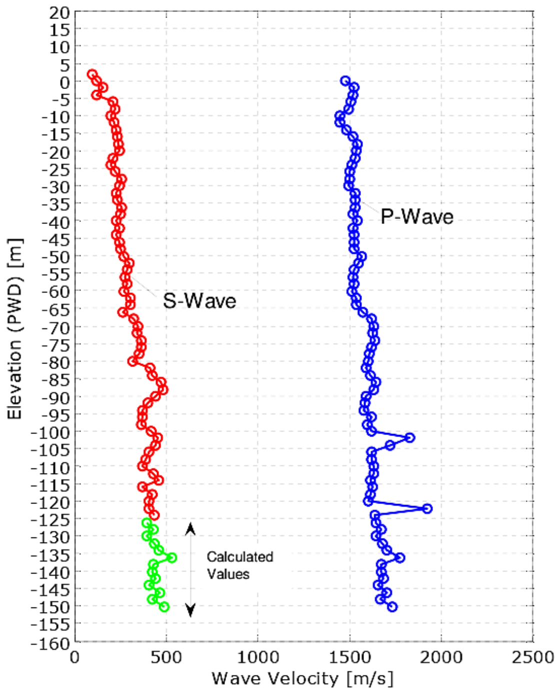

Figure 3: Typical P-wave and S-wave velocities along the depth

4. GROUND PROFILES

Based on the soil classifications, some typical ground profiles at pier locations P6, P16, P26, P33, P36, and P40, are illustrated in igure 4. P6 is located near the Mawa side, and P40 is on the Janjira side. It is seen in the figure that the ground profiles are highly non-homogeneous, having intermixed with different soil Units along the depth. In some locations, stiff cohesive layers (soil Unit 1a and Unit 1b) exist, starting at an elevation of about -113 m PWD to $-128\,m$ PWD having a thickness of about 3 m to more than 30 m.

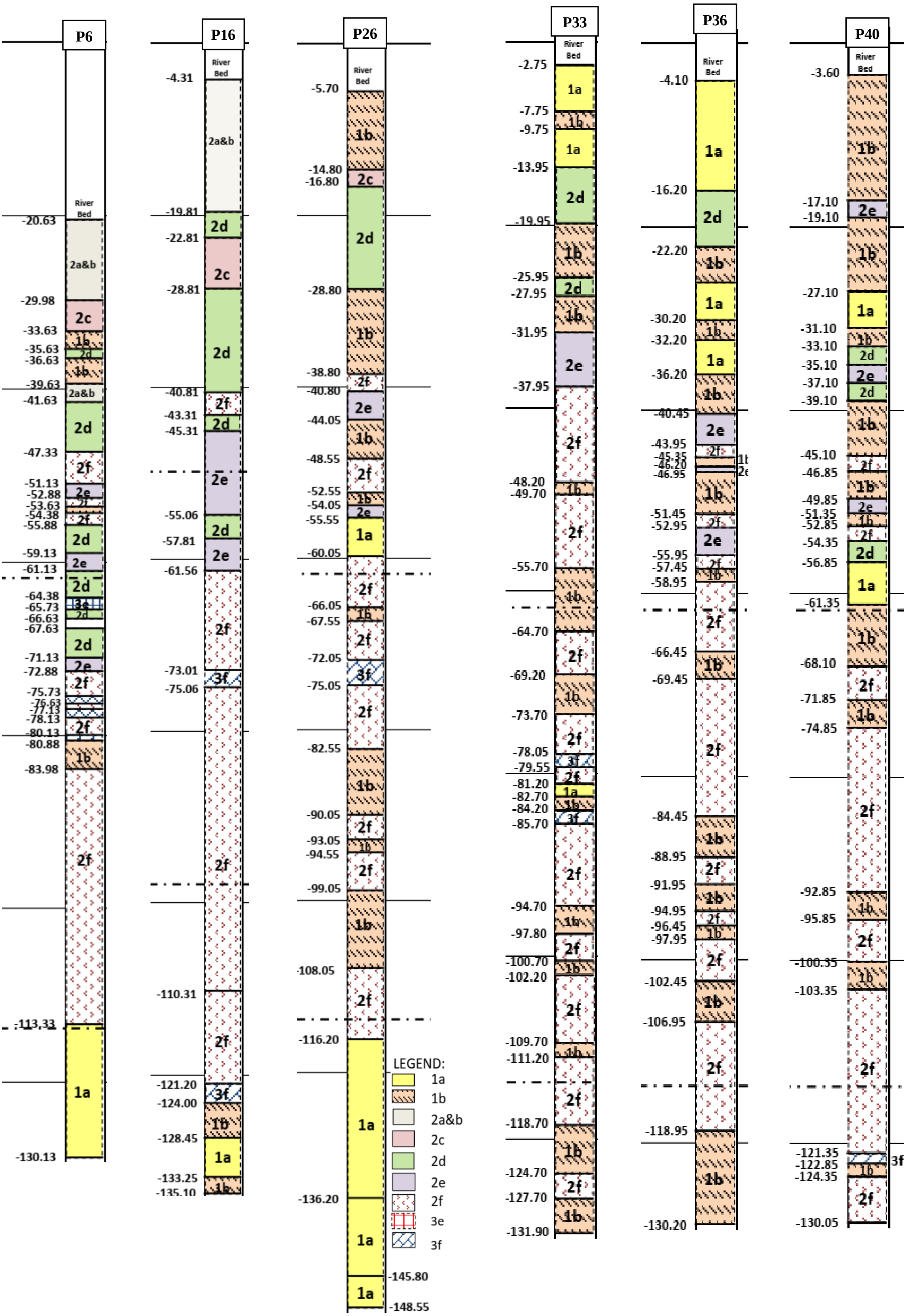

Figure 4: Ground Profiles at Piers 6, 16, 26, 33, 36, and 40

4. LABORATORY TESTING

Various laboratory tests were conducted to get accurate soil properties. Some laboratory test results are described here. Both disturbed and undisturbed samples were collected from the field. Gel Push Sampler, having a length of 1000 mm and diameter of 75 mm, was used to collect good quality undisturbed sand samples. Therefore, it was possible to carry out laboratory tests (direct shear, triaxial, and consolidation tests) for the sandy soil with the original field density. Mazier Sampler, having a length of 1000 mm and diameter of 75 mm, was used to obtain samples of cohesive soils. Split-spoon Sampler was used to collect disturbed soil samples

A. Grain Size Analysis

Both Sieve and Hydrometer tests were conducted to get particle size distribution curves. This paper presents some typical grain size distribution curves for soil Unit 1, Unit 2, and Unit 3 based on the Gel Push soil samples obtained from boreholes GPS1A, GPS2A, and GPS3A. Figure 5 illustrates grain size distribution curves for Unit 1, Unit 2, and Unit 3. In borehole GPS2A, there was no soil of Unit 3. The soils of Unit 1 are dominated by clay and silt, as seen in the figure. The soils of Unit 2 are poorly graded silty sand in all three boreholes. In some locations, fine contents were found up to 19%; in that case, the soils of Unit 2 are well-graded silty sand. Soils of Unit 3 were found only in one location of boreholes GPS1A and GPS3A. In GPS1A, coarse particles retain on 2 mm sieve are 25.5%. In GSP3A, coarse particles retain on 2 mm sieve are 10.2%. D_{50} for soils of Unit 1 ranges from 0.047 mm to 0.071 mm, for soils of Unit 2 is 0.135 mm to 0.5185 mm, and for soils of Unit 3 is 0.476 to 0.646 mm.

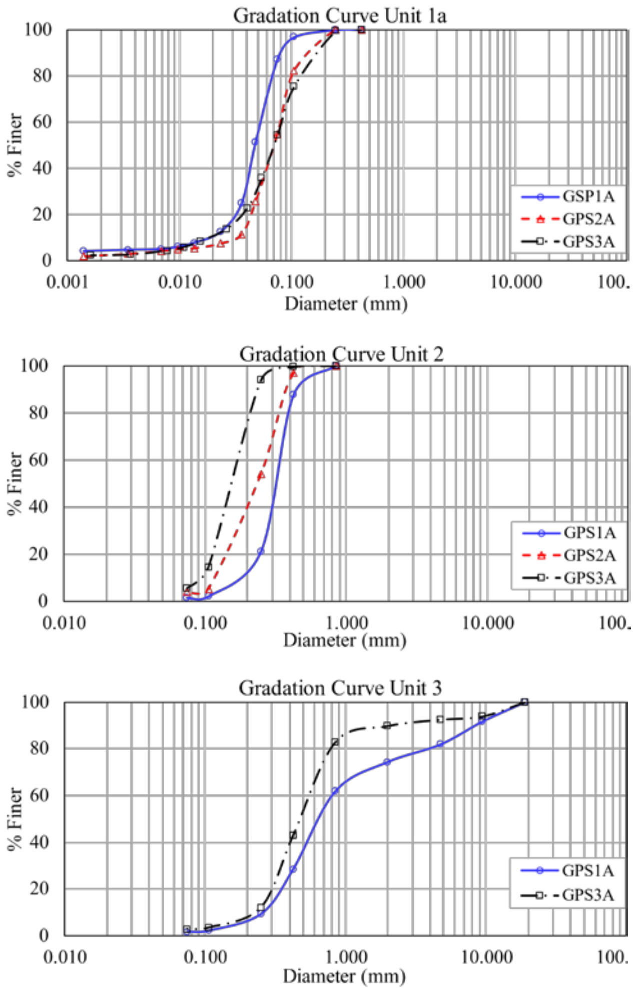

Figure 5: Grain size distribution curves

B. Mica Content

It is considered that the presence of mica particles makes the properties and behavior of the silty sand different from those of non-micaceous silica sands. The mica is likely to increase the porosity, increase compressibility, and decrease the shear strength of the soil. It is also expected to increase the damping ratio of soil due to the void ratio increase. Mica Content Tests were conducted by grain counting following ASTM D-285 guidelines. Table 5 shows mica contents at different depths of boreholes GPS1A, GPS2A, and GPS3A. GPS1A was located in the middle of the alignment (Easting 220209, Northing 2594268), GPS2A was located near the Janjira area (Easting 220151, Northing 2592792), and GPS3A (Easting 220561, Northing 2598049) was located near the Mawa area. It is seen that the mica content is higher at a shallower depth. Mica contents ranging from 17% to 44% were found in soils of Unit 1; for Unit 2, it was 0% to 17%; and for Unit 3, it was 0% to 9%.

Table 5
Mica Content in percentage at different locations and depths

GPS1A		GPS2A		GPS3A	
Depth (m)	**Mica Content (%)**	**Depth (m)**	**Mica Content (%)**	**Depth (m)**	**Mica Content (%)**
4.49 - 5.49	44	5.88 - 9.38	17	7.53 - 9.53	26
20.30 - 21.30	6	18.38 - 20.48	9	20.03 - 24.03	9
26.80 - 27.80	6	30.88 - 32.88	5	32.53 - 34.53	5
35.30 - 36.30	9	43.38 - 45.38	11	45.03 - 47.03	8
42.80 - 43.80	5	55.88 - 57.88	9	57.53 - 60.13	7
50.30 - 51.30	5	65.88 - 67.88	14	67.53 - 69.53	10
53.30 - 55.30	5	70.88 - 72.88	5	72.53 - 74.53	5
57.80 - 60.70	6	75.88 - 77.88	4	77.53 - 79.53	3
65.30 - 68.70	6	80.88 - 82.88	3	82.53 - 84.53	2
72.80 - 74.80	9	85.88 - 87.88	7	87.53 - 89.53	3
80.30 - 84.40	5			97.53 - 99.53	4

C. Soil Identification Tests

Table 6, Table **7**, and Table **8** represent the Geological Unit, natural water content, degree of saturation, bulk unit weight, degree of saturation, and field void ratio at boreholes GPS1A, GPS2A, and GPS3A. It is seen in the tables natural water content, w_n, decreases with depth, hence the degree of saturation, S_r, decreases. The unit weights (γ_t) of Unit 2f and Unit 3f are the highest, with some exceptions where the void ratios (e) of these soils are relatively higher.

Table 6
Some basic parameters of soils in GPS1A

Depth (m)	Geological Unit	w_n %	S_r %	γ_t (kN/m³)	e
4.49 - 5.49	Unit 1a	32.10	99.6	18.77	0.876
11.80 - 13.80	Unit 2d	27.90	96.9	19.07	0.778
20.30 - 21.30	Unit 2d	25.20	81.8	18.15	0.835
26.80 - 27.80	Unit 2d	28.30	95.9	18.95	0.800
35.30 - 36.30	Unit 2d	32.50	97.7	18.55	0.903
42.80 - 43.80	Unit 2d	24.60	84.7	18.60	0.793
50.30 - 51.30	Unit 2e	27.40	83.5	17.94	0.892
53.30 - 55.30	Unit 2e	28.20	91.0	18.49	0.836
57.80 - 60.70	Unit 2d	17.90	72.5	18.70	0.665
65.30 - 68.70	Unit 2f	18.70	74.0	18.69	0.682
72.80 - 74.80	Unit 2f	18.40	84.1	19.61	0.586
80.30 - 84.40	Unit 3f	13.60	66.1	19.43	0.560

Table 7
Some basic parameters of soils in GPS2A

Depth (m)	Geological Unit	w_n %	S_r %	γ_t (kN/m³)	e
5.88 - 9.38	Unit 1a	29.4	98.0	18.97	0.813
18.38 - 20.48	Unit 2c	25.3	85.1	18.47	0.808
30.88 - 32.88	Unit 2c	29.7	90.4	18.22	0.888
43.38 - 45.38	Unit 2d	29.4	83.7	17.69	0.958
55.88 - 57.88	Unit 2d	15.8	52.7	16.97	0.812
65.88 - 67.88	Unit 2d	28.1	97.6	19.08	0.777
70.88 - 72.88	Unit 2f	15.5	62.4	18.41	0.677
75.88 - 77.88	Unit 2f	10.8	48.8	18.39	0.598
80.88 - 82.88	Unit 2f	10.7	48.3	18.35	0.599
85.88 - 87.88	Unit 2f	17.4	64.5	18.50	0.765

Table 8
Some basic parameters of soils in GPS3A

Depth (m)	Geological Unit	w_n %	S_r %	γ_t (kN/m³)	e
7.53 - 9.53	Unit 1a	30.0	78.6	17.07	1.044
20.03 - 24.03	Unit 2c	16.7	50.2	16.26	0.897
32.53 - 34.53	Unit 2d	25.3	83.7	18.27	0.815
45.03 - 47.03	Unit 2e	16.2	52.9	16.91	0.834
57.53 - 60.13	Unit 2f	27.6	89.8	18.52	0.835
67.53 - 69.53	Unit 2d	14.5	50.2	17.10	0.783
72.53 - 74.53	Unit 2e	21.0	76.6	18.51	0.748
77.53 - 79.53	Unit 2e	11.2	44.1	17.46	0.685
82.53 - 84.53	Unit 2f	11.4	47.1	17.75	0.648
87.53 - 89.53	Unit 3f	13.5	56.8	18.28	0.639
97.53 - 99.53	Unit 2f	21.9	81.1	18.64	0.727

D. Compression Behavior

Consolidation tests were carried out for different soils of undisturbed samples of Unit 1, Unit 2, and Unit 3. In this paper, some typical results of the consolidation tests are presented. Here, undisturbed samples of Unit 1a were obtained from the boreholes at Piers 2, 8, and 15; for Unit 1b, the sample was obtained from the borehole at Pier 2. Here, undisturbed samples were obtained for sandy soil by Gel Push tests at boreholes GPS1A, GPS2A, and GPS3A. Figure 6 illustrates the relationships of void ratio, e, and consolidation pressure for soils of Unit 1, Unit 2, and Unit 3. The compression index and swelling index are listed in Table 9. As usual, the compression index of Unit 1a is higher than those of the other soil Units. The compression index of Unit 1a is 0.339 at a depth of 126 m. which is located at Pier 2. The value was found as large as 0.432 at a depth of 130 m in another location, which restricted

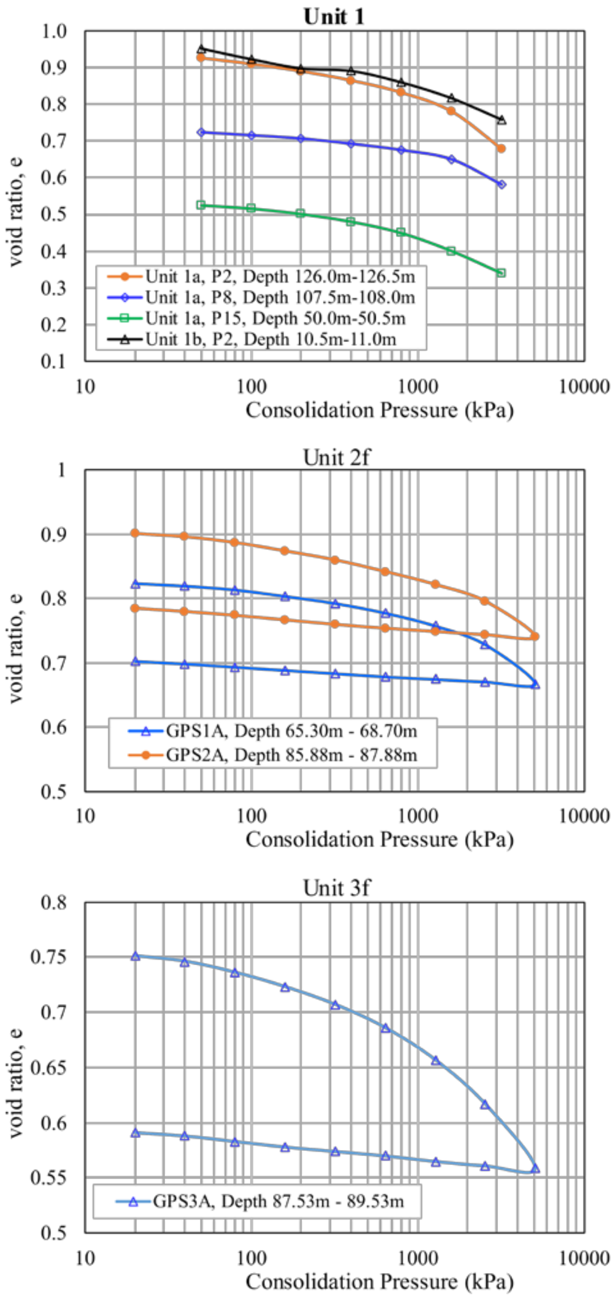

Figure 6: e-log p cuves

placing the pile tip at a location for which the load of the bridge reaches the layer of soil Unit 1. Consequently, the pile length was shortened in 22 piers inserting one more pile in each pier, and in some piles, skin grouting was applied to enhance the bearing capacity of the pile group.

Table 9
Compression index and swelling index of soils

Geological Unit	Location	Sample Depth (m)	Cc	Cs
Uni 1a	Pier 2	126.0-126.5	0.339	-
	Pier 8	107.5-108.0	0.226	-
	Pier 15	50.0-50.5	0.203	-
Unit 1b	Pier 2	10.5-11.0	0.193	-
Unit 2f	GPS1A	65.3 - 68.7	0.203	0.013
	GPS2A	85.88 - 87.88	0.183	0.016
Unit 3f	GPS3A	87.53 - 89.53	0.193	0.012

E. Cohesion and Angle of Internal Friction

Gel Push samples were used to obtain effective cohesions (c') and angle of internal friction angles (ϕ'). Figure 7 illustrates the relationships between deviatoric stress $(\sigma'_1-\sigma'_3)/2$ and mean effective stress $(\sigma'_1+\sigma'_3)/2$ for three soil units, Unit 1, Unit 2, and Unit 3. The values of c' and ϕ' are estimated based on the effective normal stress (σ') and shear stress (τ) plot.

The effective cohesion and internal friction for soil Unit 1 were obtained from Isotropically Consolidated Undrained Compression (CUC) triaxial tests.

For soil Unit 2, Isotropically Consolidated Drained Compression (CDC), Isotropically Consolidated Undrained Compression (CUC), K_0 Consolidated Drained Compression (CK_0DC), K_0 Consolidated Undrained Compression (CK_0UC), and Isotropically Consolidated Rebound Drained Compression (CRDC) triaxial tests were carried out to obtain the effective cohesion and angle of internal friction as seen in the legend of the figure for Unit 2.

The parameters (c' and ϕ') for Unit 3 are obtained from CDC, CUC, and CK_0UC triaxial tests. From the trend lines of Figure 7, it is found that the effective cohesion for soil Unit 1 is 5.0 kPa; and the effective angle of internal frictions for this Unit is 32°, for soil Unit 2 is 34°, and for soil Unit 3 is 35°.

Table 10 shows the values of the effective cohesions and internal frictions obtained from different field and laboratory tests. These values were used in the pile design for piers 1 to 18 and 20 to 24. As seen in the table, soil shear strength parameters (c' and ϕ') values vary field soil conditions.

Table 11 shows the effective internal frictions that were used in the pile design for piers 19 and 25 to 42. For these piers, both effective cohesions and friction angles were not considered for soil Units 1a and 1b. Besides, if soil Units 2a and 2b exist in a shallower depth from the river bed, both effective cohesions and friction angles were not considered in these piers. However, the effective friction angle for this soil type (Units 2a and 2b) was considered 28° for a deeper depth.

