A systematic approach to the Conceptual Design of structures in the feasibility studies for large river crossings in Bangladesh

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Summary

Conceptual design is particularly crucial in the early stages of every project, as this is when the range of possible solutions needs to be wider, and the conjunction of experience and open-mindedness leads to more beneficial outcomes in the subsequent stages.

A key example of when conceptual analysis is essential is during a feasibility study. An illustration of this can be found in the approach followed by TYPSA in the feasibility studies for large river crossings in Bangladesh, as part of the country's Transport Master Plan. Finding the most effective solution for the structures at each location is particularly critical in this case due to the vast watercourses and the limited resources available. This necessitates a thorough analysis to prioritize investments.

The procedure applied to all these studies follows a systematic approach to identifying constraints, proposing solutions, and evaluating and comparing them.

1 FEASIBILITY STUDIES. CONCEPTUAL DESIGN IN EARLY STAGES.

Feasibility studies for civil engineering infrastructures help administrations decide which projects are worth developing, acknowledging that budgets are always limited, and investments need to benefit the population in both the short and long terms. The conclusions of a feasibility study must be reliable, and to ensure this, a systematic approach should be followed.

The first step involves identifying the main constraints and design principles [1]. These will limit the available alternatives for the final solution. Once all reasonable solutions have been identified and any doubts about their feasibility have been addressed (often through simplified calculations), these options should be evaluated and compared to make a final proposal.

2 THE ASSIGNMENT

Bangladesh, with a rapidly growing economy, a population exceeding 170 million people, and a land area of 148,000 square kilometres, holds the distinction of being the world's most densely populated large country. Its unique riverine geography, defined by the Padma, Jamuna, and Meghna rivers, along with their numerous tributaries, divides the country into a mosaic of islands and peninsulas. Given this complex geography, a robust bridge infrastructure network is critical to supporting the road network and fostering connectivity among various regions and socio-economic centres. This is a challenge the Bangladeshi government is actively addressing. To do so, in 2021 the Bangladesh Bridge Authority (BBA) assigned a Joint Venture Consultant led by TYPSA to develop a comprehensive Transport Master Plan for the period 2020-2050, along with several feasibility studies.

2.1 The Transport Master Plan

This plan is designed to support Bangladesh's progress by meticulously identifying, assessing, prioritizing, and recommending infrastructure projects and public investments for the next 30 years, covering both short-term and long-term initiatives. To boost the economy and improve national connectivity, the Bangladesh Bridge Authority is implementing a roadmap and action plan (Master Plan) for transport connectivity. The Master Plan aligns with Bangladesh's Vision 2041, which aims for the country to become a high-income nation.

2.2 Feasibility Studies

The Consultant JV led by TYPSA was assigned to carry out six feasibility studies: five related to bridges and one for an elevated expressway around the city of Dhaka. Additionally, four pre-feasibility studies with a similar scope for large crossings were completed. The studies include the following projects:

- Matlab Uttar-Gazaria Bridge over Dhonagoda River (Meghna Branch).
- Chilmari-Rowmari Bridge over Brahmaputra River.
- Barishal-Bhola Bridge over Kalabador and Tentulia Rivers.
- Gazaria-Munshiganj Bridge over Meghna River.
- Shariatpur-Chandpur Bridge over Meghna River.
- Dhaka Inner Elevated Circular Road (DEICR).

The goal of the studies was to establish safe and permanent connections between regions that currently lack adequate connectivity while aligning with the broader Master Plan and its selected projects. The objectives of these studies are summarized as follows:

- Determination of preliminary corridor/site selection.
- Identification of suitable locations for the bridges.
- Determination of the most suitable typologies of bridges or tunnels for the crossings.
- Preliminary design for the bridges and associated facilities, including the choice of appropriate construction methods, configurations, and technologies.
- Estimation of capital expenditures (CAPEX) and operational costs (OPEX).
- Assessment of the socio-economic impact and necessity of the investments in the areas.
- Evaluation of the technical, social, economic, and financial viability of the projects.
- Assessment of environmental impacts and conduction of IEE and EIA processes.
- Recommendation of a mode of procurement.
- Provision of sound conclusions and recommendations regarding the viability of the projects.

