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SUSTAINABLE WATER CROSSING DESIGN NOW AND FUTURE

Connie Chan, Jason Wong and Francis Kung
Meinhardt Infrastructure and Environment Ltd

Abstract

Bridges and Tunnels are essential transport infrastructures across river or sea. The first beam bridge crossing in China was believed to be built as early as in 16th – 11th century B.C. while the world's oldest tunnel crossing is rumored to be the Terelek kaya tüneli in Turkey built more than 2000 years ago. In Hong Kong, the first large scale water crossing is the Cross Harbour Tunnel opened in 1972 and since, other tunnel and bridge crossings have been developed with the forms, construction techniques and appearances evolved with time and technology.

To support the continual growth of Hong Kong and foster closer ties with adjacent economic regions, it is no doubt that more water crossings will need to be developed. With the trend of higher level of public participation in the decision making process for infrastructure development and aspiration on higher environmental standards and cost-benefits, water crossing development now face a challenge. While least amount of dredging and reclamation requirements in protection of marine lives and natural shoreline limit the application of tunnel crossing, extensive mitigations to the air, noise and visual impacts of bridge crossing require special attention. Bridges and tunnels in the future will not only serve functional purposes for carrying traffic, but also be planned and designed to focus on environmental and social needs.

Demand for public enjoyment of the valuable natural waterfront requires a more holistic planning approach to the design of connections to the adjacent areas and incorporation of design elements to enhance the accessibility and public enjoyment of waterfront. Considerations will need to be given to maximizing the greening opportunities and pedestrianised landscape deck over depress road to tunnel. The appearance of the bridge crossing should not only be aesthetically pleasing, but also architecturally featured to prompt the uniqueness of a city with overall enhancement to the townscape. Innovative design with environmental friendly materials and sustainable features is also essential.

1 INTRODUCTION

Hong Kong is a coastal city and comprises of peninsula and islands. Over the last century, water crossings in forms of both bridges and tunnels have been developed linking different districts, satellite towns and airport forming an important part of the sophisticated transport network. The first large scale water crossing in Hong Kong is the Cross Harbour Tunnel opened in 1972. It was the first immersed tube tunnel (IMT) in Hong Kong and subsequently the Eastern Harbour Tunnel, Western Harbour Tunnel and three other rail harbour crossings in 1980’s to 1990’s. During the time, Tsing Tsuen Bridge and its duplication crossing the Rambler Channel were completed in 1987 and 1999 respectively, in the form of Reinforced Concrete Box Girder Bridge. In 1997 and 1998, several major bridges in form of cable-stayed or suspension bridges: Ting Kau Bridge, Tsing Ma Bridge and Kap Shui Mun Bridge crossing the Rambler Channel, Ma Wan Channel and Kap Shui Mun respectively were opened. Recently completed major bridge crossings also include the Hong Kong Shenzhen Western Corridor and Stonecutter Bridge.

In the 2007-08 policy address, 4 out of the 10 major infrastructure projects to be implemented include water crossings. These include the Shatin to Central Link, The Tuen Mun Western Bypass and Tuen Mun-Chek Lap Kok Link, the Hong Kong-Zhuhai-Macao Bridge and the Hong Kong-Shenzhen Airport Co-operation. With the trend of higher level of public participation in the decision making process for these infrastructure, engineers will need to look forward, not only to design achieving functional requirements but also commit to meet the aspiration of the end users and the society as a whole applying the sustainable development principles.

This paper will discuss the constraints and opportunities as well as innovations in development of water crossings.

2 CHALLENGES AND OPPORTUNITIES - ENVIRONMENTAL

2.1 Cleaner Air

It is recognized that there is a close relationship between the air quality and public health and there is public's quest for better ambient air quality as well as more stringent air quality objectives and legislation.