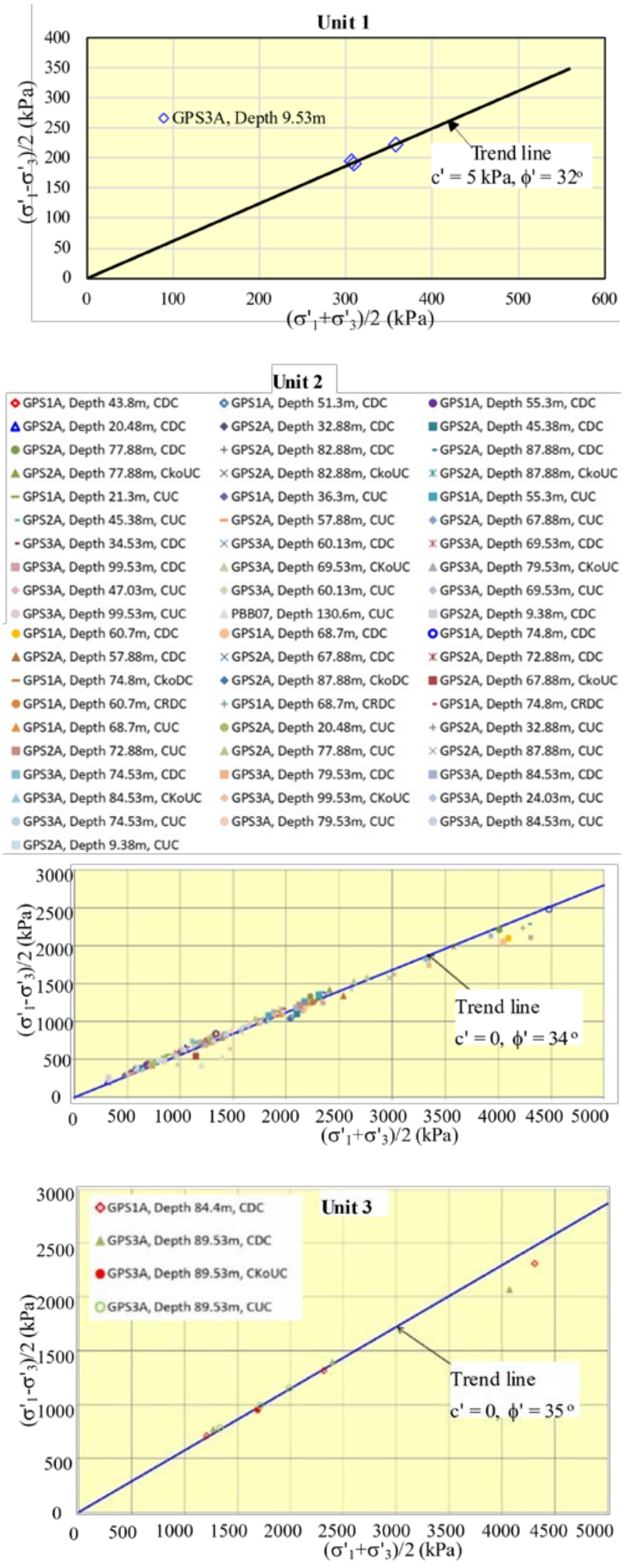

Figure 7: Relationships between mean deviatoric stress and mean effective stress

Table 10
Effective cohesion and angle of internal friction at piers 1 to 18 and 20 to 24

Geological Unit	c' (kPa)	ϕ' (degree)
Unit 1a	15 to 33	3 to 20
Unit 1b	3 to 20	17 to 29
Unit 2a, 2b	-	24 to 25
Unit 2c	-	24 to 30
Unit 2d	-	26 to 32
Unit 2e	-	28 to 33
Unit 2f	-	28 to 34
Unit 3e	-	31 to 33
Unit 3f	-	31 to 34

Table 11
Effective cohesions and angle of internal frictions at piers 19 and 25 to 42

Geological Unit	c' (kPa)	ϕ' (degree)
Unit 1a, 1b	-	-
Unit 2a, 2b	Shallower depth	-
	else	28
Unit 2c	-	30
Unit 2d	-	32
Unit 2e	-	34
Unit 2f	-	36
Unit 3f	-	38

5. SITE SEISMICITY

The maximum Peak Ground Acceleration (PGA) was used based on the report of the Bureau of Research, Testing & Consultation (BRTC), BUET, 2009. The maximum PGAs were derived using the attenuation relationship (Abrahamson & Silva, 2008). The site specific ground accelerations at an elevation of -120 m PWD and river bed are listed in Table 12. Here, bedrock is considered at an elevation of -120 m PWD.

Table 12
PGA values for various Return Periods

Return Period (Years)	Horizontal PGA at -120 m PWD (g)	Horizontal PGA at river bed (g)
2	0.004	0.008
10	0.011	0.022
50	0.032	0.064
100	0.051	0.102
200	0.080	0.160
475	0.141	0.282
1000	0.230	0.460

Ground response analysis was performed with SHAKE software. As seen in Table 12, the general design amplification factor for the site soil conditions is about 2.0. The response analysis was based on the assumption that bedrock is at an elevation of -120 m PWD.

Three strong ground motions (No.1, No.2, No.3) were adopted in the dynamic analysis of the bridge those proposed by the Japanese Codes, “Design Specification for Highway Bridge Part V: Seismic Design”, published by the Japan Road Association. In addition, two strong ground motions (No. 4 and No. 5) were proposed by the BRTC, BUET, 2009. The strong ground motions are depicted in Figure 8.

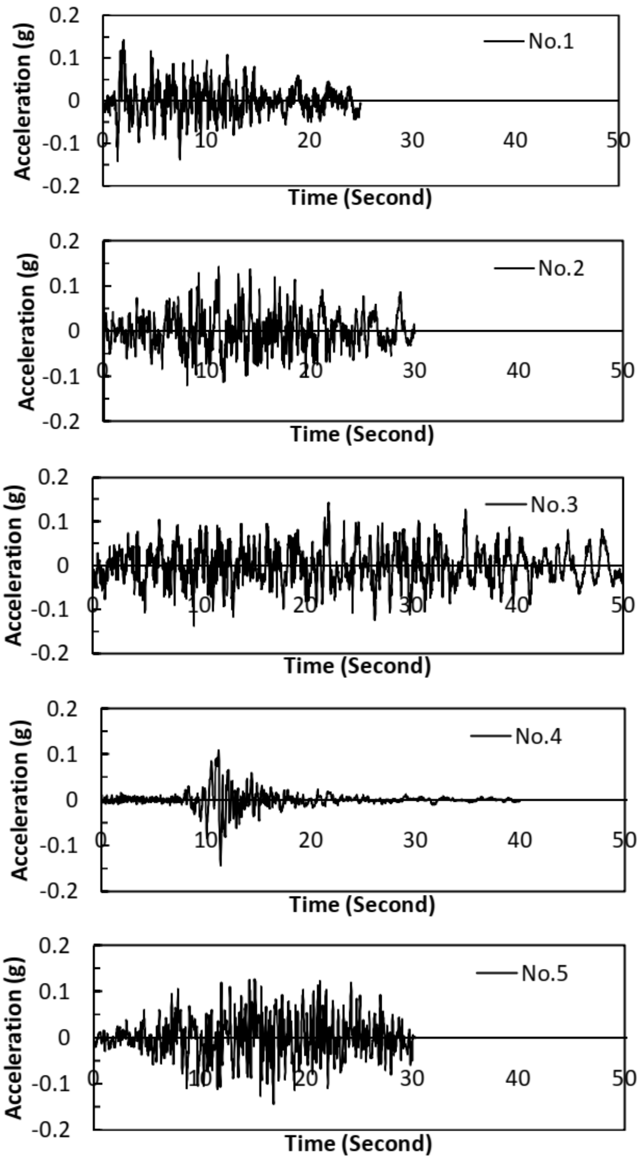

Figure 8: The Strong Ground Motions used in SHAKE Analyses

Figure 9 illustrates the ground response spectra those were obtained using the strong ground motions (No.1 to No.5) and the ground conditions at the site. The figure also shows a comparison with the response spectra recommended by the AASHTO (2009), Guide Specifications for LRFD Seismic Bridge Design – Section 3, corresponding to soil types II and III for to site coefficients S=1.2 and S=1.5, respectively.

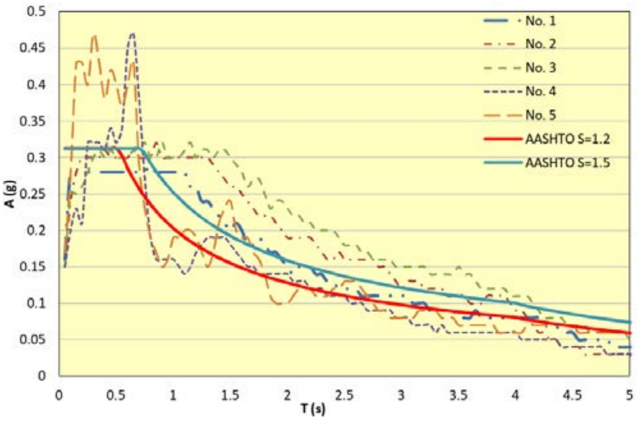

Figure 9: Ground Response Spectra

A. Seismic Hazard Levels and Performance Criteria

In the design, following two levels of seismic hazards and corresponding performance criteria were considered.

i. Level 1 – Operating Level Earthquake (OLE)

Seismic Hazard: the OLE events have a 65% probability of being exceeded in the design life of 100 years or a return period of 100 years. The OLE events have a PGA of 0.052g in the very dense sand at an elevation of -120 m PWD.

***Performance Criteria**: fully functional*

The bridge shall survive the OLE events with no damage, and full service is available to all vehicles immediately after the OLE events.

ii. Level 2 – Contingency Level Earthquake(CLE)

Seismic Hazard: The CLE events have a 20% probability of being exceeded in the design life of 100 years or a return period of 475 years. The CLE events have a PGA of 0.144g in the very dense sand at an elevation of -120 m PWD.

***Performance Criteria**: Life Safety*

The bridge shall survive the CLE 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.

9. CONCLUSIONS

From different in-situ tests, accurate ground profiling was done along the longitudinal section of the Padma Multipurpose Bridge. Also, soil parameters were obtained with a high degree of accuracy in the bridge area from the different types of laboratory and field tests. The soil parameters were verified by different test methods. With the proper soil parameters and ground profiling, it was possible to design the Padma Multipurpose Bridge with safety. It was also possible to place the pile tips at safer ground locations for all piers of the bridge for accurate ground profiling. Therefore, it can be said that proper estimation of soil parameters and ground profiling is required to construct any important structure.

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Structural Health Monitoring of Large-Scale Bridges: A Synopsis of the Padma Bridge

Tanvir Mustafy[1*] and Raquib Ahsan[2]

[1]Department of Civil Engineering, Military Institute of Science and Technology (MIST), Dhaka, Bangladesh
[2]Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh

emails: *[1*]t.mustafy@ce.mist.ac.bd; and [2]raquibahsan@ce.buet.ac.bd*

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ABSTRACT

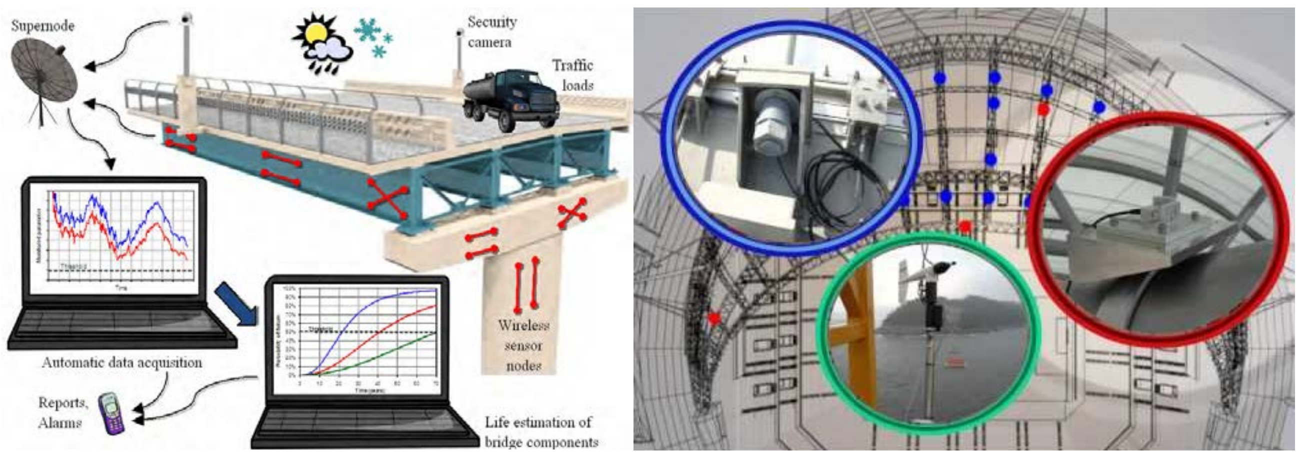
In the recent decade, the concept of "structural health monitoring," or SHM, has gained prominence due to its promise of reflecting the condition of structures and facilitating the monitoring of their behavior. Bangladesh is a country with a long coastline, thus it is unfortunate that the SHM system has not been more widely deployed on the country's many highway bridges across rivers. Saving money on manpower, remote monitoring allows for accurate, up-to-date assessments of a bridge's structural soundness. Recent developments in sensor, communication, and storage technologies have made a worldwide SHM system for infrastructures possible. The primary goal of this investigation is to assess the performance of the structural health monitoring system on the Padma Multipurpose Bridge. Recent developments in SHM's integration with ITS show the usefulness of ITS devices (such as traffic cameras and traffic detectors) in analyzing bridge responses to multimodal traffic with varying loads or during critical events that cause excessive vibration beyond the normal limit, which can be of great assistance in tackling the Padma bridge's serviceability challenge. Integrating information from an ITS device with SHM may increase the reliability and precision of the SHM system. As a consequence of this integration, the SHM system would be less likely to misdiagnose damages (i.e., vibrations caused by big cars on a bridge may be perceived by a SHM sensor as a structural health concern of the bridge), resulting in decreased maintenance costs. This investigative study provided a summary of the SHM systems now in place for major bridges in Bangladesh, such as the spectacular Padma Bridge, and discussed their use and appropriateness in the near and far future.

1. INTRODUCTION

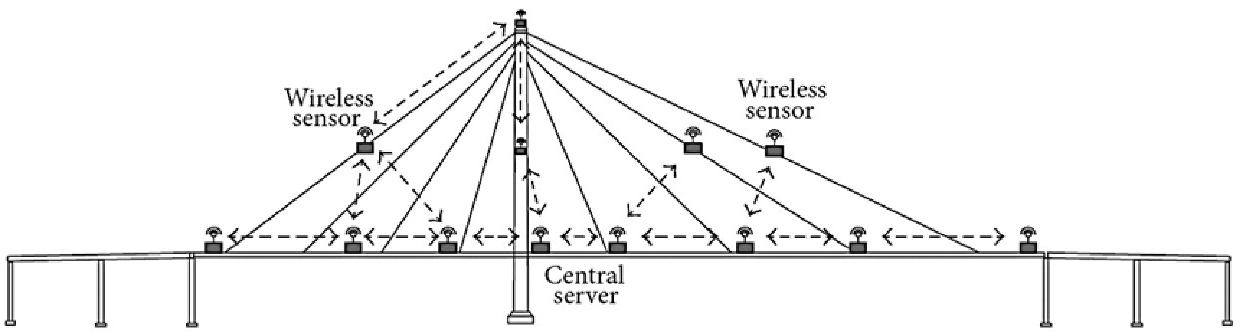
Bridge designs have a tendency to become more flexible throughout time, and their shape and function are becoming more complex. Therefore, ensuring the safety of these bridge structures is a crucial concern. Although safety monitoring is costly, it is impossible to guarantee a bridge's safety based solely on inspections and upkeep. Thus, the use of structural health monitoring (SHM) techniques has become crucial for ensuring the safety of bridge structures, particularly those with a long span. Due to the high expenses of bridge repairs and high-rise building rehabilitation, it is essential to continuously check structural health. SHM has the ability to extend the design lives of structures, ensure public safety, and significantly lower the cost of restoration. While failure or a loss of functionality in the structure can be avoided, damage, or the decline of system performance, cannot be prevented but can only be reversed. Therefore, SHM approaches are important topics for research in the field of engineering and academia [1]. Other than performance, safety, dependability, and serviceability are essential components of any engineering structure [2]. In consideration of these, it is crucial to use technology to monitor the engineering structures through evaluation and assessment [3-5]. In recent years, structural health monitoring (SHM) research has received increased attention from academic institutions, governmental organizations, and businesses in a variety of industries, including civil, marine, mechanical, military, aerospace, power generation, and offshore oil and gas. Engineering constructions function differently depending on their age, kind of material, service condition, and arrangement. Around the world, SHM technology is used in a variety of applications. For instance, in large-span bridges, such as the Hakucho Bridge in Japan [6], the Bill Emerson Memorial Bridge in the United States [7], the Jindo Bridge in South Korea [8], the Tsing Ma Bridge and the Ting Kau Bridge in Hong Kong [9], and the Sutong Bridge and the Jiangyin Changjiang River Bridge in China, SHM techniques have been developed extensively. These systems ensure the safe operation of the bridge, and numerous techniques are used to extend the life of bridges [10-13].

2. SIGNIFICANCE OF STRUCTURAL HEALTH MONITORING

Structural health monitoring (SHM) is the formulation and application of methodologies and procedures that are helpful for the continual monitoring and upkeep of the structure's functional value. The primary goal of SHM is to warn the system in the early phases of damage start and prevent further failure propagation with the use of ongoing structurally integrated sensor monitoring. The development of SHM aids in damage detection and strategy analysis, which further aids in extending the useful life of engineering structures or components by preventing failure [14]. Any nation or state grows and prospers only if they carefully maintain and keep an eye on the key structures such as bridges, roads, railways, skyscrapers etc. In addition to averting financial losses, maintaining and monitoring the structures will promote public safety and health. It is obvious that if major structures are not adequately maintained and the recommended maintenance rules are not followed, this would have disastrous effects.



(a) Structural Health Monitoring equipment for a typical bridge segment



(b) WSNs-based bridge health monitoring system [17]

Figure 1: Structural Health and WSNs-based bridge health monitoring

These mishaps result in a great loss of life and hurt both the national and global economies. Enhancing public safety is one of SHM's key advantages. Sensors are used in advanced SHM techniques to gather data, which is then properly analyzed (Figure 1a). The government makes sure everyone is secure by requiring local governments to monitor all important buildings. Structures begin to age and have numerous cracks and weak places. The SHM procedure can be used to find flaws and cracks in older buildings. The management can either fix the problems or isolate the building for everyone's safety once the flaws are identified [15, 16]. The use of SHM by engineers enables them to identify early signs of poor structural health and related risk. Floods, which are brought on by broken dams, pipelines, and dykes, can be avoided with the aid of early detection [3]. Regular structural health monitoring aids in the early detection and correction of cracks and failures. This increases their lifespan as well as their effectiveness.

Advanced SHM techniques including the optical method, transient thermo graphic method, and eddy current method make it simple to detect even the smallest failure. Even the slightest cracks may be repaired with ease. This delays the spread of cracks that could eventually result in structural failure [18]. Implementing SHM not only increases the life of the structures and ensures public safety, but it also lowers both the short- and long-term costs related to structures. In particular, the business sector supports effective SHM as a way to boost total earnings. The maintenance schedules for the entire structure can be extended with the prompt detection and repair of minor faults. Fixing problems early on helps structures prevent significant damage and reduces costs associated with demolishing and rebuilding the entire structure [19].

3. REGIONAL STUDIES ON BRIDGE CONSTRUCTION WORLD-WIDE

In the past, SHM systems have included wired data collecting devices that may periodically collect structure data. These systems use various sensing device types, specific damage diagnostic and prognosis techniques, and structural conduct measurements to evaluate structural safety conditions. However, because expensive communication connections must be constructed and maintained on a regular basis, wired structural monitoring systems are not generally used due to their high cost. Low-cost wireless structure monitoring systems are now conceivable because of recent advancements in WSN and MEMS technologies (Figure 1b). In comparison to conventional wired SHM systems, the collaborative nature of WSNs for SHM application has a number of advantages, including self-organization, quick deployment, flexibility, and built-in processing power. In this light, WSNs are crucial in developing a highly adaptable and affordable SHM system that can act appropriately and quickly in response to real-time events.

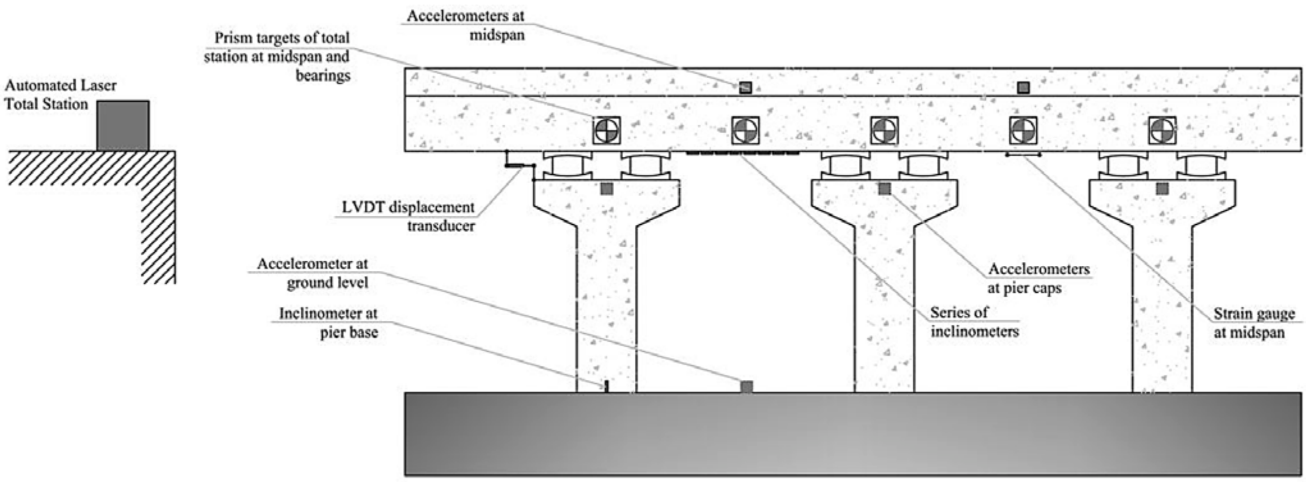


Figure 2: Placement of sensors on the bridge deck and piers [20]

Over 135 bridges in the United States are said to have partially or completely fallen between 1989 and 2000. Due to the scour of a bridge masonry pier, the Entre-os-Rios Bridge in Portugal fell in 2001, killing 59 persons. The significance of SHM systems for bridges is readily apparent.

Pre-stressed concrete box Girder Bridge known as St. Marx Bridge is situated in Vienna. In order to identify severe vehicle loads that could result in structural damage, a structural health monitoring system and a video control system were installed in 1998. There are currently four accelerometers and one temperature sensor installed. The Meriden Bridge has undergone extensive bridge health monitoring thanks to the installation of WSSNs and a wired system. A wired monitoring system with 38 different types of sensors was installed along with five Imote2 sensors [17, 21] (Figure 2). The first bridge with an extensive, self-contained wireless monitoring system is South Korea's second Jindo Bridge. A total of 71 WSS nodes with 427 sensing channels were installed on the girder, pylons, and cables. The nodes are made up of a sensor board, a battery, and the Imote2 (which has an integrated power management circuit, radio, and CPU on board) [22, 23]. Full-scale bridge health monitoring of the Meriden Bridge was carried out by deploying WSSNs and a connected system. A wired monitoring system with five Imote2 sensors and 38 sensors of various types was installed.

A. Geumdang Bridge of South Korea

In Icheon, South Korea, there is a bridge called Geumdang that has two structural systems: the northern span has a concrete deck supported by four pre-cast concrete I-beam sections, and the southern span has a continuous concrete box girder supported by three concrete piers. In order to monitor the bridge's vertical acceleration, a dense network of wireless sensors was fitted with a high sensitivity PCB Piezotronics 3801 accelerometer (sensitivity is 0.7 V/g).

In Figure 3, a continuous concrete box girder supported by three concrete columns supports the southern span and the concrete I-beam sections.

B. Tamar Bridge

Structure, Cable loads and environment temperatures as well as wind speed and profile were all monitored using the Structural Monitoring System (SMS) installed by

Fugro Structural Monitoring. Engineering data on the performance and state of the bridge before, during and after the strengthening and enlargement has been provided by the SMS (Figure 4). During the strengthening operations, it was specifically employed to track deck profile and cable loads. Among the sensors utilized in the SMS are:

- Fluid pressure-based level sensing system to monitor vertical displacement of the deck;
- Temperature sensors for the main cable, deck steelwork, and air;
- Extensometers and resistance strain gauges to measure loads in supplementary cables.
- Electronic tower top-to-tower distance measurement.