3 BANGLADESH. CHALLENGES TO INFRASTRUCTURE

3.1 Growth

Bangladesh is one of the fastest-growing economies in the world and a member of the South Asian Free Trade Area and the World Trade Organization. According to the World Bank: *"Bangladesh has a strong track record of growth and development, even in times of elevated global uncertainty. Despite uncertainties and frequent natural disasters, Bangladesh has witnessed robust economic growth and poverty reduction since its independence in 1971"*. This growth imposes increasing pressure on the demand for infrastructure and connectivity.

3.2 Large changing rivers

Bangladesh forms the delta of the Ganges, Brahmaputra, and Meghna rivers. Within the country, the Ganges and Brahmaputra are known as the Padma and Jamuna, respectively. These rivers account for 10% of the country's land area. The country's flat and low-lying topography gives rise to meandering river branches that can shift over time. Additionally, during the monsoon season, water levels can rise by up to 6 meters, leaving 80% of the country's surface prone to flooding. This disrupts ferry navigation, making the limited number of bridges the only viable transportation routes.

3.3 Winds associated with typhoons

Bangladesh experiences periodic cyclonic winds originating from the Bay of Bengal. The most devastating recorded typhoon in history, which caused over half a million casualties, occurred in November 1970. The typhoon had a maximum wind speed of 222 km/h in the coastal region. Due to Bangladesh's flat topography, these strong winds travel inland with little attenuation.

As a result, the Bangladesh National Building Code (BNBC) specifies wind speeds of up to 80 m/s (approximately 290 km/h) in 3-second gusts for a 50-year return period, which is associated with these cyclonic winds. This is equivalent to a basic wind speed of 56 m/s, as the characteristic 10 minutes mean wind velocity, as considered in the EN 1994-1-1.

3.4 Geology and Scour

As Bangladesh is a delta, most of the country has a significant sediment thickness. In general, bridge piles are founded on a dense, consolidated layer located about 50 to 70 meters deep. Above this, there are loose, unconsolidated soils, which present a potential scour risk during the rainy season, as water velocity increases. These significant scour values are also linked to substantial sedimentation in certain areas. When selecting a proper location for a large river crossing, it is crucial to identify a stable site where both sedimentation and erosion are moderate, as shown in Figure 2. In these feasibility studies, this results in access spans (outside the riverbanks) with concrete bored piles ranging in length from 50 to 80 m, and main spans over the river with steel driven piles ranging from 90 to 130 m in length.

3.5 Seismic Activity

Bangladesh is considered a seismically active region. The Himalayan system to the north and the Arakan subduction-collision system to the southeast are the two major tectonic mechanisms that can generate large earthquakes in the Bengal Basin area. Bangladesh has experienced several large earthquakes over the past 130 years, seven of which had a magnitude greater than 7.0.