According to the data of Environmental Protection Department (EPD) of Hong Kong Special Administrative Region (HKSAR) on the Air Quality Objectives Compliance Status in 2005, objectives of nitrogen dioxide (NO2), Respirable Suspended Particulates (RSP) and Total suspended particulates (TSP) have not been achieved, not to mention the potential change to higher AQO standard, which is currently under review. Clearly, more work would need to done on these pollutants. These pollutants are commonly found in vehicle emissions.

Bridge water crossing tends to have higher dispersion of the pollutants in open air environment requiring reduction of pollutants at source. Also, application of Titanium Oxides, so-called "air-cleaning" agent on the bridge structure could be further considered. TiO_2 degrades nitrogen oxides (NOx) gases and organic compounds in contact with the TiO_2 nano-particles by triggering 'photo-activation' with absorption of ultraviolet (UV) light. A test conducted by EU using similar photo-catalytic material for pavers in Milan, Italy, showed a reduction in concentration of NOx at street level up to 60%. Pilot test for application on pavers has been conducted in EcoPark in Tuen Mun Area 38 and extensive application may be considered should the performance is proven.

While for tunnel, pollutants will be collected and discharged at single or several discharge points through ventilation building in a concentrated manner. Therefore, the locations of ventilation building and the associated deteriorated air quality usually are controversial topics in public consultation of tunnel projects.

Adopting air cleaning system in tunnel ventilation system could be a sustainable solution to the tunnel crossing. Air cleaning system has been developed since late 1980's and proven to be successful in many countries including Japan, Spain, Italy, Norway, Austria and Germany. The system is designed to remove air pollutants (essentially NO2 and Total Suspended Particulates (TSP)) in the emission before discharging to the surrounding. There are two sub-system namely, electrostatic precipitation (ESP) and Denitrification (DeNO2).

ESP system is typically applied in boilers, incinerators, coal-burning plants and other industrial processes to remove dust and particulate matter in air. ESP is proven to be capable of operating in a wide range of temperatures and achieving a high particle collecting efficiency of 80% for removal of Respirable Suspended Particulate (RSP) for both PM10 and PM2.5 of TSP in the examples of aforementioned countries. Figure 1 shows the principle of electrostatic precipitation.

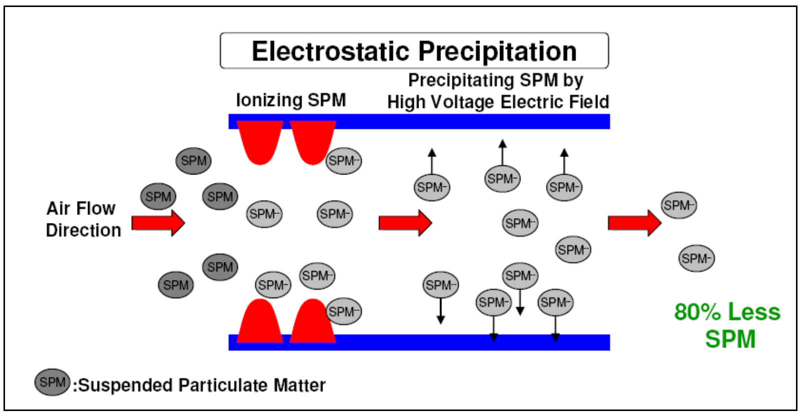

Figure 1 **Principle of Electrostatic Precipitation**

Another system, Denitrification (DeNO2), can be conducted by two ways: *absorption* and *adsorption*. Performance of NO2 removal system is in the range of 80% to 90%. Figure 2 and 3 show the mechanism of No2 removal by absorption and adsorption respectively.