A brief description of the measurement/sensing systems are as follows:

i. Temperature: Platinum Resistance Thermometers (PRTs) on stainless steel shims with adhesive in their positions serve as temperature sensors for steel and cable monitoring. Temperature probes with shielding from radiation make up temperature sensors for air monitoring.
ii. Strain gauges: Resistive strain gauges mounted to main tensioning bolts at deck anchor points are used. Epoxy (protected by foil-backed putty) or micro-welding are two methods of fixing (covered by butyl rubber and neoprene). Around the bolt, gauges are set in pairs 180 degrees apart, with an axial element and an element to measure hoop strain in each pair. The temperature adjustment is provided by the hoop gauges, which are connected to a full Wheatstone Bridge by the four gauges.
iii. Wind detectors: At the top of the Saltash Tower, where wind direction is also monitored, as well as at the deck level of the Saltash Tower and Saltash Approach, wind speed is measured mechanically.
iv. Tower displacement measurements: A Plymouth Tower upper portal-mounted electronic distance measuring device (EDM) measures the distance between two towers. This makes use of a laser that is reflected off a vertical array of tiny prisms on the Saltash Tower upper portal wall; the size of the array permits in-plane movement of the Towers.
v. Level sensing system: A fluid manometer system with fluid-filled pipes runs along the primary span of this level sensing system. Level sensing stations (LSS) with 1/8 span centres monitor heights by taking pressure readings on the fluid head. The system is modelled after a comparable system that Fugro placed on bridges on the Lantau Fixed Crossing. The height measurements are updated every 10 seconds and have a +/5mm accuracy specification [24] (but sampled at 1Hz). Each LSS additionally has a set of fluid temperature sensors.

In order to track the dynamic behaviour of the bridge deck and particular cables, University of Sheffield installed an additional set of sensors in 2006. Four stay cables, P4N, P4S, P1N, and S2S were equipped with two accelerometers, one oriented horizontally and one in the vertical plane of each cable, in order to verify the damper solution's excellent performance (Figure 5 - 7).

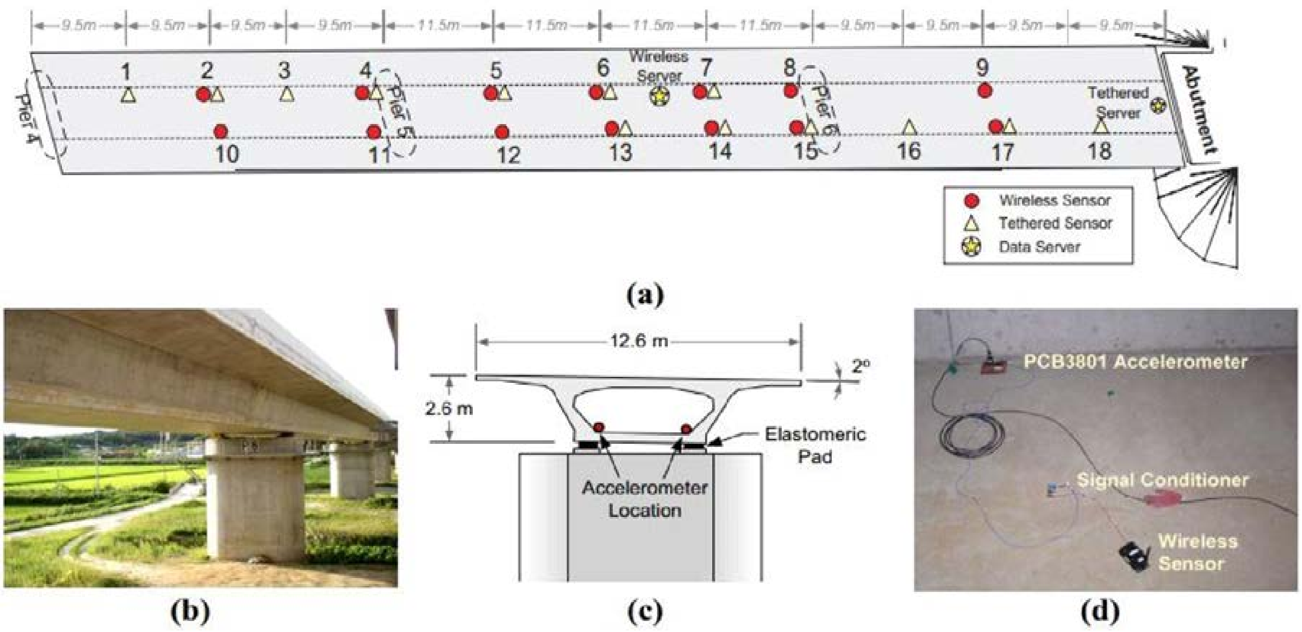


Figure 3: (a) Location of wireless sensors installed along the length of the Geumdang Bridge; (b) External view of the box girder bridge; (c) Cross-section of the box girder showing the location of accelerometer location; (d) Typical wireless sensor-accelerometer installation [21]

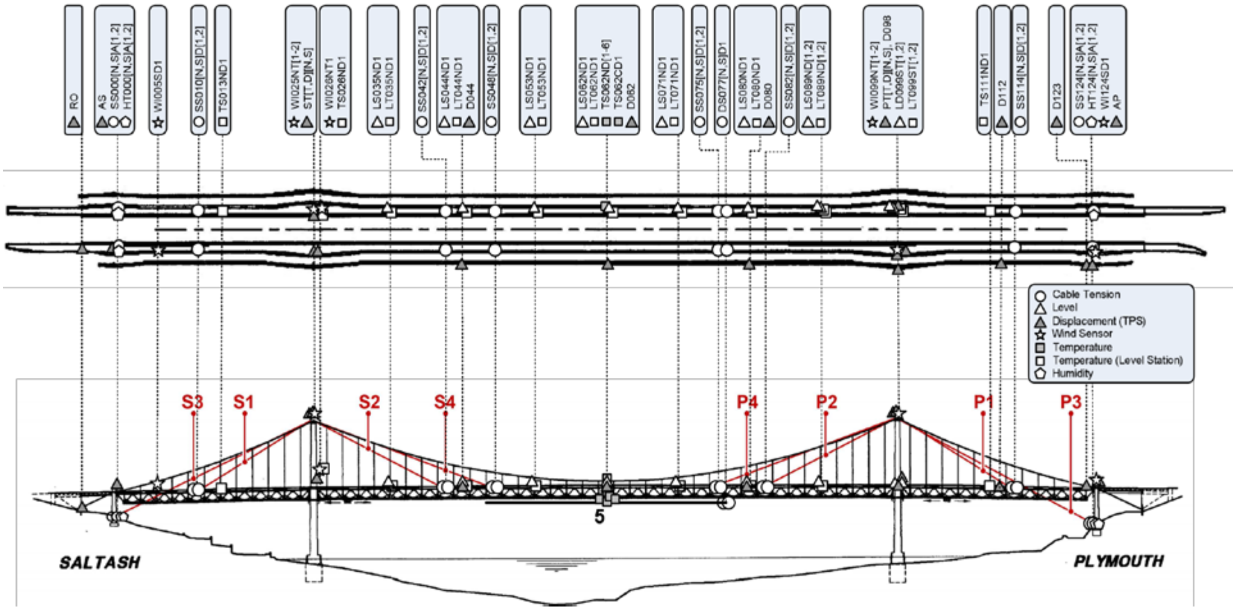


Figure 4: Sensors in Tamar Bridge [25]

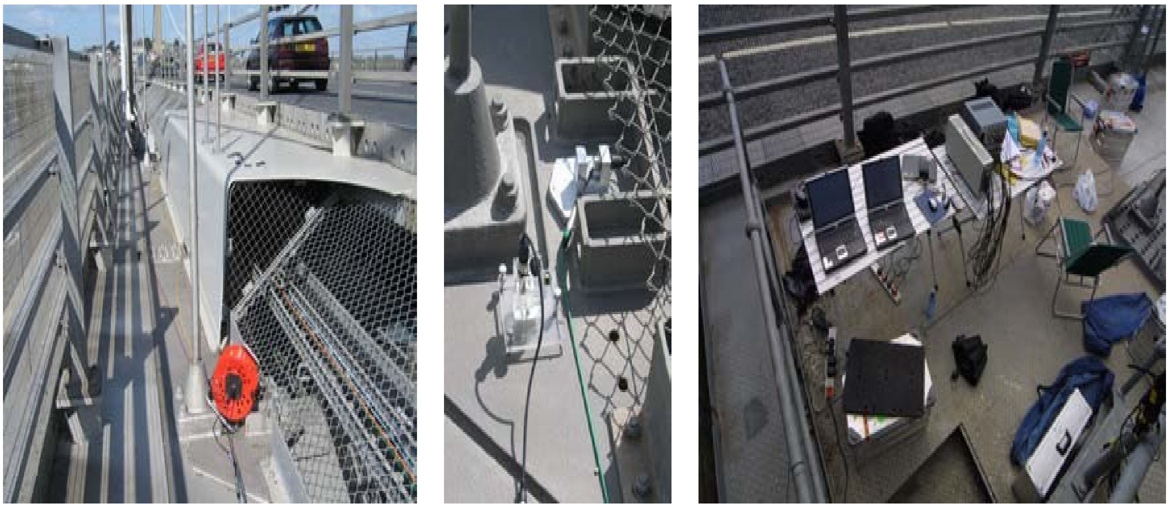


Figure 5: AVT in progress, displaying where the accelerometers are located next to the shear box and the data gathering facility is located close to the tower [25]

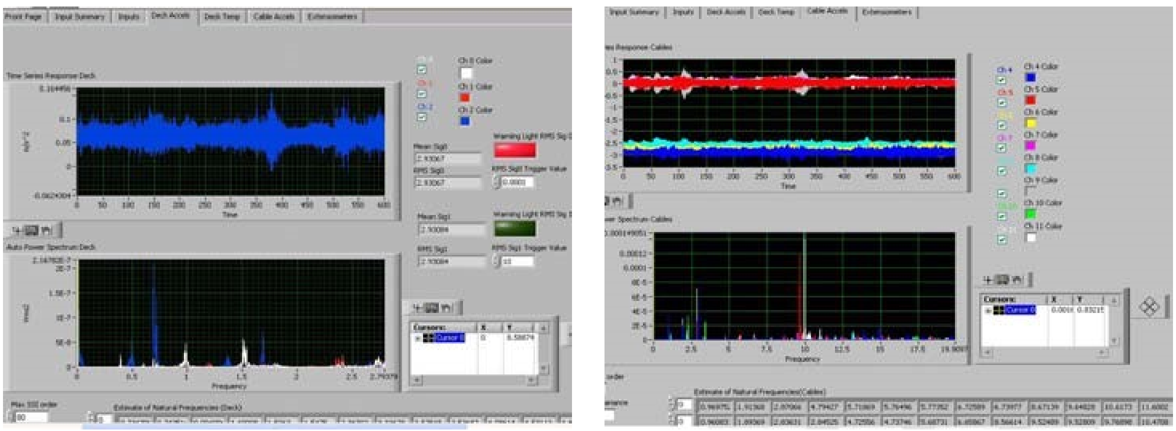


Figure 6: Lab VIEW virtual instrument pages displaying time- and frequency-domain signals from cable and deck accelerometers [25]

Figure 7: Reflector in bridge deck [25]

C. Jinghang Canal Bridge (JCB)

China's Jinghang Canal Bridge is a pre-stressed concrete single-cell box girder bridge with a span length of 150 meters. For long-term monitoring, variables like temperature, reinforcement strain, and deflections are used. Vibrating strain gauges with built-in temperature couplings were incorporated into the bridge to reduce the expense of the long-term monitoring system. Eight cross-sections, including sections Z2 and Z3, A1 to A4, B1 and B2, were employed with the hydrostatic leveling system for long-term deflection monitoring. On the inside surface of the box girder's web, each DT was mounted. The major span support strain increment is determined to be negligible, indicating that concrete shrinkage or creep is negligible there. But the effect has been found to be strong at the middle of the major span. Deflection at mid-span is one of the primary issues with pre-stressed concrete bridges, as evidenced by the discovery that the measured time dependent deflections are greater than the design values [21]. Figure 8 depicts the sensor configuration for the stages of monitoring throughout construction, completion testing, and service.

D. Kishwaukee River Bridge in Illinois

Since December 2001, an automated bridge monitoring system has been installed on the Kishwaukee River Bridge in Illinois, USA. Because of the structure's long-term stability, crack opening displacements can be directly evaluated using LVDT to determine how the structure will age over time [26] Seven LVDT sensors were put on the Kishwaukee bridge to measure the shear crack opening displacement on the box-girders [27] (Figure 9).

E. Bangabandhu Bridge

The pre-stressed concrete box girder Bangabandhu Bridge is situated in Bangladesh (Figure 10). With a primary span of 100m, the whole length is 4.8 km. The cost to fix surface fractures on the deck in 2014 was roughly 147 million USD. According to reports, these cracks developed as a result of temperature differences between the upper and lower parts [28]. Temperature sensors had been employed to collect data on a regular basis to monitor the temperature variation of the upper and lower parts (Figure 11). The Bangabandhu Bridge is also instrumented with two triaxial, one biaxial, five uniaxial accelerometer sensors and three displacement sensors (Figure 12) [27]. There are sixteen channels of data. The data are fed to three digital data recorders. The recorders are connected to one communication enclosure for data transfer to the server of a Data Control Centre through 2.4 GHz. Wireless radio antenna. One borehole sensor is placed at the west end of the bridge. In addition, six free field stations, three on each side of the Jamuna River, are set up to measure the ground motions. The free field stations are 70 to 90 km apart.

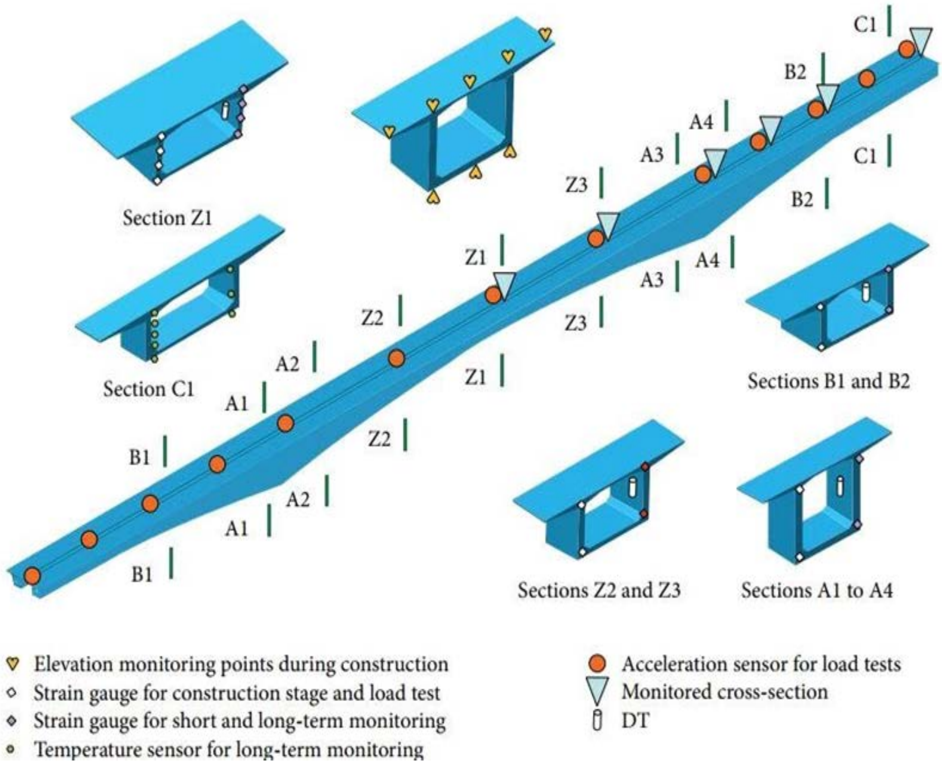
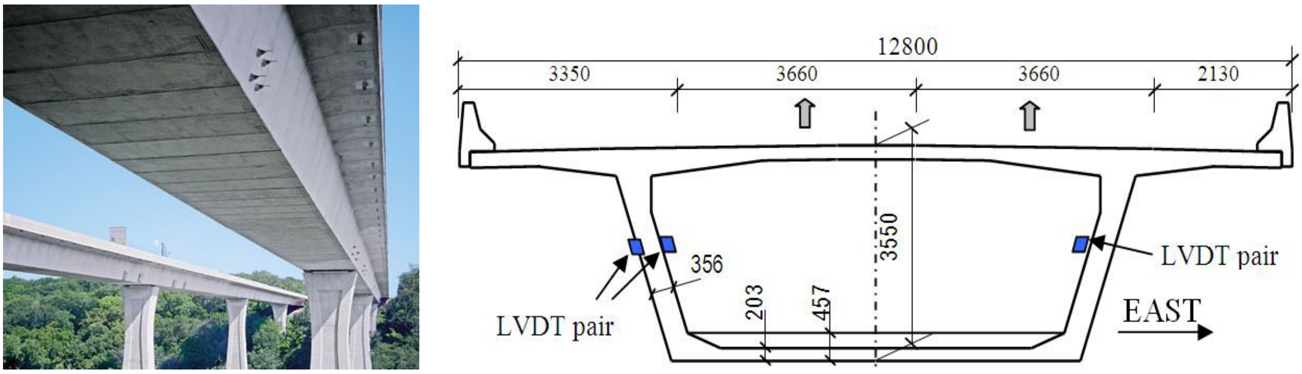


Figure 8: Sensor layout of Jing hang Canal Bridge [21]



(a) (b)

Figure 9: (a) Kishwaukee Bridge, (b) Location of LVDT sensors (unit: mm) [27]

Figure 10: Bangabandhu Jamuna Bridge[21]

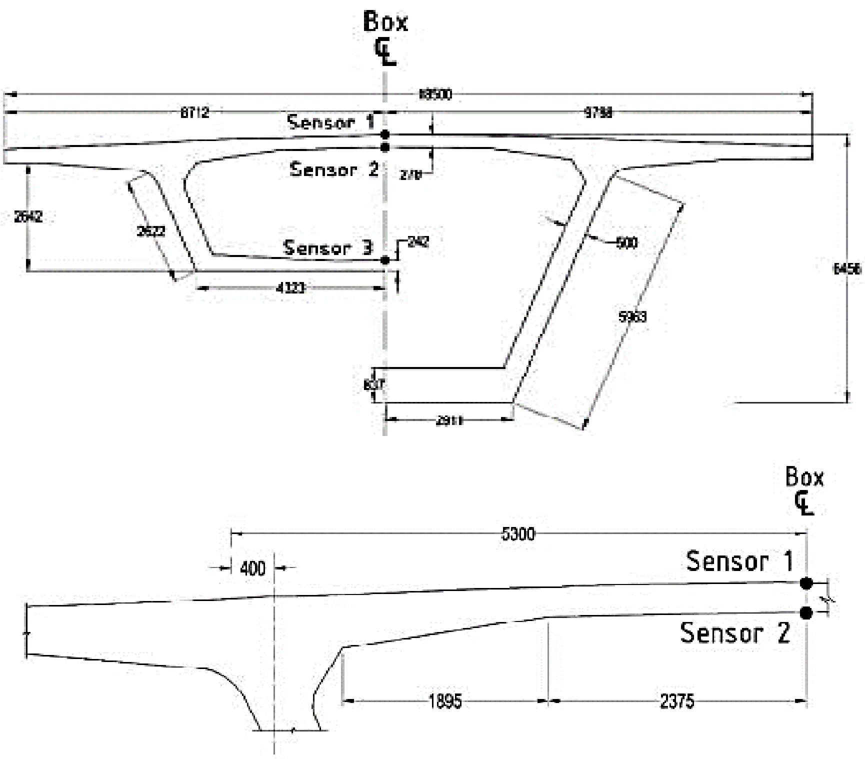


Figure 11: Location of sensors to monitor temperature variation in box girder of Bangabandhu Bridge [28].

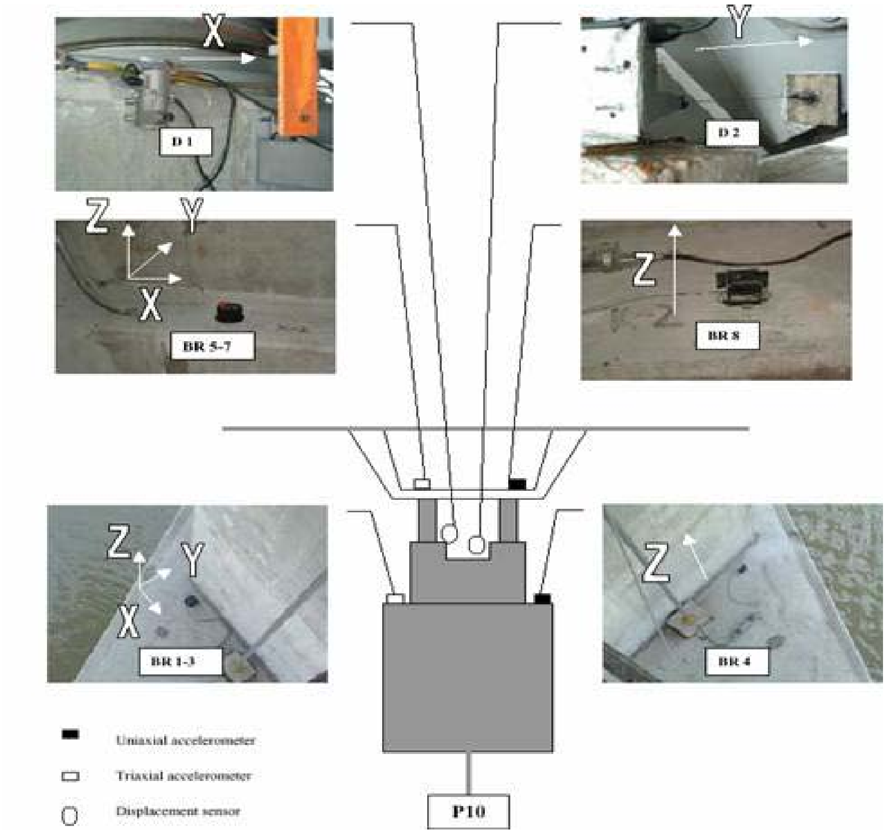


Figure 12: Location of various accelerometer and displacement sensors in Bangabandhu Bridge [28]

Table 1

Sensors used in different notable pre-stressed concrete box girder bridges of the world [21]

Bridge name/ SHM equipment	*Strain*	*Deflection or rotation*	*Support displacement*	*Acceleration or velocity*	*Corrosion*	*Crack*	*Pre-stress loss*	*Traffic camera*	*Temp*	*Weather station*
Ferriby Road Bridge (UK)	Absent	Present	Absent	Absent	Absent	Present	Absent	Absent	Absent	Absent
PI-57 Bridge (France)	Absent	Absent	Absent	Present	Absent	Absent	Absent	Absent	Present	Absent
Leziria Bridge (Portigal)	Present	Present	Present	Absent	Absent	Absent	Absent	Absent	Present	Absent
401 Southbound Bridge (USA)	Present	Present	Present	Absent	Absent	Absent	Present	Absent	Present	Absent
California Pilot Bridge (USA)	Present	Present	Absent	Present	Absent	Absent	Absent	Present	Present	Absent
Utah Pilot Bridge (USA)	Present	Present	Absent	Present	Absent	Absent	Absent	Present	Present	Present
Kishwaukee Bridge (USA)	Present	Absent	Absent	Present	Absent	Present	Absent	Absent	Present	Absent
New 135W Bridge (USA)	Present	Present	Present	Present	Present	Absent	Absent	Absent	Present	Absent
Kamikazue Viaduct (USA)	Absent	Absent	Absent	Absent	Absent	Absent	Present	Absent	Absent	Absent
A curved Bridge (USA)	Absent	Present	Absent	Present	Absent	Absent	Absent	Absent	Present	Absent
West street Onramp Bridge (USA)	Absent	Absent	Absent	Present	Absent	Absent	Absent	Absent	Absent	Absent
North Halawa valley Viaduct (USA)	Absent	Present	Present	Absent	Absent	Absent	Absent	Absent	Absent	Absent
Zhaoqing Xiajiang Bridge (China)	Present	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Present	Absent
Chongqing Shibanpo Bridge (China)	Present	Present	Absent	Absent	Absent	Absent	Absent	Absent	Present	Absent
Xushuigou Bridge (China)	Present	Present	Absent	Absent	Absent	Absent	Absent	Absent	Present	Absent
Jiangin Yangize River Highway Bridge (China)	Present	Present	Absent	Absent	Absent	Present	Absent	Absent	Present	Absent
Anwen Bridge (China)	Absent	Present	Absent	Absent	Absent	Absent	Absent	Absent	Present	Absent

Present (green)
Absent (red)

Bangladesh contains a variety of subsurface soil conditions for bridge foundations since it is a deltaic formation made by the alluvium and sediment deposition carried by the three major rivers, the Ganges/Padma, Brahmaputra/Jamuna, and Meghna, as well as their tributaries and distributaries. The Standard Penetration Tests are the primary field testing for subsurface research in the nation (SPT). At roughly 1.5m intervals, disturbed and undisturbed samples are collected, and those samples are then subjected to the requisite laboratory tests outlined by the designers. Based on the results of the aforementioned tests, the pile bearing capacity—which combines shaft resistance and end bearing of piles-is calculated, and pile settling is evaluated. However, the majority of SPT equipment utilized in the nation is not of the conventional type; the cutters' size, shape, and materials are inadequate to allow for quality sampling and provide representative SPT readings, which in turn is likely to result in an inflated estimate of pile carrying capacity [28, 29].