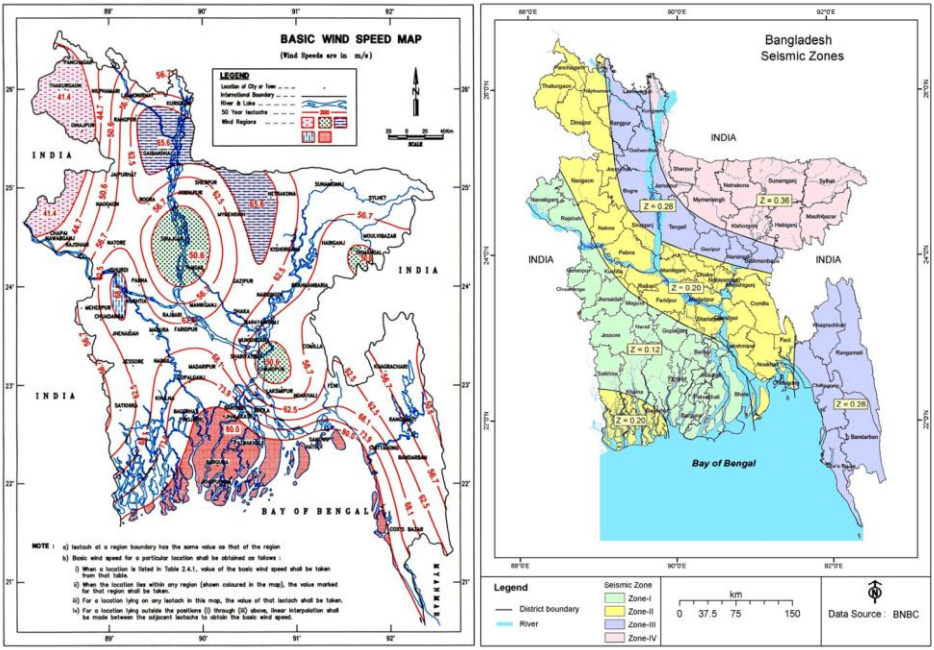

Fig. 1 Left: Basic wind speed for a 3-second gust with TR = 50 years. Right: PGA for a 2% exceedance probability over 50 years (TR = 2475 years). Source: BNBC

3.6 Ship Impact and navigation clearances

The riverine conditions of Bangladesh support a significant freight transportation sector, with barges in the range of 5,000 to 7,500 displacement weight tonnage (DWT) already navigating the inland waters. Given the importance of rivers in the country, much of its current and future commerce relies on river traffic. Additionally, the shipyard industry is growing. Major navigation routes have a draught ranging from 6 to 15 meters, even during the dry season, which allows large vessels to operate. Consequently, an accidental ship impact load on the foundations was considered in this conceptual design.

Minimum vertical and horizontal clearances for rivers are determined based on the classification and information from the Standard High-Water Level provided by the Bangladesh Inland Water Transport Authority (BIWTA). According to these criteria, river spans should be at least 100 meters if navigation underneath is allowed. However, this would limit the possibility of two boats crossing under the span. In such cases, spans of at least 170 meters are required. Longer spans can be justified in many instances, as they may offer cost savings or be necessary due to environmental factors.

4 METHODOLOGY FOR THE FEASIBILITY STUDIES

4.1 Systematic approach

The "Technical Report" of each feasibility study contained a systematic analysis of the structural elements, their constraints, and the proposed solutions, to ensure consistency across all studies, with results varying based on the unique characteristics of each project. Summary of the Technical Report strategy:

- Identification of the main constraints for the crossing. Including general principles applicable to all studies (as described in the previous chapter) and specific constraints for each study.
- Evaluation of the different alignment alternatives considered.
- Explanation of the design criteria used during the development of the feasibility study.
- Identification of applicable structural solutions for each specific location.
- Comparison of solutions, both conceptually and numerically (cost-wise), with a focus on two main areas: approach spans and main (river) spans.

Such structured approach reflects the effort to break down the complexity of a large-scale project into smaller, more manageable topics. The method creates useful similarities in how the documents are structured, helping the reader follow each study and compare them effectively.

4.2 Alignment and river stability.

First, the different alignment options under comparison (three or four, depending on the specific site) are described to provide the reader with a comprehensive overview of the alternatives. This analysis is a critical step in the design process. While drawing lines by hand over the bathymetry of the meandering rivers in Bangladesh, small changes in the proposed location of the crossing can result in significant variations in road length, river width, water depth, or riverbank stability. Therefore, a thorough analysis of the bathymetry and historical river layout images to identify stable areas and those prone to erosion or sedimentation is essential.