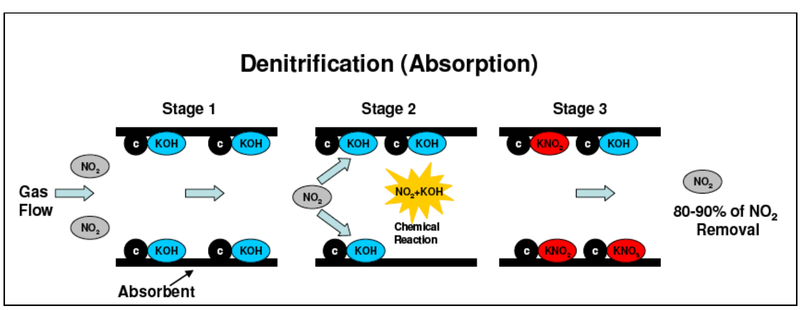

Figure 2 **Mechanism of NO2 Removal by Absorption**

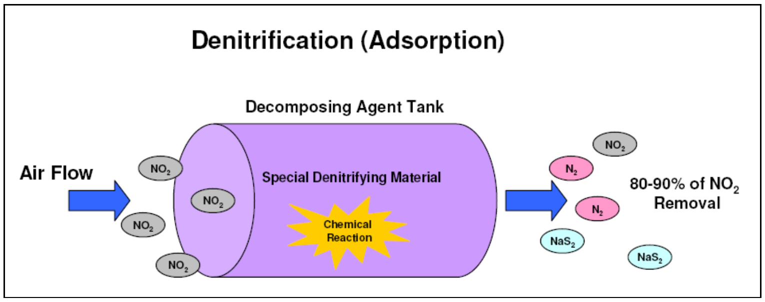

Figure 3 Mechanism of NO2 Removal by Adsorption

These systems can suit typical design of jet fans in longitudinal ventilation, by-pass tunnel design, installation into the ventilation building and application in widened underground ventilation adits.

Other than the improvement in the ambient air quality in the vicinity of ventilation building, the in-tunnel air quality and the airflow could also be improved and beneficial to tunnel users. With the improved air quality, the designed height for discharge and airflow velocity at the ventilation building could also be reduced. This could be realized as economic benefit in terms of reduction in capital cost and economic rate of return, though it will be discounted by the additional equipment cost and long term energy cost for additional jet fans. The improved air quality can mitigate the pollution problem generated from long underwater tunnel where ventilation buildings can only be located at both ends of tunnel with considerable amount of emissions.

Other than the compliance and improvement to the air pollutants currently benchmarked in the Air Quality Objectives, low carbon emission, a major source of green house gas (GHG) leading to climate change, is a new focus to the environmental friendly living and economy.

In 2006, Hong Kong contributes to around 390,039 thousand metric tons of CO2 by burning of fossil fuels only, which is 19.6% higher than the world's per capita average. The energy sector alone contributes around 63% of Hong Kong's carbon emissions. The HKSAR Government has set a target of achieving a reduction in energy intensity of at least 25% by 2030 (with 2005 as the base year). Clearly, the power savings and replacement with other renewable energy will need to be considered.

2.2 Sustainable Construction Materials

The production of Portland cement, an essential constituent of concrete, leads to the release of a significant amount of CO2 and other Green House Gases. Alternative concrete design using cement replacement, fly ash, should be considered as far as possible. Fly ash is a by-product of coal combustion, most commonly as a result of electricity generation.

Another innovation of sustainable material is Ji Zhao Cable-stayed Bridge, Tianjin, currently under detailed design and proposed to use composite glass elements for main structural members. Glass is a recyclable and environmental friendly construction material requiring relatively little re-processing energy compared to initial production. Glass has very high compressive strength (>1000N/m^2) and stiffness and does not suffer from fatigue; however, relatively brittle. The proposed Ji Zhao Bridge has been sensitively designed to ensure all glass elements are working simply at compression under all loading conditions and avoid the possible limit state regime in brittle failure. Figure 4 and 5 show the isometric perspective and the architectural impression of the proposed Ji Zhao Bridge.