The AASHTO HS20-44 truck and the lane loads that go along with it are used by the RHD when constructing bridges for Type NH, R, and Z highways and roads. On the basis of IRC: 6-2000, they use an IRC Class A train of vehicles to test the design. The design live loading has been improved to Type HL-93 in AASHTO's 2007 Bridge Specifications. It uses the same design truck as the HS20-44 truck. In addition, a single tandem design with two 110.00 KN axles spaced 1200 mm longitudinally and 1800 mm transversely is employed. Depending on which generates a heavier load, the load combination follows the design truck or design tandem in conjunction with the design lane load. Bridge loadings for Bangladeshi bridges must be standardized to account for all types of traffic, including military vehicles. In Bangladesh, there is currently no independent national design standard or guideline for bridges [28, 29]. The American Association of States Highway and Transportation Officials (AASHTO) Specifications are the most widely used at the moment, with various designers using editions ranging from 1992 to 2007. Additionally, other specialized material is consulted. In some instances, the British Standard (BS) 5400 (1978) has been adhered to. For instance, the Jamuna Design Specification for the Jamuna Multipurpose Bridge was created in accordance with this standard [29]. Specifications from the Indian Roads Congress (IRC) are also frequently consulted. After reviewing the Bangladesh National Building Code 1993 [30] to determine the wind and seismic loading of bridges, the design of the second Kachpur, Meghna, and Gumti bridges mainly adhered to JRA regulations [29].

Table 2

Major river crossings in Bangladesh in order of major span, year of construction, total length, superstructure and foundation type [28]

Geological formation/ Canal	Name of bridge	Major Span (m)	Year of completion	Total length (m)	Superstructure for longest span	Foundation
Ganges-Brahmaputra Meghna	Padma Bridge	150	2022	6150	Steel-composite	CFT6
	Lamakazi Bridge	122	1984	226	Steel truss	Bored pile
	Sadipur Bridge	120	2000	163	Steel truss	Bored pile
	Sunamgong Bridge	115	2015	403	Steel truss	Bored pile
	Bhairab Road Bridge	110	2002	1191	PC box girder	Bored pile
	Lalon Shah Bridge	109.5	2004	1640	PC box girder	Bored pile
	Hardinge Bridge	109.5	1915	1640	Steel truss	Caisson
	Moktarpur Bridge	100	2008	1514	PC box girder	Bored pile
	Khan Jahan Ali Bridge	100	2005	1360	PC box girder	Bored pile
	Bangabandhu Jamuna Bridge	100	1998	4800	PC box girder	CFT6
	Bhairab Rail Bridge	91.5	1937	640	Steel truss	Caisson
	Sultana Kamal Bridge	90	2010	1072	PC box girder	Caisson, bored pile
	Gumti Bridge1	87	1994	1410	PC box girder	Bored pile
	Meghna Bridge2	87	1991	930	PC box girder	Bored pile
	Dapdapia Bridge	85	2010	1390	PC box girder	Bored pile
	Keane Bridge	75	1936	387	Steel truss	Steel pile
	Buriganga-I Bridge3	72	1989	847	PC girder	Bored pile
	Kachpur Bridge	72	1977	397	PC I-girder	Caisson
	Gorai Rail Bridge	56	1870	515	Steel truss	Steel pile
	Tora Bridge	54	1972	646	PC girder	Caisson
	Teesta Bridge	50	1901	650	Steel truss	Caisson
	Aminbazar Bridge	46.4	1972	252	PC girder	Caisson
	Jaigir Bridge	46.4	1962	493	RC box girder	Caisson
	Noyarhat Bridge	42	1975	154	PC girder	Caisson
	Baral Bridge, Baghabari	38.1	1978	572	PC I-girder	Caisson

The Padma Bridge (Figure 13), which has a steel truss and composite deck, has the longest 150 m span length, although steel trusses could only reach a 122 m span [26]. The key to lowering the foundation load is achieving the highest stiffness to mass ratio. In this way, the authors understand the challenges of building long span bridges in the Ganges-Brahmaputra-Meghna basin, but they also see how short and medium span bridges (50 m to 200 m) may develop as solutions with higher efficacies. In passing, it is important to remember that even before the Hardinge Railway Bridge was built, there were technologies available to build and erect spans longer than the Hardinge Railway Bridge, such as the 240.9 m single span Lansdowne Bridge Rohri, which was inaugurated in 1887 and spans the Indus River, which is very dissimilar to the Ganges basin. With two main spans of 160 meters each, the 363-meter Jubilee Bridge in Hooghly (22°54'26.10"N, 88°24'16.48"E) is of the cantilever steel truss type. In relation to the Ganges basin, the bridge is situated the furthest west [26, 28].

Figure 13: Padma Bridge

4. STRUCTURAL HEALTH MONITORING OF PADMA BRIDGE

For Bangladeshi bridges, in particular, scouring is a crucial criterion for structural health monitoring in bridges. The government have installed sophisticated computerized sensor-controlled weighing machines on the Mawa and Janjira ends to stop overweight cars from using the Padma Bridge (Figure 14). The main infrastructure operations to set up the weighing machines, according to those who are concerned, have already been finished. The installation of the weighing equipment, which has been inaugurated at the earlier this year, are in full functioning. Furthermore, each freight vehicle will need to cross the bridge after being weighed. For the first time in the nation, a weight scale is being placed that does not need stopping moving traffic to assess weight. Once the car is close enough, the machine's electrical sensors will begin to measure the weight immediately. Electronic sensors will be used to gather the data and transmit it to the main server. Six weight scales will be installed, three on each end of the bridge, by the Seoul-based Korean Expressway. Despite the fact that the bridge is allegedly capable of supporting cars up to 27 tones in weight, it does not yet have a measurement system in place. Since June 25 of this year, the eagerly awaited bridge has been accessible to vehicles. Property Development Limited, which has already finished building two stockyards on both ends of the bridge, is the contractor company for installing the infrastructure, according to the Bangladesh Bridge Authority. Eight guard stations and two driver huts have also been built at the bridge's ends.

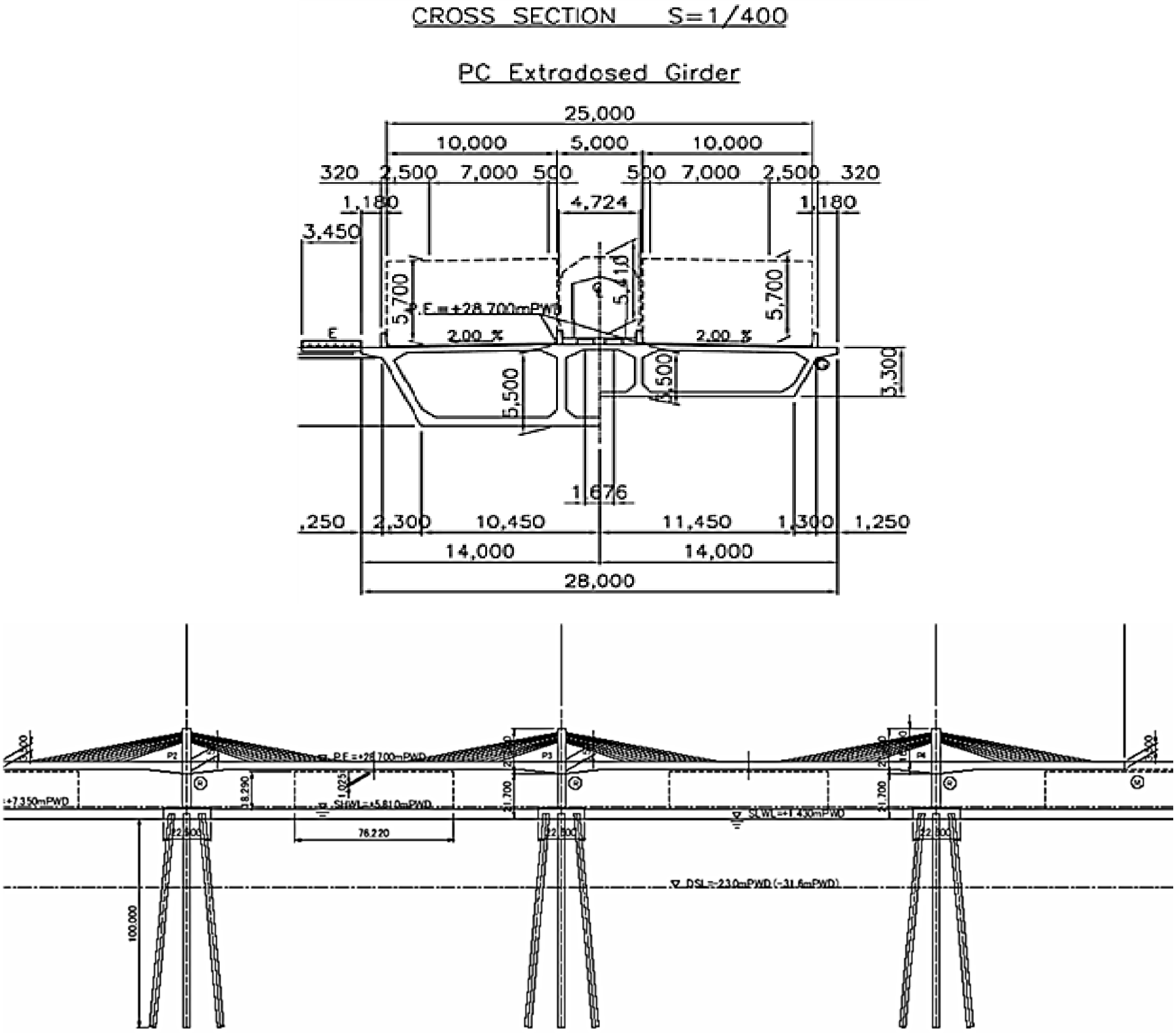


Figure 14: Feasibility Study Preliminary Design for Main Bridge [31, 32]

According to officials, after weighing their loads, cargo trucks that are loaded with goods up to the maximum of 27 tones will be permitted to pass the bridge through the green zone. To get to the stock yards, though, vehicles weighing more than 27 tones must pass through the red zone. The stockyard could accommodate the larger vehicles for a 72-hour parking period. However, additional items could be kept in the stockyard for a week. One of the most unique features of the Padma Bridge is its foundation comprising the deepest driven piles in the world. The pile length is as deep as 127 m. As mentioned earlier scoured depth is a major problem of this river. To investigate the performance of these ultra-long piles vibration measuring instruments may be installed at the pile cap. Some strong motion accelerometers (SMA) can be placed on either side of the river to measure free field motion. Based on the vibration measurements, the effectiveness of the piles may be ascertained. Another interesting feature of the Padma Bridge is use of friction pendulum bearing (Figure 15) to isolate the superstructure from the earthquake ground vibration. Friction pendulum bearings reduce the earthquake induced forces by lengthening the natural period of the isolated structure. They also introduce damping by sliding mechanism. By using friction pendulum bearings, the earthquake induced loads on piles are greatly reduced. However, the actual efficacy of the bearings should be examined through the SHM approach. vibration sensors may be attached at the pier top and girders along the length of the beams. By comparing the motions at different levels of the bridge during a moderate shaking, the performance of the bearings may be understood. Eigenvalue Realization Algorithm (ERA) based system identification approaches may be adopted for SHM of the bridge. Artificial Intelligence (AI) and big data analytics with data over a long period of time may be used for this purpose.

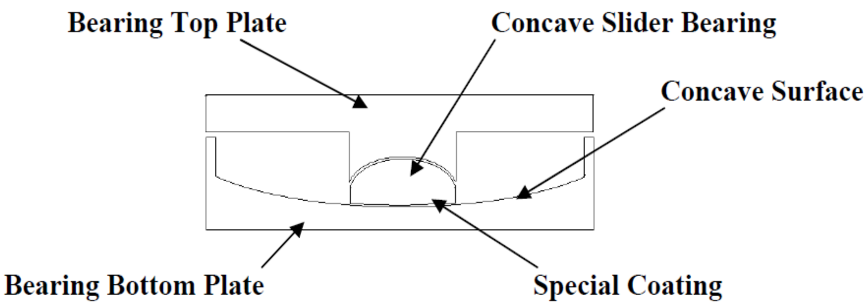


Figure 15: Cross-Section of a friction pendulum bearing [32]

5. CONCLUSIONS

Significance and applications of Structural Health Monitoring (SHM) are discussed in this paper with examples all around the world. The important issues related to the long span bridges particularly in Bangladesh are discussed in length. The SHM approaches adopted for the Padma bridge are described. The unique features of the Padma bridge make the bridge more deserving of constant monitoring of the bridge. Different prospective ways of SHM that can be adopted for the Padma Bridge are briefly mentioned here. The authorities may take all of these ideas into consideration and apply them to ensure that this magnificent bridge continues to function flawlessly for future generations.

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

K. S. Ahmed[1*], S. M. Moniruzzaman[2], Tahsin Reza Hossain[3], and Shamim Z Bosunia[4]

[1,2]Department of Civil Engineering, Military Institute of Science and Technology (MIST), Dhaka, Bangladesh
[3]Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh
[4]Department of Civil Engineering, University of Asia Pacific (UAP), Dhaka, Bangladesh

emails: *[1*]drksa@mist.ac.bd; [2]moniruzzaman94@gmail.com; [3]tahsin@ce.buet.ac.bd; and [4]szbosunia@uap-bd.edu*

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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	

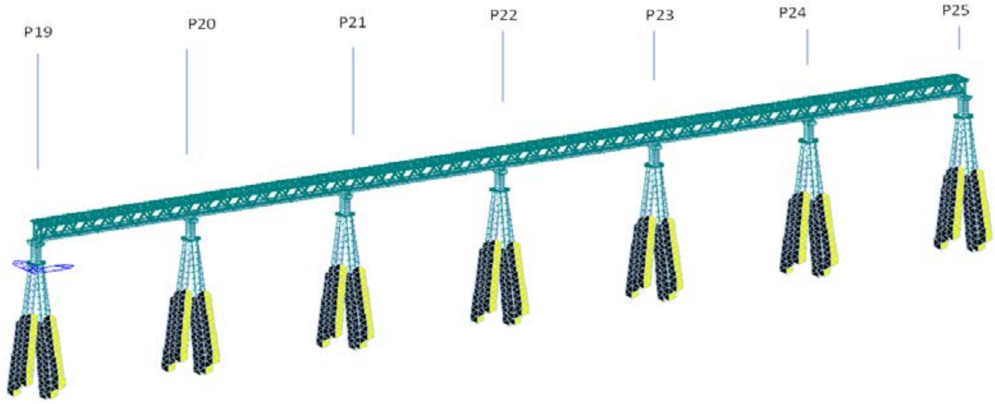

Figure 1: 3D Finite element model of the bridge module with soil-structure interaction

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).

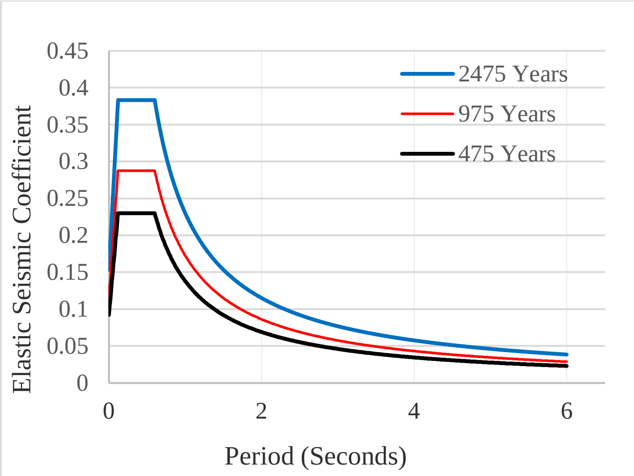

Figure 2: Response spectrum curves for the different earthquake return periods

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		Period (sec)
	(rad/sec)	(cycle/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.

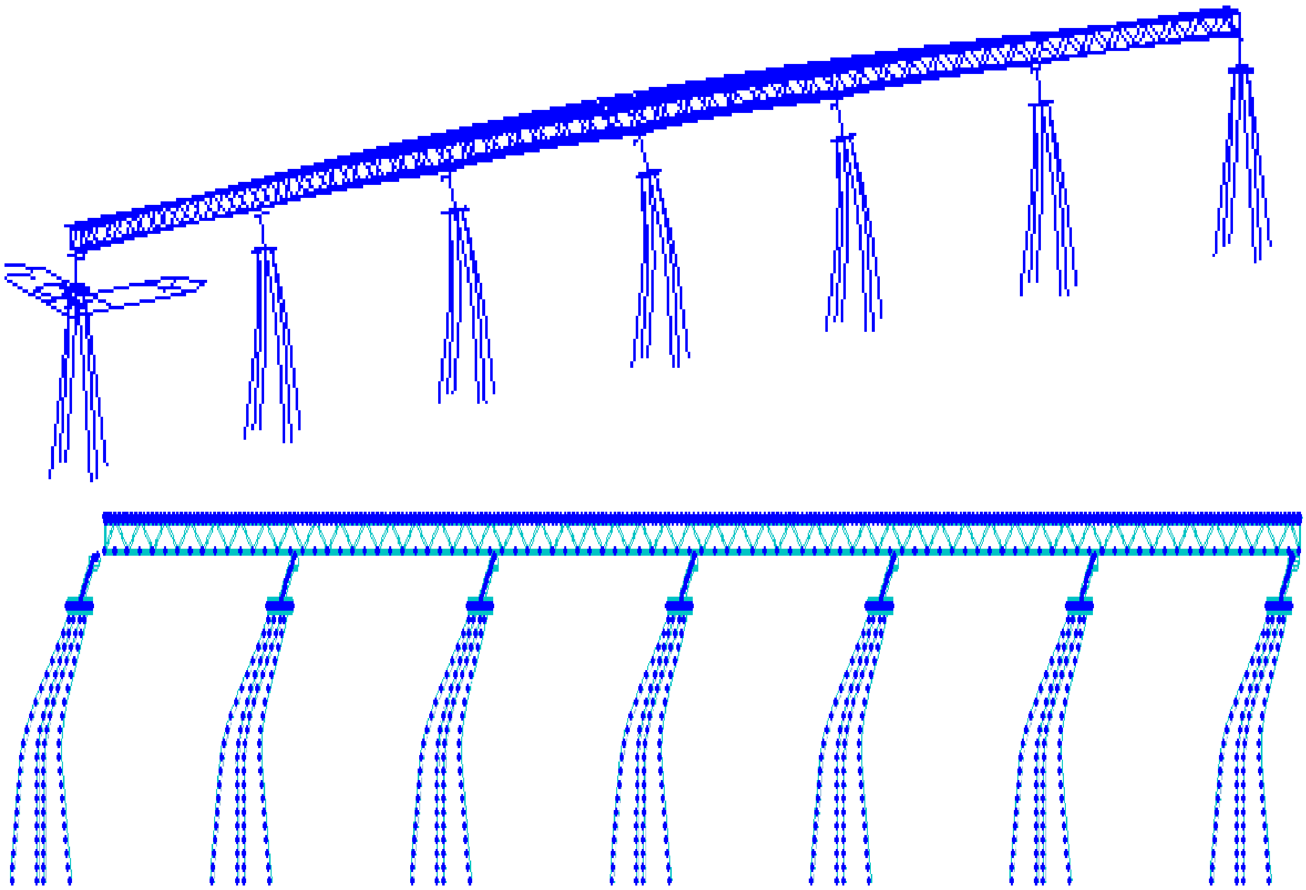

Figure 3. Deflected shape of the bridge in the transverse and longitudinal direction

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

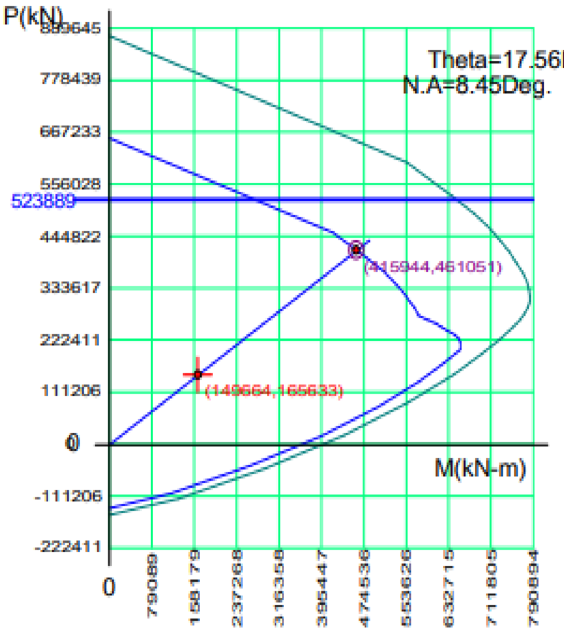

Figure 4. P-M interaction diagram

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.

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Dynamic Responses of Padma Multipurpose Bridge Truss due to Moving Train Load

Khondaker S. Ahmed[1*], Max T. W. Chuan[2], Jian Dai[3] and Ang K Keng[4]

[1]Department of Civil Engineering, Military Institute of Science and Technology (MIST), Dhaka, Bangladesh
[2,4]Department of Civil and Environmental Engineering, National University of Singapore (NUS), Singapore, 117576
[3]Department of Civil Engineering, Oslo Metropolitan University (OMU), Pilestredet 35, 0166 Oslo, Norwegian

emails: *[1*]drksa@mist.ac.bd; [2]maxtan@u.nus.edu; [3]jiandai@oslomet.no; and [4]kk_ang@nus.edu.sg*

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ABSTRACT

Padma Multipurpose Bridge (PMB) is one of the most important projects in the history of Bangladesh due to its regional importance, economic benefit, and primary connectivity of one-third population of the country. The bridge is 6.15km long, connecting the ends of Mawa and Janjira in Bangladesh. The entire project is challenging to construct and complex in design as it contains both four-lane highways and train tracks supported by a double-deck composite warren truss. In this study, the dynamic response of the truss due to the moving train has been analyzed using the Moving Element Method (MEM). In this process, a separate finite element model has been developed using Finite Element (FE) program to convert the double deck truss into an equivalent beam. Analysis has been conducted for a series of different load cases, converging to the most realistic case where the actual train parameters are considered. Parametric studies have been carried out to determine the dynamic responses of the bridge with varying pier spacing and speed of the train. The most optimal solution has been discussed with the effect of the vibration of the train acting on the multi-purpose Padma bridge. The bridge's dynamic amplification factor (DAF) at a design speed of below 100km/hr is found 1.05. The parametric study shows that the critical train speed for the PMB is 1400km/hr resulting in the bridge resonance with a DAF of 18. It is also evident that with the increase of pier spacing the resonance of the bridge is expected to occur at a relatively lower speed.