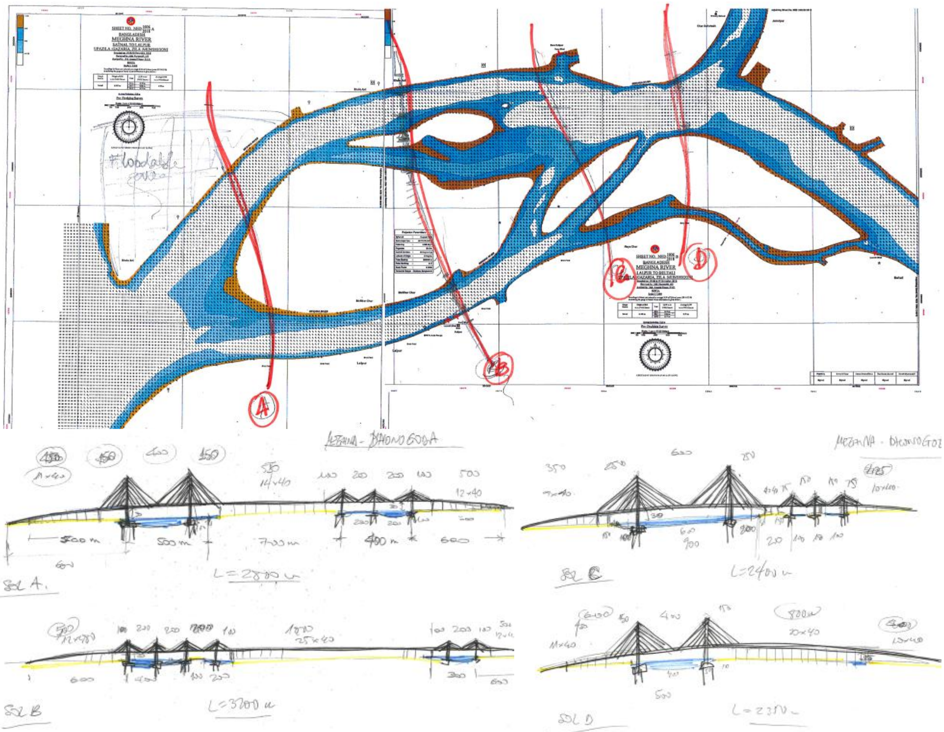

Fig. 2 Alignment options and associated preliminary structural options for the crossing over a River Megna branch.

4.3 Tunnel option

The feasibility of crossing under the rivers via a tunnel was explored at a conceptual level. Three options were considered: immersed tunnel, double tunnel with transversal galleries, and two-level tunnel. However, the tunnel alternative has generally been discarded, as it has been estimated to cost approximately four times more than a bridge, both in terms of construction and maintenance. Additionally, the tunnel solution involves significant environmental challenges, which, combined with the higher cost, led to the decision not to further explore this option for these large river crossings.

4.4 Preliminary design

General criteria and methodology for the preliminary bridge design, including the applicable solutions for the superstructure, substructure, and foundation, are presented in the chapter titled "Preliminary Design" in the Technical Report of each feasibility study. Additionally, various construction methods for each structural solution, including the superstructure, substructure, piles, and pile caps, and how they apply to the site under analysis are included in this chapter. The solutions for the approach viaducts are also included. In the preliminary design of the approach bridges, several alternatives for deck sections and span ranges were studied, and two of these alternatives were developed in greater detail. For the deck sections, two options were considered and developed: a post-tensioned concrete box girder (60 m typical span), and a deck formed by precast concrete beams with a cast-in-situ reinforced slab (40 m typical span). For the latter option, both I-shaped and U-shaped beams were analysed.