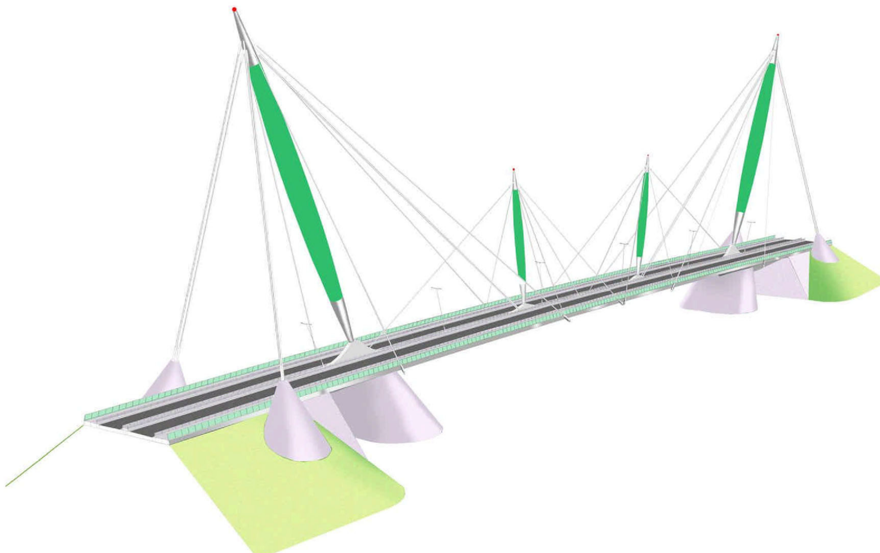

Figure 4 Isometric Perspective of proposed Ji Zhao Bridge

Figure 5 Architectural Impression of Ji Zhao Bridge

The proposed Ji Zhao Bridge is a cable stayed bridge comprising 2 main and 2 secondary glass pylons, arranged in a radial manner to integrate the bridge structure with the townscape. The structural arrangement is designed so as to utilize the high compressive strength, the high corrosion resistance, and no-creep properties of glass material. Therefore, the masts are arranged as far as possible to be designed as pure compression struts with simple structural function.

Pylons are designed to be in cigar-shaped to enhance the buckling resistance. The pylons are in hollow shape to limit the dead load creating an efficient structural member and allow prestressing bars to passes through the interior to ensure the members will stay in compression under all loading conditions. The pylons will be formed by thin layers of glass segments bonded by engineering polymers. Such arrangement could eliminate the notches or holes can avoid stress concentration. Figure 6 indicates the typical section of glass pylon.

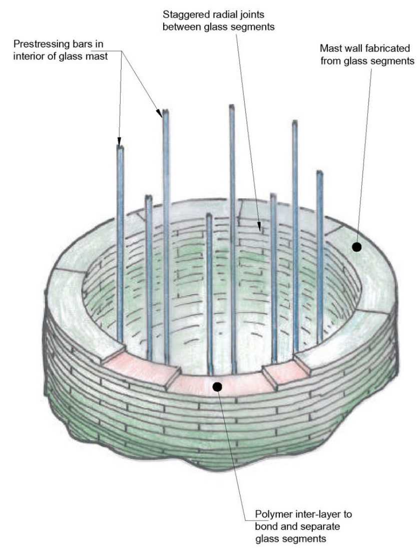

Figure 6 **Typical Section of Glass Pylon**

Further use of recycled glass in the concrete mixing for the abutment and other structures may also be considered. Use of recycled glass as aggregate in concrete may be further considered. Many researches have been conducted and some researches have shown that concrete made with recycled glass aggregates have shown better long term strength and better thermal insulation due to its better thermal properties of the glass aggregates.

2.3 Minimal Dredging and Reclamation

Dredging and reclamation will potentially have territory-wide and permanent impact on the water quality and ecological impact over Hong Kong waters due to transport of toxic sediments via the current. In developing alignment options, the extent of dredging and reclamation will need to be minimized. In particular, the prevailing ruling under the Protection of Harbour Ordinance of HKSAR clarified that, the Victoria Harbour is to be protected and preserved as a special public asset and natural heritage of Hong Kong people, and for that purpose there shall be a presumption against reclamation in the harbour; unless it is rebutted by establishing an overriding public need. The need must be compelling, present, and without any reasonable alternative taking account of the economic, environmental and social cost, time and delay implications of each alternative.