1. INTRODUCTION

Ever since the 18th century, the use of the railway has been commonly adopted in many countries. This mode of transport has many advantages over conventional car usage and can be used for inter-city, inter-country, and even inter-continent traveling and may be regarded as a viable alternative to air travel. In developed countries like Europe and Japan (Loubinoux, 2012), HSR has been a popular form of transportation between states and countries. HSR not only shortens the time for inter-city traveling, but it also greatly reduces the use of conventional car usage, leading to a decrease in carbon footprint. This in turn, translates into significant energy savings and reduced demand for oil (Institute, 2018). The International Union of Railways (UIC) has stated that energy efficiency for high-speed rail is about four times compared to car and nearly nine times compared to air travel (Institute, 2018).

With a speed of more than 200 kilometers per hour, HSR may not be feasible for intra-city traveling in a city like Dhaka, though it could be a potential mode of transport to inter-cities (Dhaka and other Cities) and neighboring countries. The average speed of a Bangladeshi train is 60km/h, and the maximum speed is well below 100 km/h, which is much lower than the speed of high-speed rail. However, Bangladesh has been in collaboration with China for a high–speed rail to connect Southeast Asia. It is essential to carry out a detailed investigation, including the dynamic response of HSR to understand the impact of adopting such an expensive investment.

Fast-moving loads like high-speed train loads could cause excessive vibration on the supporting structural system during movement, which yields substantial dynamic stresses to the supporting columns (Cao *et al.*, 2018). The dynamic responses caused by the moving train may amplify the structural responses of the support structures, which could cause discomfort to the passengers. Furthermore, the railway in many developed countries is discretely supported such as pier supported, where the deflections of the rail track between the supports are a point of interest. Therefore, train–track dynamics research should be evaluated for the different structural and loading conditions. Several studies are carried out for train-track dynamics assuming tracks to be continuously supported by subgrades. These include the work by C.G. Koh (Koh *et al.*, 2003) and Dai *et al.* (2018b), which presented an analytical solution for moving loads resting on foundations with different stiffness. Dai et al (2018b) evaluated that the motion of the discrete supports due to the moving train load may experience more numerical complications in the analysis procedure.

Bridge pier and superstructures are considered critical structural components of bridges and are always a point of interest to engineers, researchers, and other stakeholders. Previously, bridge piers were investigated by many researchers, particularly under seismic loading or innovative reinforcing materials (Farzana and Ahmed, 2020). Evaluating Performance-based damage states of the pier using a displacement-based design approach may illustrate the accurate pier responses and hence potential repair and retrofitting (Mahmud and Ahmed, 2020, Ahmed *et al.*, 2021) strategy after the seismic event (Farzana and Ahmed, 2022). Recently, a study on the seismic evaluation of the Padma Multi-purpose bridge pier shows that the seismic demand of the bridge pier is only 36% of its capacity for an earthquake return period of 2475 yrs (Ahmed & Moniruzzaman, 2022). However, the dynamic response of the padma bridge pier or bridge superstructures due to the seismic event or moving train has not been investigated yet.

The focus of this study is to investigate the dynamic response of the Padma Multipurpose Bridge, a mega lifeline project of Bangladesh. The bridge structure consists of a series of steel warren trusses supported by piers at every 150m. The main bridge has a total length of 6.15 km with two different levels, servicing the vehicles and cars on concrete decking at the top and railway system travel across the middle level (Bangladesh Bridge Authority, 2022). This structure can be considered rather complex for a composite truss bridge with an effective length of 150m between discrete supports with different level vehicle movements. The construction work of the bridge has already been completed and is already operational for vehicles. The design speed of the train is set to 80-100 Km/hr for the bridge, where the train in developed countries is operated in the range of 200-300 km/hr. At this stage, assessing the dynamic response of the Padma multi-purpose bridge at higher speeds is crucial.

This paper presents the results of investigating the dynamic response of the Multipurpose Padma bridge of Bangladesh using the moving element method. Here, a conventional railway track is incorporated into the bridge where the truss is simplified into an equivalent beam. The analysis focuses on the vertical displacement of the bridge despite being subjected to bending in both vertical and lateral directions. Parametric studies are conducted to understand the effect of spacing between discrete supports and the train speed on the dynamic displacement of the bridge. Although the truss system is designed for both motor vehicles and trains at two different bridge levels, MEM analyses are performed for the bridge solely for the moving train in view of the fact that the magnitudes of train loads are much higher than road vehicles.

2. METHODOLOGIES, ASSUMPTIONS, AND FORMULATIONS

The Moving Element Method (MEM) has been adopted to compute the dynamic response of the bridge under different parameters. For a more simplified analysis, the Euler–Bernoulli beam theory is adopted in view of the slenderness of the bridge girder. Furthermore, train–track interaction and wheel-rail contact models are not included. The computer program, SAP2000 has been utilized to carry out Finite Element Analysis (FEA). Composite warren trusses are simplified to an equivalent beam with Finite Element Method (FEM) by assuming coherent beam properties for the whole bridge. A MEM software code written in MATLAB is developed and employed to carry out the numerical analysis. The dynamic response of the bridge under different parameters has been further studied with the MEM formulation.

A. Computational Method and Assumptions

A moving train with derived parameters is primarily modeled to travel at a constant speed of 100km/h. Track properties have been incorporated into the bridge without dampers and springs on the Moving Load. This is justifiable since the study's main purpose is to evaluate the dynamic response of the bridge truss under different situations.

In this study, the composite superstructure of the Warren Type Steel – Truss Girder is transformed into an equivalent beam with coherent properties. As there are two levels of service lines, namely, the motor vehicles and the railway viaduct, there may be challenges to incorporating the moving cars and trains simultaneously into the numerical solution. Therefore, only the moving train traveling on the railway viaduct is considered for analysis, as the speed and weight of the moving train govern the majority of the vehicle live load of the Multipurpose Padma Bridge. The train is idealized into four concentrated moving loads, simulating the wheel loads of the locomotive. The parameters for the train and structural conditions are insufficient to induce resonance effect to the bridge, hence having a nominal vibration effect for analysis. Nonetheless, non – operational parameters have been employed to investigate the dynamic response of the Multipurpose Padma Bridge.

B. Truss as an Equivalent Beam

The truss is modeled as an equivalent beam with parameters derived from the existing truss geometry and subjecting the beam to moving loads. Figure 1 shows a truncated section of the Padma Bridge that has been analyzed to fit with the Moving Element Method. Two scenarios will be investigated; the case of numerical validation, where the adopted method is verified, and parametric studies carried out with actual loading conditions. In the parametric analysis, results with different parameters will be discussed, converging into the critical contributing factor for the dynamic response of the bridge caused by the moving train. Excitation due to rail corrugation, wheel-rail contact model, and track irregularity factor are ignored in this study since it may create outliers for the research and increase complexity for the formulation. Track interactions and wheel-rail contact model are adopted from the previous research conducted by C.H. Lee et al (Lee *et al.*, 2006) and Sun et al. (Sun *et al., 2014*).

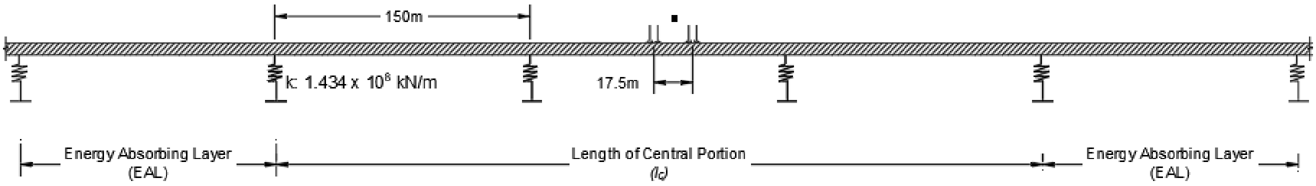

Figure 1: Equivalent beam model

C. *Moving Element Method*

The moving Element Method has been widely adopted and applied to analyze highway bridges, and railroad structures with high-speed moving loads (Lin and Trethewey, 1989). The MEM is employed in this case study due to the following reasons:

i. Force and displacement vectors at every contact point can be avoided.

ii. It allows finite elements with unequal lengths to be formulated. This could be useful when the distances between the wheels have different dimensions.

iii. Infinite boundary conditions can be assumed as the boundary constantly moving at every step – simulate realistic train conditions where boundary conditions are ignored.

The MEM method considers the mass-spring model with two displacement degrees of freedom (DOF) – u_1 and u_2, where the DOF of lumped ballast mass is ignored. In the formulation, each nodal point has two degrees of freedom (DOFs), and nodal points are equally spaced on the track model. Spacing between the nodal points depends on the element size and is based on the parameters of the moving train load. Nonetheless, a smaller element size requires more time steps which relate to a more accurate analysis. This study adopts a constant time step of 80 between two discrete supports. According to the Euler – Bernoulli Beam Theory (Erochko, 2020), displacement along (x - the axis) is ignored. Therefore, u_1 refers to the translational deformation along the z-axis, and u_2 refers to the deformation along the y – axis. In MEM, the x coordinate of the train model is fixed in the longitudinal direction of the beam with an arbitrary origin. Therefore, the default input for the start of the analysis will be at x = 0 and t = 0 (Koh *et al.*, 2003). While the beam is moving towards the left, the point mass P will move from Node 1 (N1) to Node 80 (N80).

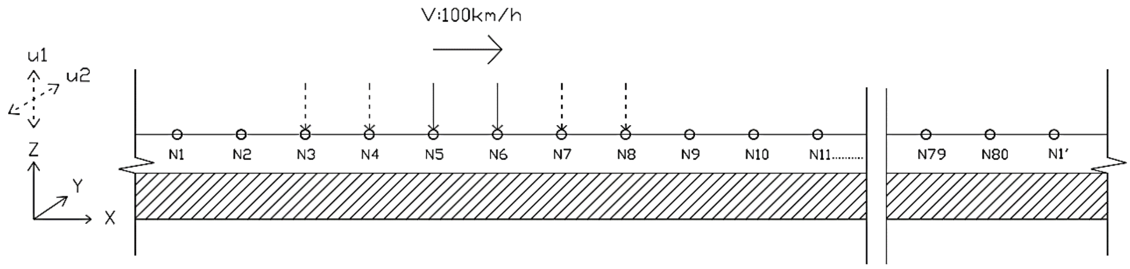

Figure 2: Moving Element Model Idealization

In this MEM formulation, parameters must be ascertained for train, tracking, supporting, and moving element parameters for the MEM domain. For the moving element parameters, these are the specifications that need to be inserted; domain and element size ($_{domain}$ and l), the duration for each time step (t), number of time steps (N_{ped}) to travel from n1 to n1' and distance traveled (l_{travel}).

Number of time steps to travel between two same points, N_{ped}, is assumed. A sufficiently large value should be adopted to ensure more steps between two repetitive points. This confirms that most nodes' response is captured with accurate results. However, it should not be exceedingly large as the movement of the model is still controlled by the element size. Uniform element size, l, is assumed to be 2.5m as it corresponds with the spacing between two wheels for the selected train. The ratio for the length of l_{domain} must be kept constant throughout the whole study to ensure consistent dynamic responses of the moving load.

With the spacing between two piers (l_s), and the speed of the train (V), the duration of each time step (t) can be derived with Equation (1)

$$t = \frac{l_s}{N_{ped} \times V} \tag{1}$$

Note that l_s is different from l_{travel}, where l_s is the spacing between two piers and l_{travel} is the total distance set for P to travel (includes a series of l_s). The governing Equation for the vertical displacement of the rail beam can be idealized as shown in Equation (2).

$$EI_{zz}\left(\frac{\partial^4 z}{\partial x^4}\right) + \sum m\left(\frac{\partial^2 z}{\partial t^2}\right) + k(z) = P(t)\delta(x - Vt) \quad (2)$$

Here P is the magnitude of the moving load on the track, m is the mass of the self–weight of the beam, k represents the stiffness of the piers, and δ represents the Dirac Delta function of the train. Dirac Delta function is a function that denotes a point mass where the difference in integral is mapped to zero(Eftekhari). Note that z denotes the rail's displacement while u indicates the displacement of the point mass, which is the vehicle model (Koh *et al.*, 2003).

A moving ordinate, r, can be translated from the global ordinate system by generalizing the initial node and the subsequent node with the speed and time taken for the moving load to travel. Therefore, the Equation can be written as

$$r = x_0 - x_1 - Vt \quad (3)$$

where x is a global ordinate system. Incorporating equations (2) and (3), the vertical displacement of the beam can be converted into the moving ordinate system in the following Equation (Koh *et al.*, 2003),

$$EI_{zz}\left(\frac{\partial^4 z}{\partial r^4}\right) + \sum m\left[V^2\left(\frac{\partial^2 z}{\partial r^2}\right) - 2V\left(\frac{\partial^2 z}{\partial r\,\partial t}\right) + \left(\frac{\partial^2 z}{\partial t^2}\right)\right] + k(z) = P(t)\delta(r + x_1) \quad (4)$$

where the Delta function (δ) is employed for tracking the locations of the vertical wheel loads with respect to the speed of train (V), bridge (EI_{zz}, M) and pier (k) properties. The function varies with P(t), which is the mass of the point load, and the speed of the moving particle, which can be referred to $(r + x_1)$.

Therefore, the slope can be calculated based on Equation (2)

$$\emptyset = \frac{y}{\epsilon}, \emptyset = \frac{M}{EI} \quad (5)$$

Based on all the abovementioned assumptions, the Bernoulli – Euler Beam equation can be derived and used to find the design parameters as

$$\emptyset \approx \frac{d^2\Delta}{dx^2} = \frac{d\theta}{dx}; \frac{d^2\Delta}{dx^2} = \frac{M}{EI} \quad (6)$$

D. Train Parameters

Train parameters are given and based on AASHTO LFRD specifications as shown in Figure 3 (Kim 2017, Dai *et al.*, 2018a). Since the primary consideration is to examine the dynamic response on the bridge under train loading, the stiffness and damping coefficient is assumed as 1. The train parameters and their values are presented in Table 1.

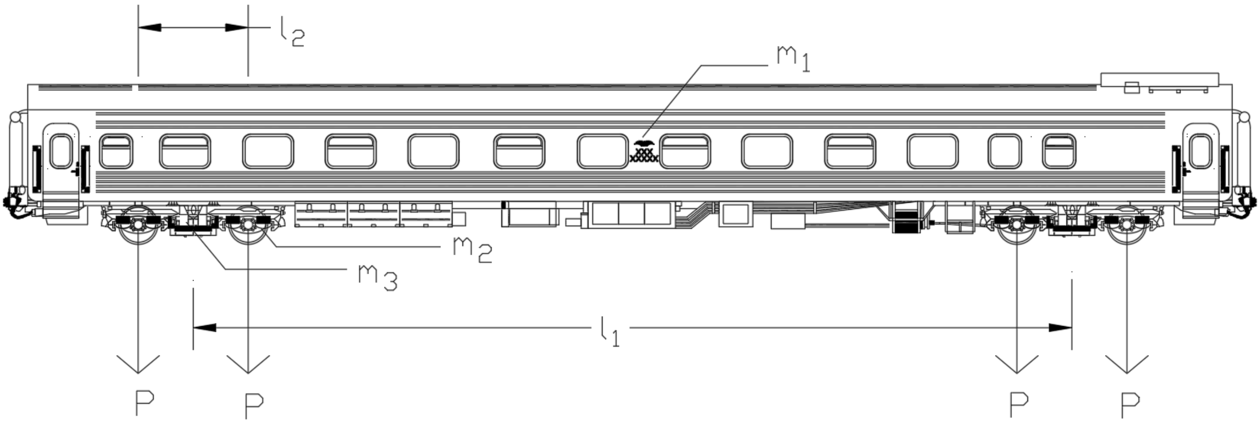

Figure 3: Train model of one locomotive

Table 1
Train Parameters (Dai *et al.*, 2018a)

Description	Notation	Value	Unit
Mass of Carriage	m_1	26000	kg
Mass of Wheelset	m_2	750	kg
Mass of Bogie	m_3	2309	kg
Distance between Bogie to Bogie	L_1	17.5	m
Distance from Wheelset to Wheelset	L_2	2.5	m
Wheel Load	P	78.74	kN
Primary Suspension Stiffness Coefficient*	k_p	1.87	MN/m
Primary Suspension Damping Coefficient*	c_p	500	kNs/m
Secondary Suspension Stiffness Coefficient*	k_s	1.78	MN/m
Secondary Suspension Damping Coefficient*	c_s	196	kNs/m

E. Conversion of Truss to Equivalent Beam for MEM

In order to accommodate the moving element method for the series of warren trusses of PMB, equivalent beam properties are determined from the actual truss properties. The entire bridge contains 6 identical modules, and each module includes six equally sized spans of 150m each. One similar module is modeled in SAP200 to understand their dynamic modal shapes. Subsequently, a single 150m span is also modeled to determine the stiffnesses in all three directions. Structural properties from the chords of the composite truss system have been extracted from the actual drawings to derive the equivalent beam properties. Figure 4a depicts an illustration of the composite truss superstructure, annotating the location of the chords. The element is pinned supported at the sides and roller supported at the other ends. Similarly, the finite element model for one module comprising six spans has been developed as shown in Figure 4(b). Modal analysis has been conducted for the module to find the mode shapes that match the loading direction. Twelve different modes are analyzed to determine the critical mode for moving the train. Among them, mode eight is found vital to the train loading as shown in Figure 4(c). In this mode, the vertical displacement Uz is more critical as most loads mainly act in the z – direction. Mode 8 shows the largest deflection about the z-axis out of the 12 different modal analyses.

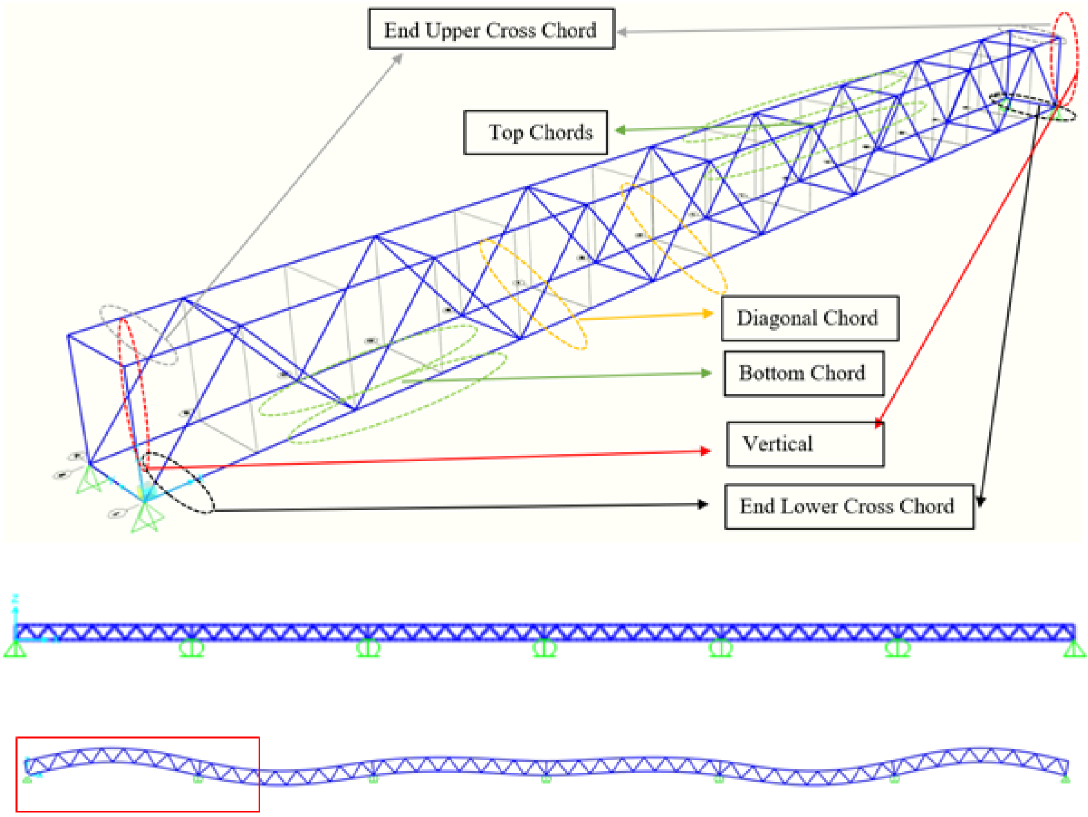

Figure 4: (a) Components of each module of the bridge, (b) One Repetitive Module of the whole bridge, and (c) Typical deflected shape of the module

Based on this, mode 8 is further used to elaborate the mass participation of the structure. After modeling in SAP2000, it was deduced that the total weight of a truncated element is 27776.5kN, which is 185.2kN/m for the whole bridge. Using the developed model axial stiffness has been determined and hence equivalent solid cross-sectional area has been evaluated. Similarly, stiffness in longitudinal and transverse directions is also determined through the required forces to yield unit deformation in the corresponding directions. The important stiffness parameter in the Z direction (along the loading direction) has been determined using the self-weight of the structure. The area and stiffness parameters of the equivalent beams are presented in the table.

Table 2
Equivalent beam parameters

Description	Notation	Value	Unit
Length of Bridge	L	6,150	m
Length of Truncated Beam	l_s	150	m
Mass	M	185.2	kN/m
Cross-Sectional Area	A	1.22	m^2
Second Moment of Area About Minor (Y-Y) Axis	I_{yy}	750	m^4
Second Moment of Area about Major (Z-Z) Axis	I_{zz}	37	m^4

The track has been incorporated into the equivalent beam properties with the rail properties in place. The damping of the rail is considered as 10% of the critical damping associated with the circular eigen frequencies of the equivalent beam with respect to the rigid-body mode. The formulation of MEM code assumes the wavelength of track irregularity is assumed as 1m; the amplitude of track irregularity is 1mm for the whole study. However, the train stiffness and spring are excluded in this study which may lead to a slight difference in the wheel-rail contact model.

In this analysis, the loading conditions of the moving train and the equivalent parameters from Table 2 are used in the simulation. For numerical validation, only two wheels are idealized, which is a representation of half of the locomotive. After a series of validation, these parameters are determined for the formulation. N_{ped}, the number of steps to travel the length of l_s, is assumed to be 80. Therefore, the duration of each time step (0.0675) can be determined from the predefined values for V and l_s. To prevent P from traveling incomplete domain, the size must be multiple of l_s. For accurate response prediction, at least five spans should be modeled; where each EAL and $l_{c\ \text{length}}$ should be at least 1:3. Domain size (l_{domain}) must be sufficiently large to ensure convergence of results. Therefore, these parameters are assumed for the domain; EAL as 450m, and L_c as 1500m. With two EALs on each end of l_c, the domain size will be 2400m. Two domains will be modeled to ensure stability for a transient response for a more accurate result. Therefore, the total distance for P to travel is 4800m. Each element size, l, will be modeled as 2.5m, as the distance from wheel to wheel is 2.5m; $l = l_1$. Element size refers to the length of travel for each time step. In conclusion, in each time step (0.0675), P will travel 2.5m.