Annexures are provided to guide the reader to more detailed information, such as the specific calculations for each structural solution while keeping each report concise. The annexures followed a similar structure across all feasibility studies, with differences arising from the specifics of each project. The general arrangement of the annexures was as follows: Annexure 1: Design Basis \ Annexure 2: Vessel Impact Study \ Annexure 3: Approach Viaducts \ Annexures 4 and onwards: one annexure for each applicable structural solution for the main spans (e.g., extradosed bridges, balanced cantilever bridges, truss bridges, cable-stayed bridges, and suspension bridges) \ Final annexure: Indicative Bridge Cost Estimation. The term "main span" refers to spans greater than 100 metres in length.

Some annexures did not apply to all feasibility studies. For example, the suspension bridge annexure was only relevant to the Shariatpur-Chandpur Bridge, as it was the only location where this solution was considered viable. However, after detailed analysis and structural calculations, the suspension bridge was not the proposed solution for this project due to challenges related to the anchor blocks, including large soft deposits and potential scour.

4.5 Water depth

During the development of potential solutions for each location, water depth (drought) emerged as a key parameter. The riverbed depth significantly affects the cost of the foundation. In the analysis of the span length that would result in the minimum total cost, it was found that as the riverbed depth increases, the optimum span length also increases. As a rule, foundations at depths greater than 15 meters during the dry season were avoided, and the number of foundations at depths over 10 meters was minimized. In the case of the Shariatpur-Chandpur Bridge, this led to a central length of 700 meters (with a riverbed depth greater than 15 meters) and a total length of 1,500 meters in water depths over 10 meters. Thus, these constraints are compatible with two of the proposed solutions:

- A cable-stayed bridge with span arrangement 400+700+400.
- A suspension bridge with a span arrangement of 250+1000+250.

As previously mentioned, this is a general criterion, and the comparison was extended to include other structural solutions with smaller typical spans, generally in the range of 100 to 200 meters.

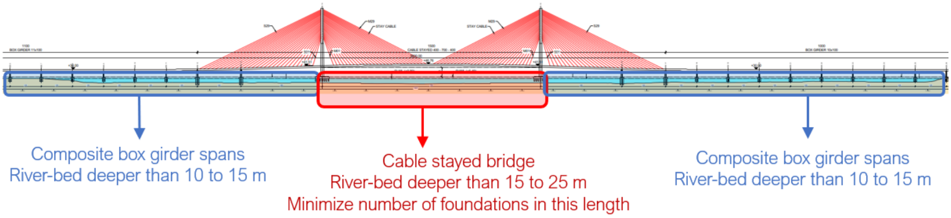

Fig. 3 Foundation arrangement based on river-bed depth. Example of Shariatpur-Chandpur F.S.

4.6 Structural Typologies

The same vertical clearance is used for all the solutions. The following list includes the typologies considered for spans equal to or greater than 100 meters:

- Concrete box balanced cantilever bridge (up to 200 m span).
- Steel composite box (up to 100 m span).
- Extradosed bridge (up to 200 m span).
- Truss bridge (up to 200 m span).
- Cable-stayed bridges (concrete deck up to 450 m span).
- Cable-stayed bridges (composite deck up to 700 m span).
- Suspension bridge (up to 1000 m span).

For each proposed solution an indicative construction period is determined for comparison purposes. Bridge types being considered for the subsequent preliminary design were compared based on construction cost, construction duration, aesthetics and constriction for river section by bridge piers.

Costs, including those for superstructures, piers, and foundations, are estimated for comparison purposes. Quantities for superstructures, substructures, and foundations were estimated based on data from bridges of similar structures and calculations developed in each of the annexes, addressing the specific constraints of each study (e.g., scour and geotechnical capacity).

Following this, the most suitable structural solution is determined for each alignment option, and the total project cost for each alternative is summarized in a table. This table includes costs for riverbank protection, earthworks, toll plazas, and site facilities. This way, an alignment, along with the associated proposed structural solution and estimated investment cost is presented as the conclusion of the report.