3. RESULTS & DISCUSSIONS

Using the Matlab program for the moving element method, results are extracted to observe the dynamic response of the Padma Multipurpose Bridge. The extracted results determine the vertical dynamic responses with different speeds as pier spacings and their mutual dependencies. Before presenting the dynamic response, MEM has been validated with the Finite element solution for the static response of the bridge. In the verification, maximum static deflections at the mid-span are also checked through the FEA of SAP2000.

A. Midspan Deflection using FEA

In the MEM formulation, it encompasses a series of FEM equations. Finite Element Analysis is adopted with the same model and loading conditions and is carried out using SAP2000. Five spans were modeled and P is loaded on the third span from the left, spaced 2.5m apart. Although it was indicated that *EAL* and l_s are 450Nm and 1500m respectively, a much smaller domain is used for comparison analysis. Therefore, a domain size of 750m is simulated; where *EAL* is 150m and l_c is 450m with an exact proportion of 1:3. The displacement curve over five spans is displayed in Figure 5, where the crests of the curve are observed at 240m, which is the second span, and 505m, which is the fourth span of the whole domain. This indicates that there is a slight hogging effect of 0.2mm at these two points. Comparatively, a significant increment of vertical displacement is observed at 375m, which matches the position of P.

Figure 5: Deflection of the whole domain and Max Displacement at Mid-span using SAP2000

As the steady-state response of the rail beam is of interest, static loading is simulated in this analysis. Using the equivalent parameters, five spans are modeled where only the displacement under the loading at the middle span is considered. The observed maximum vertical displacement at the mid-span is 0.789mm.

The analytical governing Equation for vertical displacement can be written as

$$\delta_{zz} = \frac{Pb(3{l_s}^2 - 4a^2)}{48EI_{zz}} \tag{7}$$

Since, P, two identical loads are placed symmetrically, the Equation for total displacement can be idealized as

$$\delta_{zz} = 2\left(\frac{Pb(3{l_s}^2 - 4a^2)}{48EI_{zz}}\right) \tag{8}$$

The Equation evaluating the deflection for self–weight as the uniformly distributed on the equivalent beam is

$$\delta_{zz} = \frac{5w{l_s}^4}{384EI_{zz}} \tag{9}$$

where E is the young modulus for steel, 200 GPa. As observed in Figure 5, the maximum vertical displacement for the moving load is 0.786mm at mid-span. This can be also directly calculated using Equation (7). Using Equation (8), the static displacement due to the self–weight of the equivalent beam can be calculated. The maximum vertical displacement due to dead load is 165mm. According to Eurocode 7, the deflection limit of the given span is L/360 – the most conservative assumption for deflection limits.

$$\frac{L}{360} \rightarrow 420mm > 165mm \tag{10}$$

Therefore, a maximum displacement of 165.78mm fulfills the serviceability of the given structure. However, the serviceability design of the Padma bridge may be over-designed as most of the parameters utilized are conservative.

B. Comparison between MEM and FEA

Comparatively, the MEM formulation gave a slightly larger displacement of 0.798mm while the FEM analysis led to a value of 0.784mm. As computed, the difference in results is only 1.2%. Moreover, the MEM formulation may produce more reliable results as the element model size and domain may be larger compared to the one defined in FEM.

C. Dynamic Response of the PMB using MEM

Since the study's main purpose is to investigate the dynamic response of the bridge, only the finite element method may not be efficient in producing the required results. It may be cumbersome to carry out parametric studies using FEM as the whole model needs to be remodeled in a larger domain. For example, the change of l_s requires remodeling of the whole domain in SAP2000 as the spacing must be edited individually. Non-uniform discretization of track elements can be adopted in MEM.

Therefore, the adoption of the Moving Element Method results in a more efficient and accurate way of analysis.

As a basic outcome of the MEM, a repeated sinusoidal curve is observed throughout the response of the composite truss, where the peak of the curve relates to the position of P (directly on the supports); the crest of the curve is related to the position when P is at the mid-span of the equivalent beam. Realistically, the vertical displacement of the bridge girder above the piers where the axial rigidity is the largest as such this direction of the bridge should experience the least displacement, and the mid-span has the largest displacement. Therefore, this results in a sinusoidal curve with smooth connecting points. The profile has been compared to verify the accuracy of the dynamic response of a moving train as conducted by (Dai *et al.*, 2018b, Dai *et al.*, 2018a). The dynamic response patterns are quite close and similar to those studies.

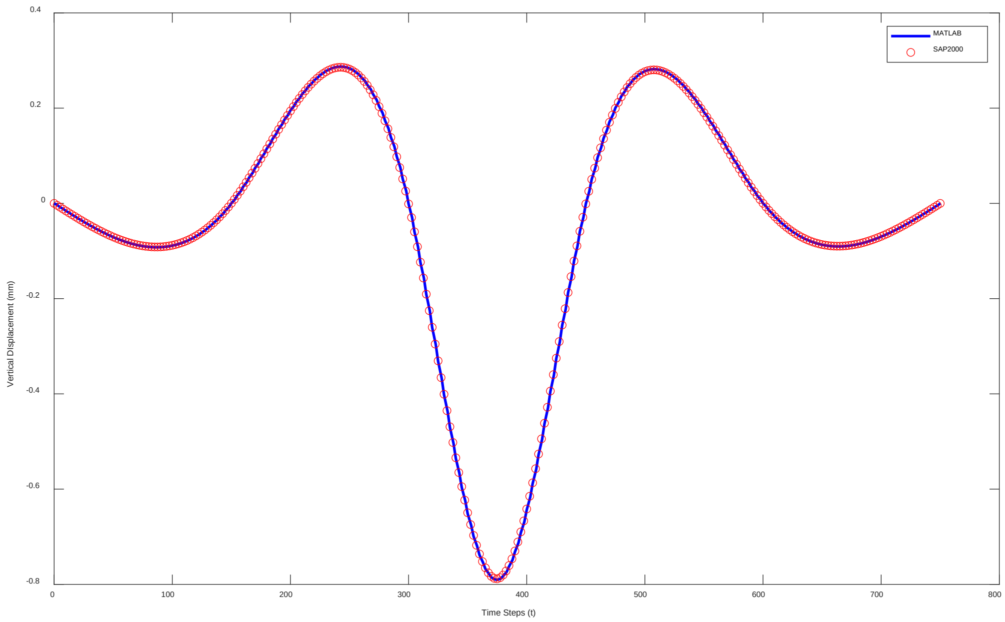

Figure 6: Static deflection curve using MEM and FEM

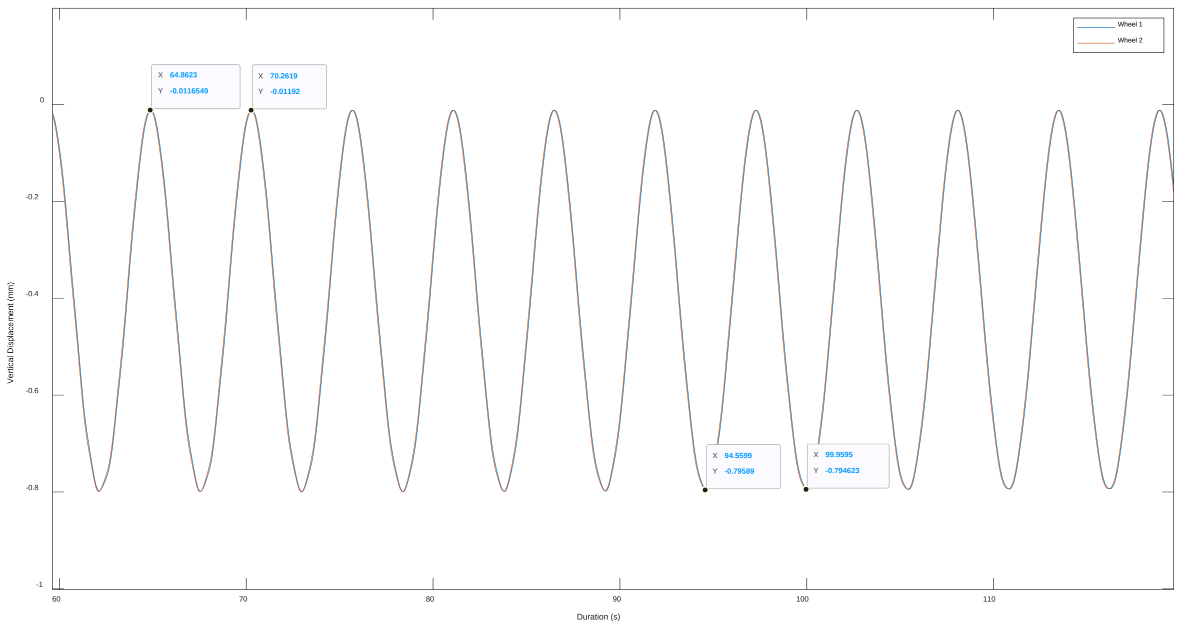

Figure 7: Dynamic response of the PMB (Time Steps)

Figure 7 demonstrates the dynamic response of the bridge with time steps. As the size of the time step is too insignificant compared to the domain size, it leads to the cramped illustration of the graph. In this figure, we observed that the transient response is in the first half of the analysis where the values fluctuate from 0.81mm to 0.793mm. It is important to model a larger domain to notice an accurate displacement due to the vibration of the bridge. With a larger domain modeled, the values began to converge to 0.795mm towards the end of the analysis where $l_{travel} = 2l_{domain}$. With a speed of 100km/h, the rail used 172.8 seconds to travel 4800m. Since the point of interest of the study is the transient response due to moving load, subsequent analysis will utilize the results between 60 to 120 seconds, the period where the transient response of the sinusoidal curve has stabilized.

In order to compare the static and dynamic effects, static and dynamic loads have been plotted to do the comparison as shown in Figure 8. The maximum dynamic amplification factor (DAF) is ≈ 1 (1.05), where DAF denotes the ratio of maximum dynamic to static response on the Padma bridge(Dai *et al.*, 2018a). Therefore, it can be concluded that the vibration effect caused by the moving load is not that dominant for the design rail speed of the Multipurpose Padma Bridge. In this plot, it can be observed that the difference between static and dynamic loading is about 0.1mm, where the DAF ≈ 1 (1.033). Despite increasing the effective length between pier supports, the static and dynamic response of the bridge is similar. An exaggerated effective length of 400m between supports is investigated and resulted in a DAF of 1. Therefore, the effective length of pier spacing is independent of the dynamic response at an effective length at l_s = *150m.*

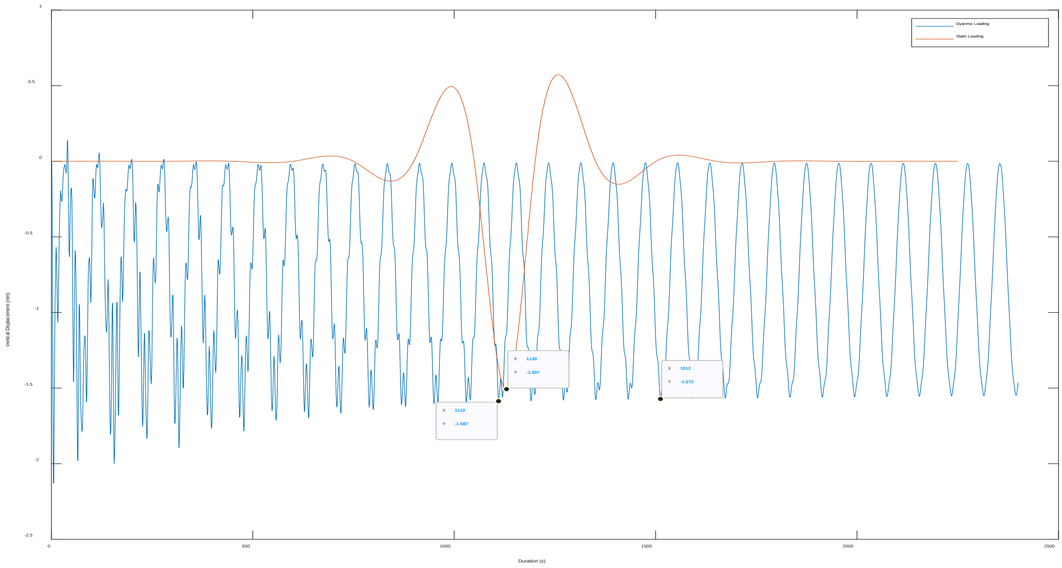

Figure 8: Comparison between dynamic and static loading

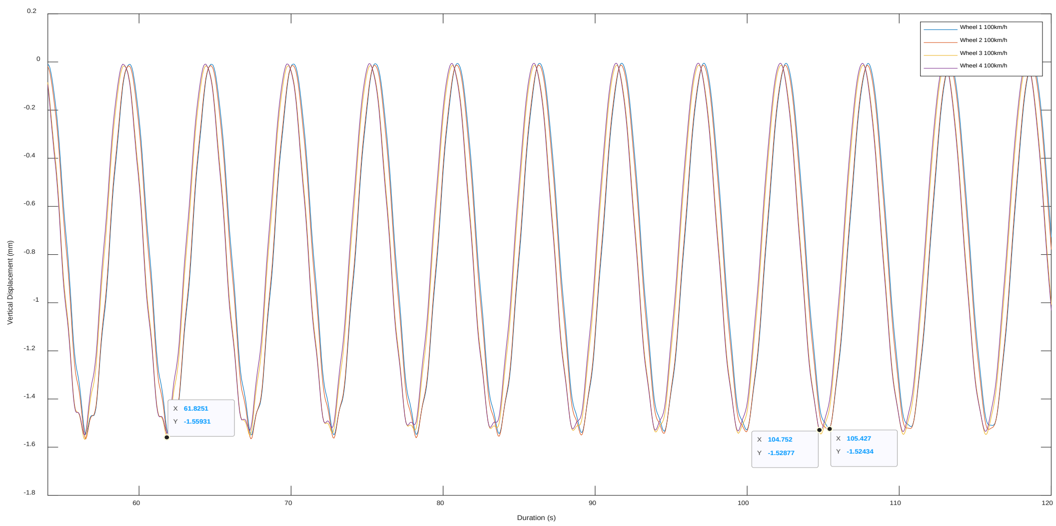

Figure 9: Dynamic displacement response of different wheels

Figure 9 depicts the dynamic response of the Padma Bridge due to loading conditions where the four moving loads are considered in one locomotive of the whole train model. It was assumed that the magnitude of the moving load is identical. It was clear that the dynamic response is quite stable. It is also observed that the vertical dynamic displacements are very close for all-wheel loads and their dynamic response overlaps each other at different time steps.

4. PARAMETRIC STUDIES

Parametric studies are conducted to investigate the speed and spacing dependencies of the dynamic response of the PMB. According to Dai et al(Dai *et al.*, 2018b), with the increase in speed, dynamic loading will result in a larger amplitude in the vertical displacement. The speed of the moving train also affects the frequency of the sinusoidal curve of the dynamic response. As the second moment of area for the equivalent beam contributes to vertical displacement, the effective length between discrete supports will be investigated.

A. Speed Dependencies

As the train is taken as a moving load, the effect of different speeds on the dynamic response of the bridge has been investigated. At Padma bridge, the train is expected to travel at a top speed of 80km/h. To be more conservative, the train is assumed to travel at a constant speed of 100km/h. Six different speeds; 100km/h, 150km/h, 200km/h, 250km/h and 300km/h and 350km/h are considered in this parametric study. Speed is investigated up to 350km/h, since the fastest high-speed rail (excluding maglev trains) in Asia has a record high of 317km/h- during normal operations.

In Figure 10, the dynamic response of moving load with different speeds has been plotted for comparison. Different regions of 40 to 100s are employed as the moving load with a faster speed does not have sufficient travel length to see a good comparison. A different domain size ratio may affect the displacement value. The amplitude of vertical displacement is consistent for three different speeds; the difference comes only as a fraction of a millimeter. Considering a massive structure like the Padma bridge, the difference can be neglected where $\left(\frac{\partial z}{\partial t}\right)_{V=100} = \left(\frac{\partial z}{\partial t}\right)_{V=300}$.

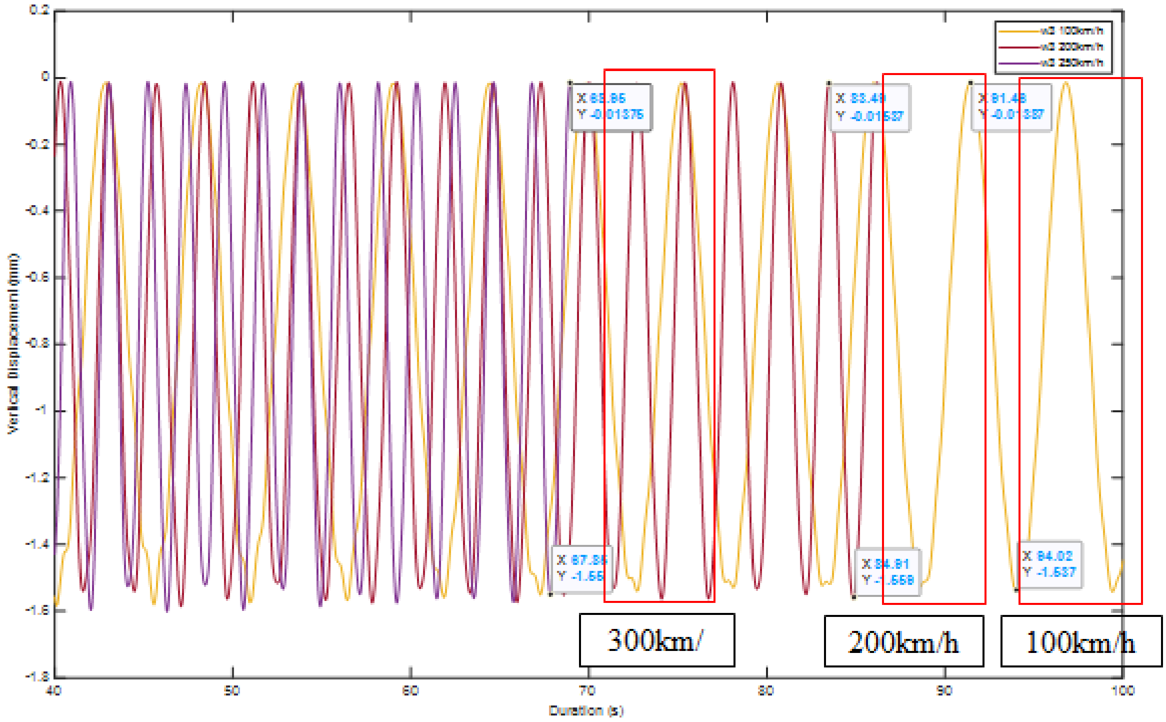

Figure 10: Dynamic response of moving load with varying speed (l_s = 150m)

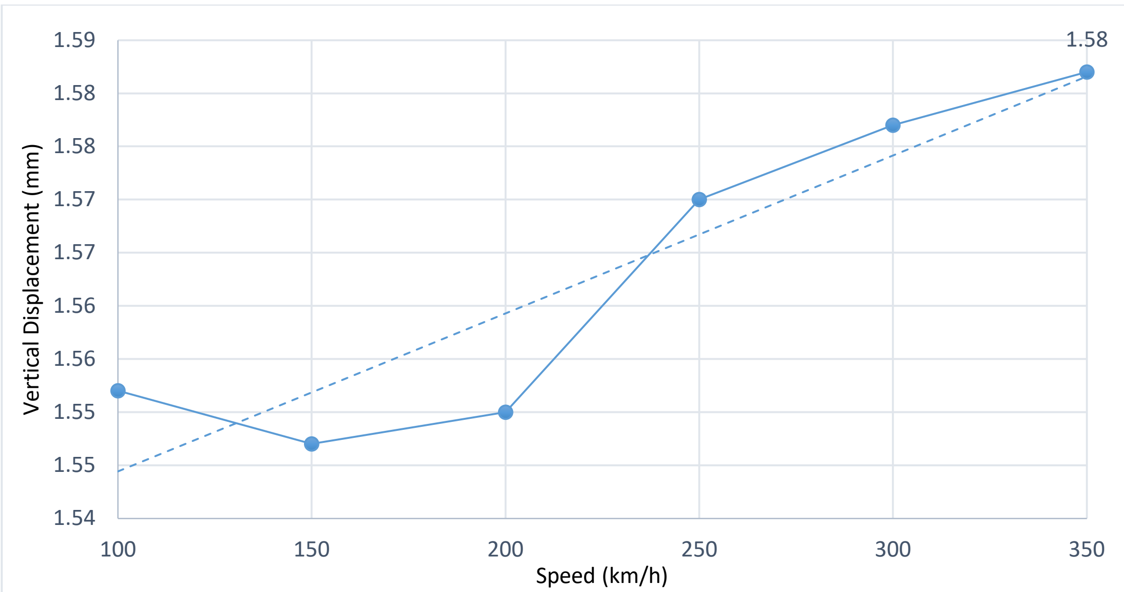

Figure 11: Relationship between speed and vertical displacement

The relationship between the speed of the moving load and the bridge's vertical displacement can be observed in Figure 11. In order to minimize observation error, an average of three different data points from the graph of every analysis has been used for comparison. An inconsistent plot is observed with a range of vertical displacement from 1.547mm to 1.583mm. The difference is about 0.04mm (2%), which can be interpreted as an observation error. According to Dai et al(Dai *et al.*, 2018b), moving loads can result in a higher amplitude of dynamic response where the amplitude of vertical displacement is amplified compared to static loading conditions. Hence, the speed of the moving load is insufficient to result in an exaggeration of the bridge's vertical displacement. Therefore, there are no dynamic amplifications of the displacement response of the bridge due to the increased speed of up to 350 km/hr.

Comparatively, the quasi-static analysis has also been carried out with the same loading conditions (P_o) to observe the difference between the dynamic and static load. Quasi – static analysis refers to a numerical solution that is based on constant speed and zero damping, simulating the same concentrated loading. The solution resulted in a vertical displacement of 1.513mm, which represents a slightly dynamic response of 0.07mm difference compared to the vertical displacement of 1.58mm when the moving load is at a speed of 350km/h. The response is nominal because the resonance of the movement is not excited enough due to the low speed of the moving load, leading to a small dynamic response. At the critical speed, the dynamic response of the bridge will be much amplified due to the source of excitation from resonant speeds(Dai *et al.*, 2018b). Nonetheless, the structural capacity of the equivalent beam is competent to resonate with the frequency of the moving load, where the dynamic response of the bridge is independent of the speed of the train.

The investigation has been extended to evaluate the critical speed of a moving load to stimulate the dynamic response where much amplified vertical displacements were observed. Pier spacings are kept constant at 150m. In Figure 12, the amplitude of vertical displacement is examined at different intervals of speed which are much faster. Although the speed employed for the load is not practical, the basis of adoption is to examine the resonant speed to excite the Padma bridge. The analysis depicts a clear increment in vertical displacement from 1200km/h, where the amplitude starts to increase from 3.43mm to the peak of 27.41mm at 1400km/h. The vertical displacement increases almost 18 times, while the initial vertical displacement is 1.55mm. The range of critical speed can be noticed between the range of 1400km/h to 1450km/h where the amplitude of vertical displacement declined from 27.41mm to 0.063mm, a much smaller displacement value compared to the initial speed of the moving load. This also translates to a DAF of 18, where the amplitude of the vertical displacement is amplified. Since the speed employed is not practical to be operational at any stage, still we can conclude that the dynamic response of the bridge is independent of the moving load's speed.

B. Pier Spacing Dependencies

The dynamic response of a bridge with a different effective length between supports is also investigated using MEM. The moving load is imposed to travel at 100km/h where the pier spacing will be analyzed from 100m to 200m, at an interval of 10m. A range of 100m to 200m is utilized to keep the analysis within the structural limits of the Padma Bridge.

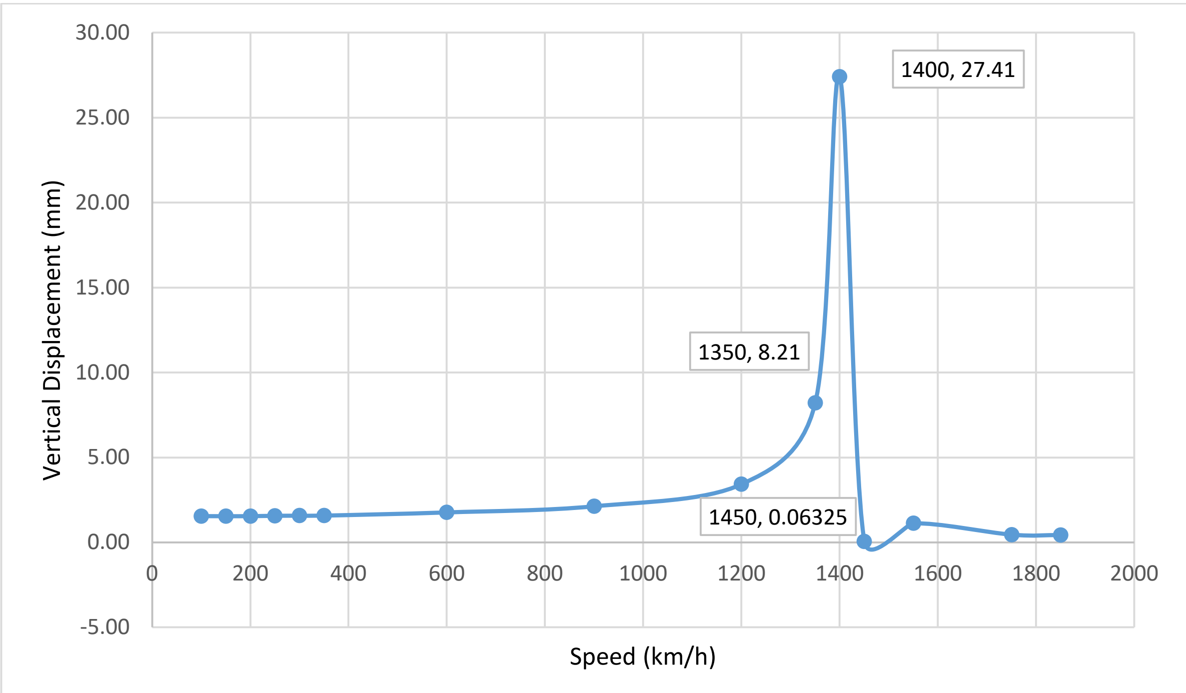

Figure 12: Relationship between speed (non-operational) and vertical displacement

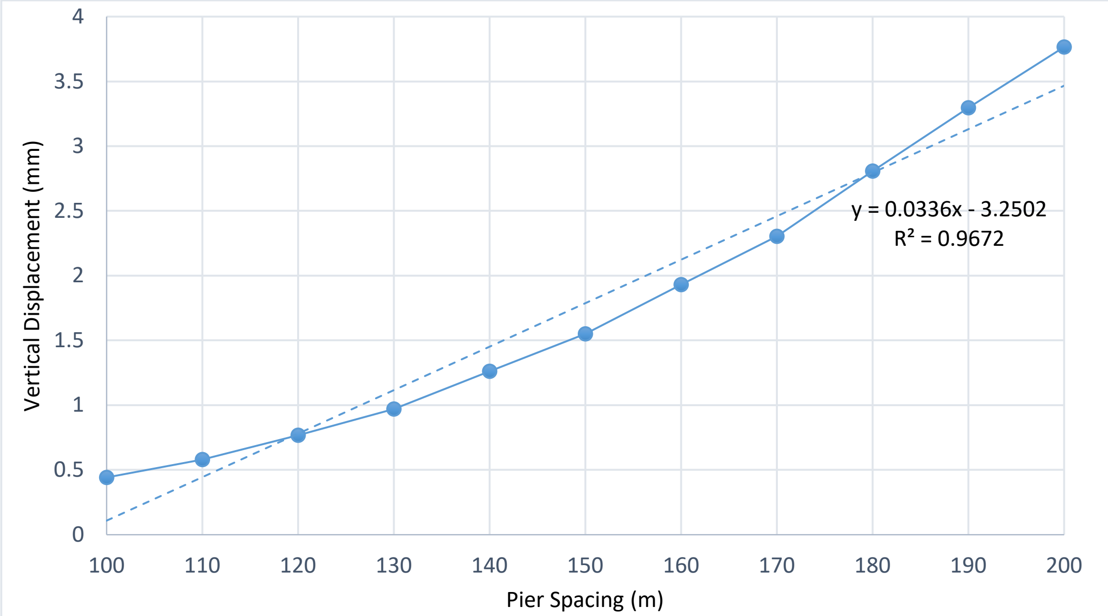

Figure 13: Relationship between pier spacings and vertical displacement

Since it was discussed that the speed of the moving load is independent of the vibration effect, it was distinctively clear that the amplitude of vertical displacement increases linearly when the spacing of the pier supports the increase. However, the reason behind the increase is mainly due to the structural stiffness of the equivalent beam in the longitudinal direction. A longer effective length between pier supports allows for a higher vertical displacement, where the effective length between supports is denoted as l_s. Furthermore, there is four imposed loading on the bridge, which will contribute to a larger difference in deflection for the calculation. However, we are interested in the difference between dynamic and static displacement for the longest effective length of 200m as it shows the highest displacement value for dynamic loading. Despite having the same ratio for *EAL* and l_c *of 1:3 and* $l_{travel} = 2l_{domain}$, the transient response of 200m may need a longer time to stabilize. It is observed from figure 14 that the vertical displacement of the bridge increases significantly when the effective length of the pier spacing increase. Accompanied by dynamic loading, the increment for the vertical displacement can be distinctively observed. Therefore, it can be concluded that the amplitude for vertical displacement increase with the pier spacing infinitely, where the type of loading (dynamic or static) remains independent to the Padma Bridge's vertical displacement.

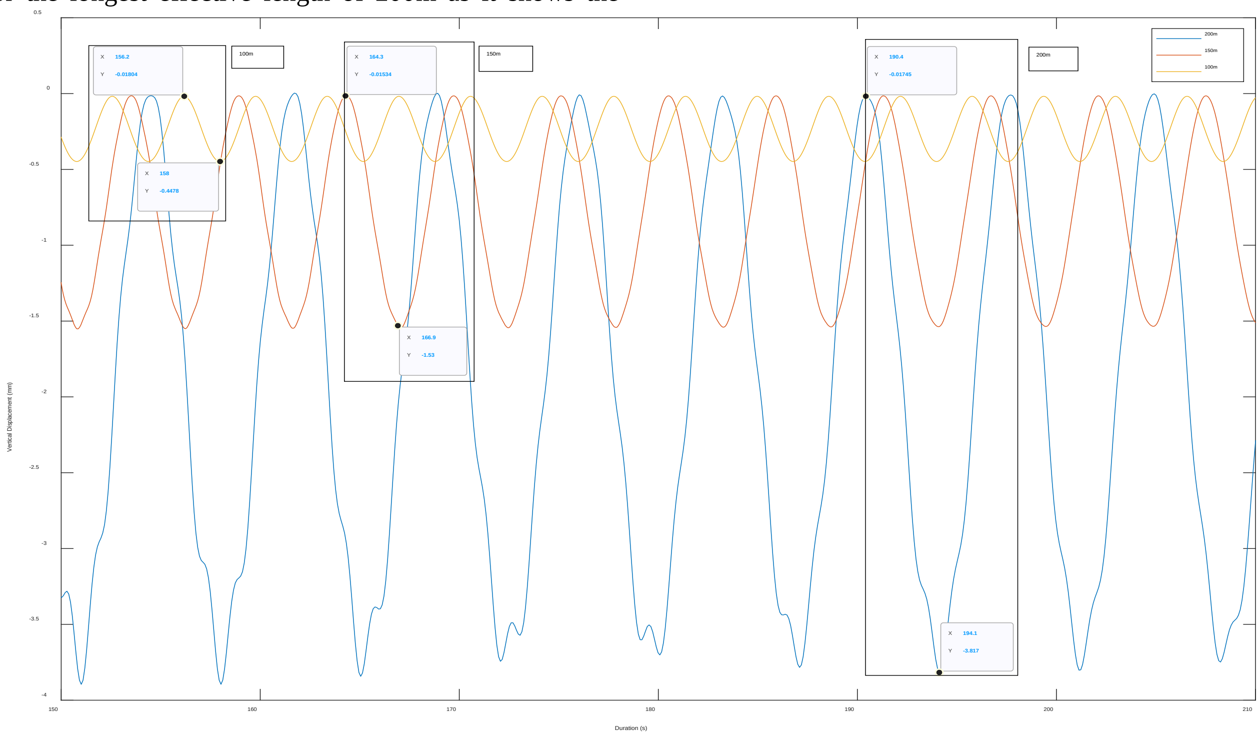

Figure 14: Comparison between dynamic response with l_s = 100m, 150m, 200m

C. Correlation Between Pier Spacings and the Speed of Train

The correlation between different pier spacings and the speed of moving load has also been investigated. As observed earlier, the speed of the moving load is insufficient to induce resonance to the beam. Therefore, the speed of the moving load is independent of the dynamic response of the bridge. The independence of pier spacing is observed previously, where the effective length between piers increases with the amplitude of vertical displacement. In Figure 15, the speed of the moving load is kept constant at 100km/h, 200km/h, and 300km/h, where the vertical displacement is taken for different pier spacings.

It is observed from the relation that the moving load with different speeds has similar vertical displacement for up to 200m. The difference between the maximum and minimum vertical displacement can be neglected where it is less than 0.5mm. However, it is noticeable that the amplitude starts to diverge from 170m, where a higher displacement is observed for the moving load at 300km/h. Due to technical difficulties and excess exhaustion of software, the relationship is only plotted up to 200m where only a minor differentiation can be observed. However, it is believed that the model will continue to diverge and displacement for the moving load with a faster speed will subsequently govern. Since the speed of the train is kept constant, the model will not reach a resonant speed and the vertical displacement will increase infinitely if the pier spacings continue to increase without changing the flexural stiffness.

In Figure 16, the pier spacings are kept constant at 100m, 150, and 200m with varying speeds. It was discussed that the increment of pier spacings increases the vertical displacements infinitely until the structural capacity of the beam is challenged. Hence, results for three different spacings have varying displacement values. As the Equation of the line is computed for each series, it is observed that the gradient of the line increases when the pier spacings increase. A steeper gradient for the Equation translates to a higher increment of displacement values when the speed of the moving load increases. Thus, the resonant speed of the moving load should be faster for shorter pier spacings, as the increment of vertical displacement with a slower moving load is smaller. As the increment of vertical displacement is larger, it will take a shorter time to reach the resonant speed. Therefore, the dynamic response for an effective length of 200m is investigated with different speeds.

In Figure 17, the difference between the resonant speed of two different pier spacings can be clearly observed. The source of excitation from the moving load will induce sufficient resonance to the bridge for the displacement to decrease significantly after reaching the resonant speed. The analysis depicts a clear increment in vertical displacement from 1000km/h, where the amplitude starts to increase from 7mm to the peak of 23.5mm at 1200km/h. The vertical displacement increases almost six times, while the initial vertical displacement is 3.78mm. The range of critical speed can be noticed between the range of 1200km/h to 1300km/h where the amplitude of vertical displacement declined from 23.5mm to 0.44mm, a much smaller displacement value compared to the initial speed of the moving load. This also translates to a DAF of 6.2, where the vertical displacement amplitude is amplified.

The resonant speed for pier spacing of 200m is 1200km/h, which is comparatively slower than the resonant speed of 1400km/h for spacing of 150m. As discussed, longer pier spacing has a steeper gradient of increment for vertical displacement. Therefore, the maximum vertical displacement for a longer spacing will be employed at a slower speed. The study also evaluates that the resonant speed decreases when the effective length between discrete supports increases.

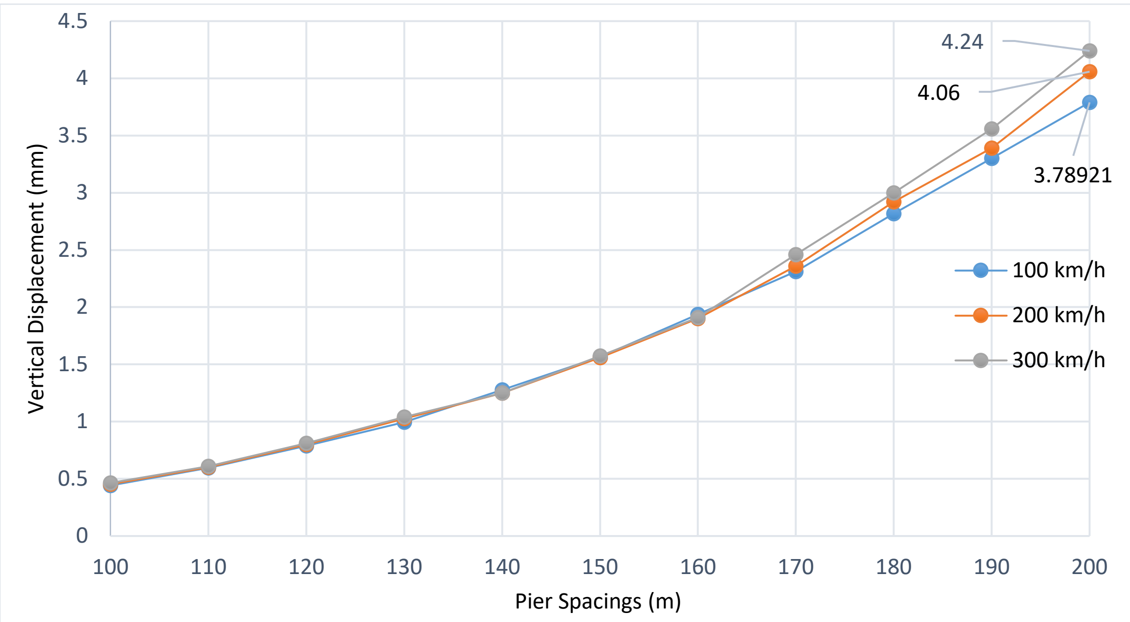

Figure 15: Relationship between pier spacings and vertical displacement for different speed

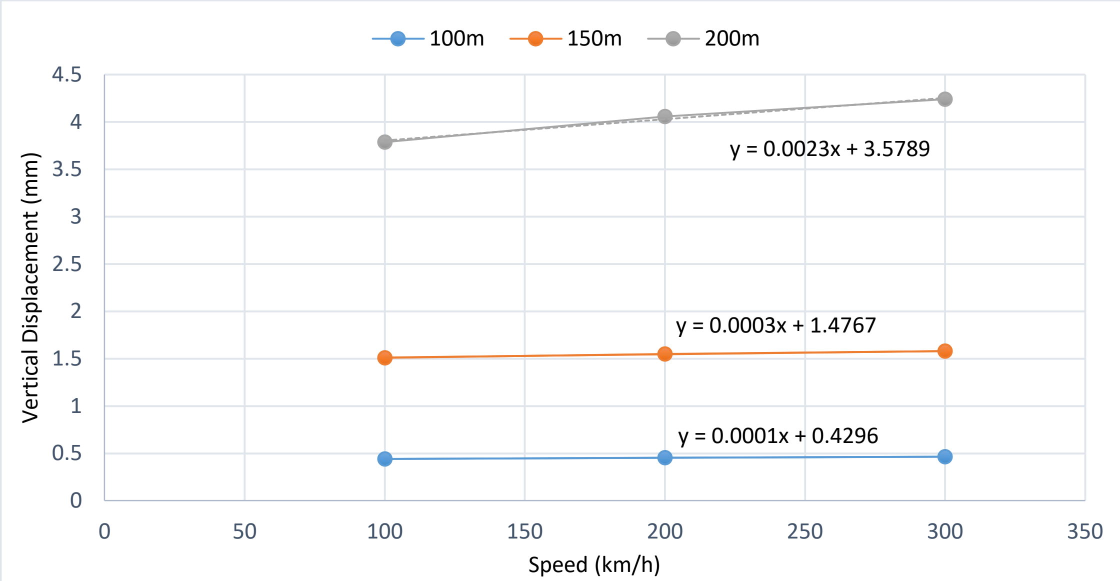

Figure 16: Relationship between speed of moving load and vertical displacement with different pier spacings

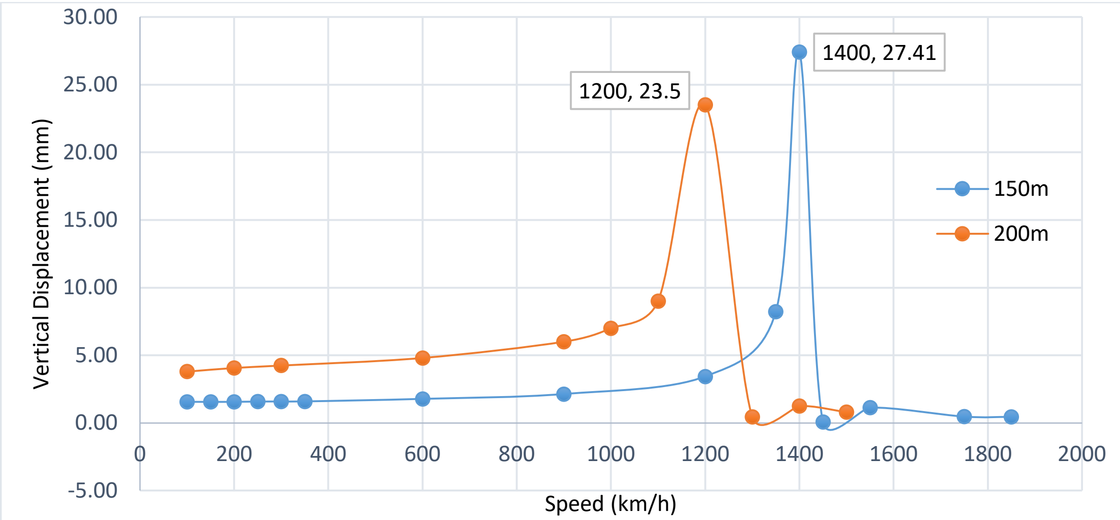

Figure 17: Comparison between the dynamic response of 150m and 200m

5. CONCLUSIONS

In this study, the dynamic response of the Padma Multipurpose Bridge due to the loadings of a moving train is investigated using the moving element method. The accuracy of the computational method has been verified and compared with the Finite Element Method. The complexity of the structural bridge has been simplified into an equivalent beam, where the deformation at vertical and lateral directions are used to derive the properties of the equivalent beam. The basis of simplification is mainly for the research of the vibration responses of the bridge under four concentrated moving loads, which is the representation of one moving locomotive. The effects of various factors such as train speed and pier spacings were investigated and the conclusions can be drawn as follows:

The dynamic amplification factor (DAF) of the bridge for the design train speed of 100km/hr is found to be 1.05. The speed of the moving train load has a very nominal effect on the DAF where the induction of resonance from the load is insufficient to trigger excitation for a substantial difference for dynamic response to be observed. The critical speed of the Moving Load that causes resonance in PMB is found to be approximately 1400km/h. The dynamic amplification factor is found to be 28 at this critical speed.

The effective length between piers is nearly independent of the DAF, where the vertical displacement for dynamic and static loading is nominal. However, the increase in the effective length of the piers contributes to a higher vertical displacement in the bridge. This is mainly due to the bridge's structural capacity or reduced stiffness (at higher spacings).

Although the critical speed for the moving load is not mobilized, the relationship between the pier spacings and the speed of the moving load is examined. The resonant speed for the bridge decrease when the pier spacings increase. For example, the the pier spacing is increased from 150m to 200m, the critical result that causes resonance reduces to a relatively lower speed of 1200km/hr. The parametric study also shows that larger pier spacings lead to an increase in the vertical displacement with a non-linear pattern. In conclusion, a longer effective span length yields higher vertical displacement as well as a reduction in the critical speed that causes resonance to the dynamic response of the bridge.

In this numerical investigation, the study is limited to only moving train load for accounting the dynamic response of the PMB though the double deck truss is subjected to both vehicles and trains. Only standard and specific types of trains are considered for the analysis. The response may change with train type, load intensity, and the spacings. Overall, the bridge is expected to experience negligible dynamic response for any practical design speed of future trains.

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Padma Bridge Rail Link Project with Special Emphasis on Padma Multipurpose Bridge, its Technological Uniqueness

Md Abul Kalam Azad

Deputy Chief Coordinator, Construction Supervision Consultant-Padma Bridge Rail Link Project (CSC-PBRLP), Dhaka, Bangladesh

emails: *kazad1968@gmail.com*

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ABSTRACT

The South and Southwestern part of the country is devoid of direct communication with the central part of Bangladesh due to the presence of the most important tributaries of Lower Ganges i.e. Padma River. To establish direct communication with those areas Government of Bangladesh Constructed Padma Multipurpose Bridge with the provision of road and rail traffic at the upper and lower deck of the bridge respectively. The Padma Bridge Rail Link Project (PBRLP) is the main passage connecting the East and the West of Bangladesh and is also a part of the Bangladesh-China-India-Myanmar corridor. This line is a single-track passenger-freight railway with a total length of 168.6 km. For the first time in Bangladesh, State of the Art technology ballast less tracks in Padma Bridge, its approach to viaducts and other viaducts are being adopted for providing a smooth operation for both freight and passenger traffic. Precast and prestressed long sleeper embedded in cast in-situ track slab ensures a maintenance-free track system for the railway. PBRLP, once completed will restore the missing link with the Trans-Asian railway and will provide a platform for connecting with the Dedicated Freight Corridor (DFC) of India in future. It will also contribute to the Gross Domestic Product (GDP) of the country by 1.0%.

1. INTRODUCTION

The Government of Bangladesh (GoB) has taken a project to construct a Multipurpose Bridge over the mighty river Padma. The objectives for constructing the said multipurpose bridge over river Padma is to connect Dhaka with South-West part of the country. The upper deck of the Padma Multipurpose Bridge (PMB) will provide four lanes for road traffic while its bottom deck will provide a single-track Broad Gauge (BG) line for rail traffic. Though the PMB has been designed based on the Dedicated Freight Corridor loading which is axle load 32.5 t but its Ballast less Track (BLT) structure been designed considering 25 t axle loading. Because of the lack of matured application of track structure considering 32.5 t axle loading, Bangladesh Railway (BR) has adopted the design of BLT with 25 t axle loading. However, based on the requirement of the BR and its connectivity with regional and sub-regional network, this track structure can be upgraded to 32.5 t axle load.