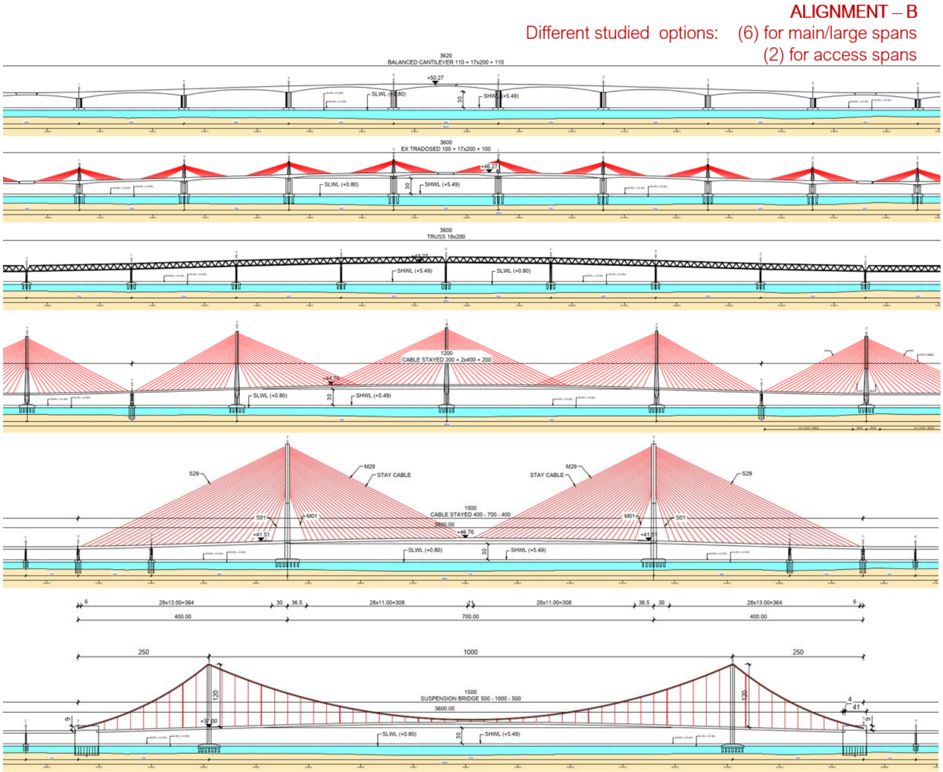

Fig. 4 Six (6) structural solutions proposed for the chosen alignment option in Shariatpur-Chandpur F.S.

5 APPLICATION WITHOUT PRECONCEPTIONS

The application of the systematic approach described leads, when considering the specific site constraints, to different results at each location. However, common patterns are observed. Most large river crossings require deep piles in soft materials. In the approach spans, the typical solution (considered the most economical) is simply supported spans of 40 m in length, with precast prestressed beams supported by foundations comprising four concrete bored piles of 1.8 metres in diameter, with lengths ranging from 50 to 80 metres. Additionally, these isostatic spans are less sensitive to potential settlements of the foundation, thus requiring less expensive treatments for the pile tips.

For the superstructure of the river crossings, when a typical span is considered, the balanced cantilever concrete bridge is the most economical solution for spans ranging from 100 to 200 m. However, this a priori assumption cannot be applied without considering other constraints. For a 200 m balanced cantilever bridge, the alignment profile needs to be approximately 7.0 m higher than for a truss bridge, or 4.0 m higher than for an extradosed bridge, to meet the same required navigation vertical clearance. With a maximum slope of 3% for the access ramps, these differences in alignment level would necessitate six additional approach spans on either side for the balanced cantilever bridge, compared to the truss bridge. Enough length of the so-called “main spans” could offset the additional cost associated with the longer ramps, as seen with the Barishal-Bhola Bridge in Figure 5.