The Padma Bridge Rail Link Project (PBRLP) is a new rail route that will connect Dhaka with Jashore through the lower deck of PMB. It is a mixed passenger and freight rail routes and will pass through Dhaka, Naraynganj, Munshiganj, Shariatpur, Madaripur, Faridpur, Gopalganj, Narail and Jashore. With a view to connect Dhaka with South-west part of the country within shortest possible period, constructing of a rail link between Dhaka and Jashore earned prime importance. The new railway route will provide a substantially shorter route by reducing the travel distance between Dhaka-Jashore, Dhaka-Khulna and Dhaka-Darsana by 184.72km, 212.05 km and 44.24 km respectively. This rail link will become a vital railway corridor in terms of national as well as regional railway traffic demand (CANARAIL, SMEC, DB, & ACE, 2015).

This rail link passes through the flood plain and low-lying areas of the South and South-West part of the country. Running through the alluvium soil deposits and flood affected areas of the country entails a design level of embankment to be very high and needs extensive soft soil improvement. In this project, different methods of soft soil improvement techniques were applied based on the soil conditions. Drainage was another important issue which was addressed properly by provisioning of sufficient bridges and drainage culverts. The railway embankment divided the people of surrounding area socially and culturally which entails the construction of adequate underpasses throughout the alignment.

2. PROVISIONS OF RAILWAY TRACK OVER PADMA BRIDGE

Padma Railway is the main passage connecting the east and the west of Bangladesh, and is also part of the Bangladesh-China-India-Myanmar corridor. This line is a single-track passenger-freight railway with a total length of 168.6km, a wheelbase of 1676 mm and a designed axle load of 25 t.

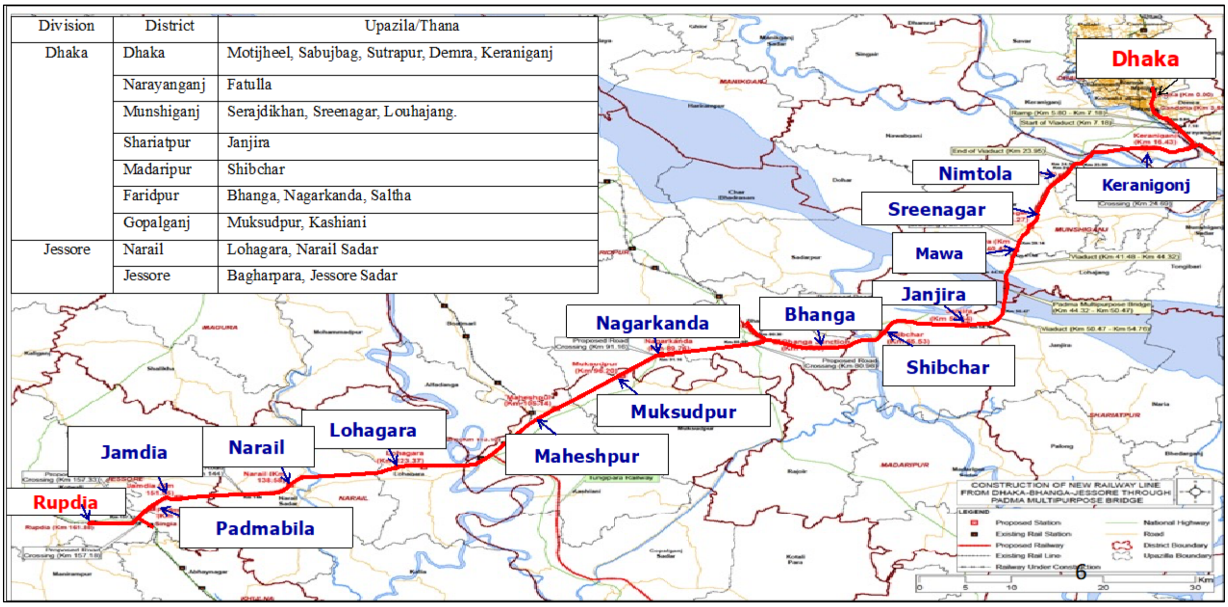
Figure 1: Padma Bridge under construction

Among them, Padma Bridge, its truss bridges at both ends and some viaducts adopt ballast less track of about 30km long. Padma Bridge, with a total length of 6.15km, is composed of 41 spans of $6 \times (6 \times 150)m + 5 \times 150m$ double-layer steel-concrete composite continuous beams (NIPPON KOEI CO., LTD & CONSTRUCTION PROJECT CONSULTANTS, INC., 2005). The upper layer is a two-way four-lane highway bridge, and the lower layer is a single-track broad-gauge railway bridge. The bridge deck of upper layer is a precast slab, which is connected with I-shaped longitudinal beam at the lower layer using embedded connectors. Meanwhile, Π-shaped reinforcements known as shear connectors are reserved on lower bridge deck slab to connect with the track slab.

Figure 2: Shear Connectors provided at the lower deck of the Padma Bridge

3. LOCATIONS AND ALIGNMENT OF THE PBRLP

The PBRLP is the second largest infrastructure project ever taken in Bangladesh after Rooppur Nuclear Power Plant.



Division	District	Upazila/Thana
Dhaka	Dhaka	Motijheel, Sabujbag, Sutrapur, Demra, Keraniganj
	Narayanganj	Fatulla
	Munshiganj	Serajdikhan, Sreenagar, Louhajang.
	Shariatpur	Janjira
	Madaripur	Shibchar
	Faridpur	Bhanga, Nagarkanda, Saltha
	Gopalganj	Muksudpur, Kashiani
Jessore	Narail	Lohagara, Narail Sadar
	Jessore	Bagharpara, Jessore Sadar

Figure 3: Alignment of Padma Rail Link Project (PBRLP)

4. SCOPE OF THE PROJECT

- Construction of new Broad Gauge 172 Km route main line and 43.22 km loop & siding line. Total track is 215.22 km including loops & siding.
- Construction of 23.377km viaducts, 60 major bridges, 230 minor bridges/ culverts/ underpass, 1 road overpass (at Mawa approach) and 29 level crossings
- Construction of 14 new station buildings and remodeling of 6 exiting station buildings along with Platforms, Platforms Shed, approach roads, functional and residential building for O&M personnel and other allied works
- Installing Computer Based Relay interlocked signaling System along with Telecommunication System of 20(Twenty) stations
- Supply of 100 BG Passenger Coaches
- Supervision Consultancy Services
- Acquisition of 1940.96 Acres private land and requisition of 206.5 Acres land from RHD and 59.32 acres from BBA including implementation of RP & EMP

5. OBJECTIVES OF THE PROJECT

- To connect Dhaka with South and South Western region of the country by rail road.
- To establish another sub-route of Trans-Asian Railway Network in Bangladesh.
- To cover new areas of Munshiganj, Shariatpur, Madaripur and Narail districts under railway network
- To create opportunity to construct second line in this route and connect Barisal and Payra Deep Sea Port in future.
- To contribute Gross Domestic Product (GDP) growth of approximately 1%.

6. TECHNOLOGICAL UNIQUENESS

- Introduction of Ballast Less Track in Bangladesh Railway.
- Initiation of railway track on elevated viaduct.
- Minimized at-grade crossing by providing road underpasses.
- Adoption of State-of-the-Art Technology in railway track, bridges and stations construction.
- Universal design for physically challenged people.
- Provision for carrying double stack containers.
- Introduction of transitional embankment at major bridge approaches
- Provision of future electric traction in railway.

7. CONSTRUCTION OF EMBANKMENT

A. Geological Strata

The whole embankment is mainly located on an alluvial plain which is flat. Except few areas nearest to the town, it has marshy area, paddy field and pond distributed on both sides of the embankment. The surface is made up of thick loose soil which provides poor bearing capacity, high compressibility and poor compression strength. The overlying layer is thick. From top down, the soil gradually changes from fine-grained cohesive soil into silty-fine sand. With the increase of depth, the soil becomes stronger and has higher bearing capacity. The ground water table is very high and close to the surface. The area also experiences frequent flood in changes climate change scenario. The foundation soil along the embankment gets soaked and the mechanical strength of the surface soil decreases seasonally.

B. Typical Embankment Cross Section

Figure 4 and 5 present Typical cross section of embankment with height $\leq \mathbf{4.0}\ \boldsymbol{m}$ and $\geq \mathbf{4.0}\ \boldsymbol{m}$.

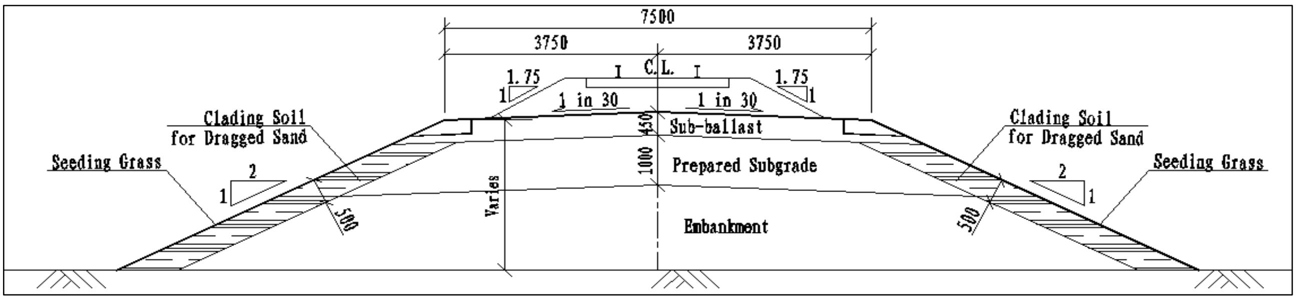


Figure 4: Typical cross section of embankment with height ≤ 4.0 m

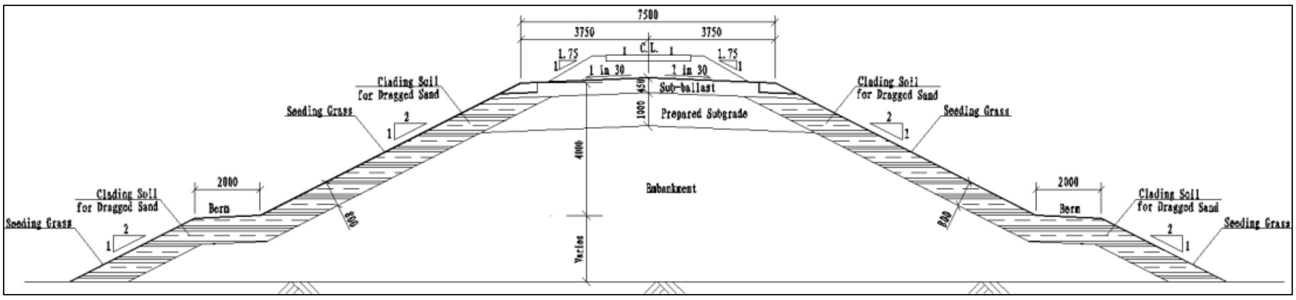


Figure 5: Typical cross section of embankment with height ≥ 4.0 m

C. Ground Treatment

i. Clearing, Grubbing and Stripping

After completion of the topographic survey, all trees, roots, stumps, weeds, and rubbish from the existing ground are to be removed. Removal of topsoil of 150mm thickness containing above rubbish are termed as clearing, grubbing, and stripping. All pits resulting from uprooting of trees and stumps are also backfilled again with required compaction.

ii. Removal and Replacement

Based on geological investigation, if the California Bearing Ratio (CBR) is less than 4.0 and bearing capacity is less than 100 KPA, then it is considered as soft soil. Soft material is fully removed and backfilled with suitable embankment materials, if the depth of soft soil and highly compressible soil is within 3m from the top of existing ground.

iii. Prefabricated Vertical Drain (PVD)

PVD, also known as Wick Drains or Band Drains are prefabricated geotextile filter-wrapped plastic strips with molded channels. It acts as a drainage path to take pore water out of soft compressible soils that consolidate faster under a constant surcharge load (Turukmane, Gulhane, Kolte, & Chaudhary, 2019). If the depth of soft soil exceeds 3m, the treatment of soft soil is done by PVD. To install PVD up to design depth, mandrel operation is adopted. The entire procedure of installation of PVD is recorded with digital corder having print out facilities. Surcharge or preloading is a must to ensure that the settlement has ceased before prepare subgrade is to be constructed in case of a railway embankment.

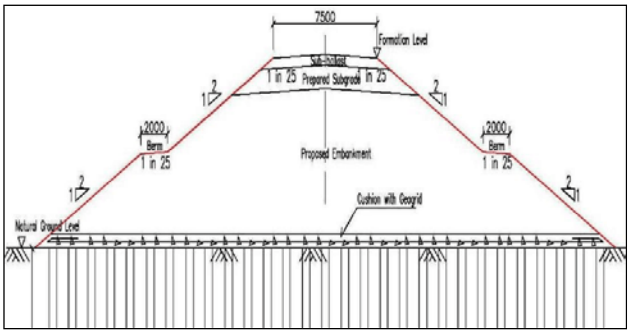


Figure 6: Cross section of soft ground treatment with PVD

Figure 7: PVD being installed in the embankment

iv. Cement Mixing Pile

Cement Mixing piles are an effective way for soft soil treatment using cement as the main curing agent. Mixing pile machine is used to inject cement into the soil body and to fully mixed with the soil. After a series of physical and chemical reaction between cement and soil, soft soil become hardened which will increase the strength of the foundation (Zotsenko, Vynnykov, & Zotsenko, 2015).

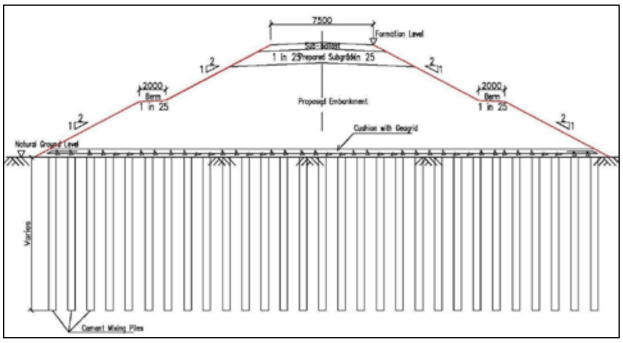


Figure 8: Cross section of embankment with Cement Mixing Piles.

Figure 9: Cement Mixing Piles after construction

Cement mixing piles are mainly provided at transition sections of both end of bridges, culverts, underpasses, and the underneath of these structure if there are soft soils. When there is a constraint of time, cement mixing piles are being used as it does not require preloading as settlement is not being expected once cement mixing piles are being used.

8. CONSTRUCTION OF RAILWAY TRACK

Two types of tracks are being used in Padma Bridge Rail Link Project. Though most of the tracks are of ballasted but for the first time BLT is being used in Padma Bridge, it's approach viaducts and other viaducts including steel bridges within the viaduct. The BLT has a definite advantage over ballasted track in terms of its high durability, stability, smoothness, and light dead load. It is normally applied in case of high-speed railway, heavy axle load, mixed freight and passenger railway track, urban rail transit, bridge, and tunnel etc.

A. Construction of BLT over PMB

The main bridge of Padma bridge is a 6×150m through steel truss bridge. The upper layer is a two-way four-lane highway and the lower layer is a single-track railway with a total length of 6.15km. The bridge layout is $\mathbf{150}\boldsymbol{m} + \mathbf{6} \times \mathbf{150}\boldsymbol{m} + \mathbf{6} \times \mathbf{150}\boldsymbol{m} + \mathbf{6} \times \mathbf{150}\boldsymbol{m} + \mathbf{6} \times \mathbf{150}\boldsymbol{m} + \mathbf{6} \times \mathbf{150}\boldsymbol{m} + \mathbf{5} \times \mathbf{150}\boldsymbol{m}$ continuous steel trusses. The layout of each span of main bridge of Padma Bridge.

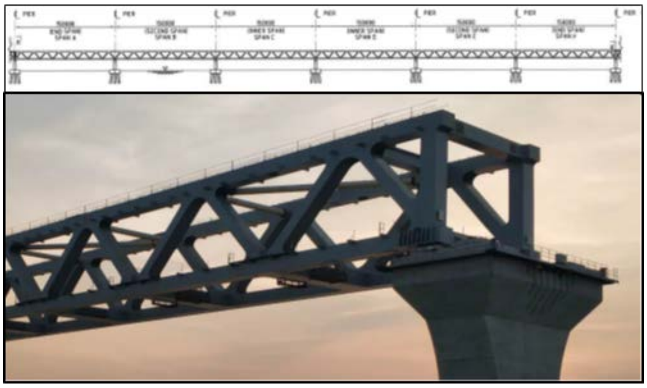


Figure 10: Spans of PMB

The span of Padma Bridge is 150m and consists of 8 sections, each of which is 18.75m long. The lower railway load-bearing system is composed of a bridge deck, longitudinal beams and lower transverse beams. The longitudinal beams are 15.9m in length and are supported on the lower transverse beams by supports and corbels. The bridge deck is a precast slab, which is connected with the longitudinal beam and lower transverse beam using shear studs.

B. Typical Cross Section of Padma Main Bridge

The top chord, bottom chord and diagonal members of the main truss are in the form of a hollow steel box. Plate thicknesses of the boxes vary depending on the location of the member. Box section is also adopted for other members including the lower cross beams and upper cross beams.

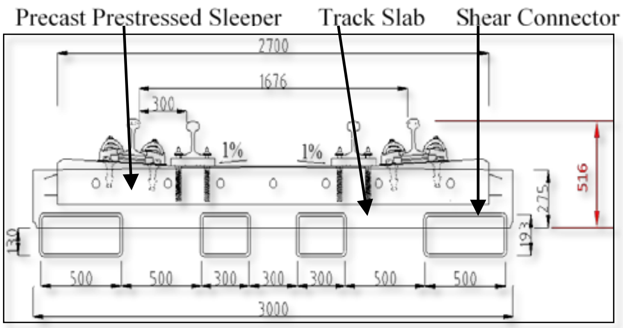


Figure 11: Cross section of Padma main bridge composite steel truss

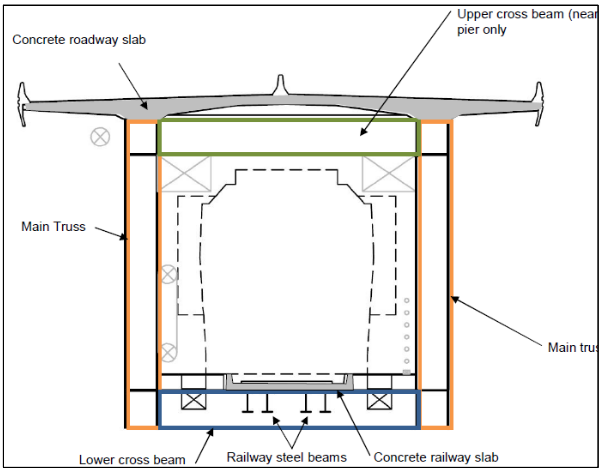


Figure 12: Deck slab over I Stringer

C. BLT Over Padma Bridge

Padma Main Bridge constitutes the Precast Sleepers Embedded Track Slab system. It is a type of BLT system which has less maintenance, and more stability since PSC sleepers are used at 600mm centres and are easy to construct. The sleepers are manufactured in the sleeper factory with high-quality standards and embedded (Cast in Situ) in M50 concrete. The track slab, deck slab and sleepers are connected by taking the bottom reinforcement of the slab through the shear connectors in the deck slab and the top reinforcements pass through the holes in the sleepers. The track structure consists of f 60Kg/meter E1 rail of R32 0. The fastening is s WJ12 system with a 32mm rail pad. The depth of the track slab from rail top to deck slab is 516mm.

Figure 13: Long Sleeper Embedded BLT over Padma Bridge

Figure 14: Semi precast cast in situ BLT

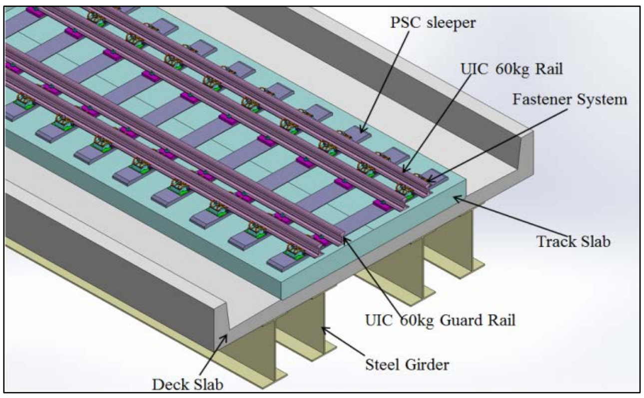


Figure 15: All components of BLT over I type Stringer

D. Construction Methodology of BLT over Padma Bridge

The track panel is assembled in the base; it is then hoisted to the bridge. The track panel is then transported to the construction site (Padma Bridge) by a gantry crane or platform wagon. Then, the track panel was lifted by the track panel laying gantry crane and laid over the lower deck. The steel bar was then placed and welded before the final adjustment of the track. The next step is the installation of mold for pouring the concrete to complete the construction of BLT.

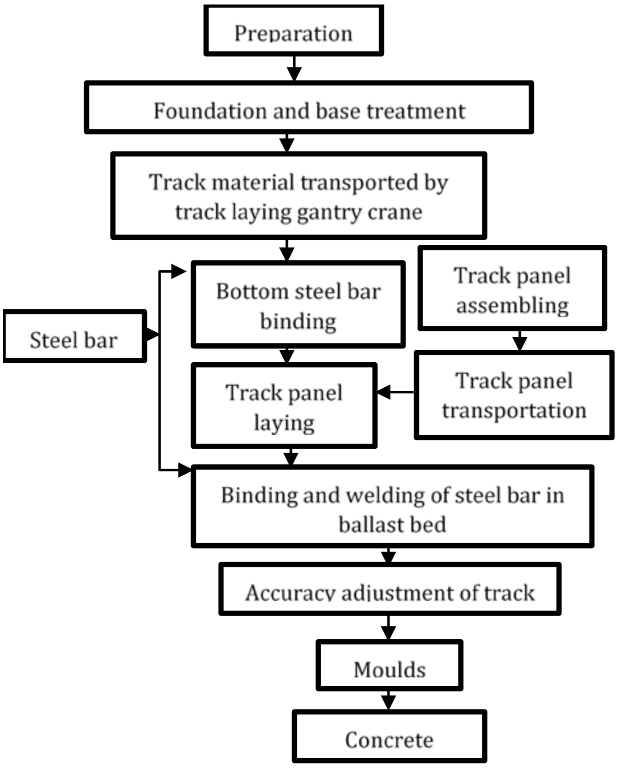


Figure 16: Schematic diagram of BLT Construction over Padma Bridge

Figure 17 Placing of precast sleeper over Padma Bridge Rail Deck by using Mechanical Layer is in progress

9. CONCLUSIONS

The Padma Bridge Rail Link Project (PBRLP) is the second-largest infrastructure project in the country. It is running through the lower floodplain of the country which is prone to flood every year. Soft soil improvement, numerous drainage culverts, bridges, grade separation and elevated viaducts including elevated stations made it a unique civil engineering project in the country. Besides, BLT and ballasted track construction with an axle load of 25 t gave exposure to Bangladesh Railway and other experts associated with it, a proper learning ground for future development and construction of the railway in Bangladesh.

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The paper is written based on the author's personal involvement with the project as Deputy Chief Coordinator of the consultant team at present and Project Manager in the past. Besides, the author has consulted different documents of PBRLP as was involved in the design review, supervision, and implementation of the project.

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