The foundation costs also play a crucial role. While balanced cantilever and extradosed bridges for typical spans of 200 m were estimated to require 12 Ø3.0 m steel-driven piles in a 28.5 x 21.0 x 5.0 m pile cap, the 200 m steel truss bridge (which is lighter and requires lower alignment) was estimated to need 12 Ø2.5 m steel driven piles in a 24.0 x 17.5 x 4.0 m pile cap.

The following table shows the average estimated construction cost for a 2+2 dual carriageway: with deck widths ranging from 20 to 24 metres. Please note that these average values vary with the pile length, which is obviously site-specific.

Table 1 Main types of bridges. Associated average construction cost in Bangladesh. 2024.

LOCATION	TYPE (span)	MUSD/km
APPROACH SPANS	Precast Double T (40 m)	42.0
	Precast U-Beams (40 m)	44.0
	Box Girder (60 m)	60.0
MAIN SPANS	Composite Box Girder (100m)	95.0
	Balanced Cantilever Bridge (200m)	155.0
	Steel Truss Bridge (200m)	165.0
	Extradosed Bridge (200 m)	170.0
	Concrete Cable-stayed Bridge (150m+400m+150m)	210.0
	Multi-span Cable Stayed Bridge (200m+400m+200m)	225.0
	Composite Cable-Stayed Bridge (400m+700m+400m)	240.0
	Suspension Bridge (250m+1000m+250m)	285.0

Another critical factor in the comparison is the indicative construction period. Even if one solution is found to be the most economical based solely on quantities, a realistic assessment of the number of teams and the construction period is necessary. For example, the Chilmari-Rowmari Bridge, with a total length of 10.8 km and 8.0 km over the river, was estimated to require 76-78 months to complete the deck for the river spans of a balanced cantilever or an extradosed bridge, with five teams working in parallel. In contrast, the truss bridge, with three workshops/assembly yards and four heavy lifting teams, was expected to require only 36 months. This means the total construction time for the balanced cantilever and extradosed bridges would be around 8 to 9 years, which is not considered practical, whereas the construction time for the truss bridges would be approximately 4 to 5 years.

Finally, hydro-morphology, river depth, and riverbank stability play a significant role too. In the case of the Candpur-Shariatpur Bridge, with a total length of 8.0 km and 3.6 km over the river, more than half of the bridge length is located over a flood-prone area. For this portion, the typical solution for the approach spans (simply supported 40 m precast beams) proved to be the most economical and allowed for significant industrialization. The river depth at the crossing had a substantial impact on the cost estimation and construction duration, with the 700 m main span cable-stayed bridge with a composite deck providing the most viable option. The Matlab Uttar-Gazaria Bridge differs from the other three examples in the Figure 5 below. In this crossing, the river features a stable nodal point, where the width has remained consistent over the past 40 years, and the confluence of two branches generates high water speeds (alignment D in Figure 2). These particularities made the 400 m main span cable-stayed bridge the most suitable option, as it allowed the pylons' foundations to be constructed in dry conditions, avoiding foundations in areas of high water speed and heavy vessel traffic.

Fig. 5 Proposed bridges for four different crossings: Chandpur (top-left), Chilmari (top-right), Bhola (bottom-left), and Matlab (bottom-right).

6 CONCLUSION

In a world of limited resources, prioritizing investments and optimizing solutions for further stages is essential. The work developed by TYPSA for the Bangladesh Bridge Authority in the feasibility studies for large river crossings serves as evidence of the utility of conceptual design in structuring projects, and how it supports long-term planning for a nation's investment calendar. The application of a systematic approach, combined with the consideration of the particularities of each location, ensures robust results for each study and consistency across all of them. This systematic approach consists of identifying constraints, proposing design alternatives, and evaluating and comparing them. Common challenges across most locations include typhonic winds, scour depths ranging from 40 m to 60 m, and soft ground conditions. Other site-specific factors, such as crossing width, riverbed depth, and bank stability, were considered uniformly, leading to a limited number of applicable options for each location and allowing for their comparison to determine the most suitable solution for each study.

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References

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