In the recent highways projects which require water crossing tunnels, it was required to demonstrate that the tunnel section involves minimum dredging extent and environmental impacts. In comparing with immersed tube tunnel method, temporary reclamation method is one of the effective methods which can minimize dredging works and adverse impacts to adjacent seawall/marine structure. The temporary reclamation method is suitable for short section of water-crossing tunnel where the traditional cut-and-cover construction method can be applied on the temporary reclaimed land. Temporary reclamation method requires relatively lesser dredging and pose least permanent effect to the environment. The extent of dredging could be significantly reduced to shallow trench through the marine deposit stratum for the base of the temporary vertical seawall. The spoil requiring disposal will also be significantly reduced. The use of temporary block seawall and sand filling and excavation within the confinement can effectively limit the environmental impact of the reclamation. The temporary reclamation will also be removed permanently and has relatively transient environmental impact. Figure 7 indicates the difference in dredging extent between immersed tube tunnel method and temporary reclamation method.

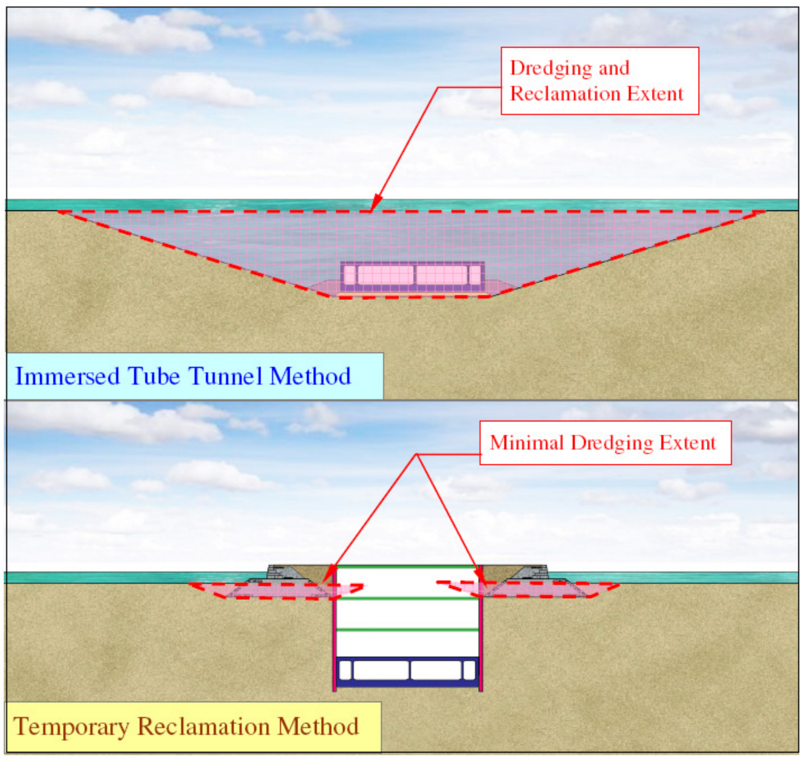

Figure 7 IMT Method and Temporary Reclamation Method

3 CHALLENGES AND OPPORTUNITIES - DESIGN

The design of water crossing bridges and tunnels is becoming a very challenging task to nowadays engineers. To overcome longer and longer length of water crossing design is not only relying on the innovation of engineering design but also the development of advanced construction technology. The longest suspension bridge, the Messina Bridge in Italy with a main span of 3,300m, to the longest dual-three carriageway underwater tunnel, the 8,000m long Yangtse River tunnel in Shanghai, proves that engineers are aggressive and capable to achieve longer and longer water crossing under difficult physical constraints.

3.1 Sustainable Design of Suspension Bridges

In the design of long span suspension bridge, the major consideration is aerodynamic stabilities, such as vortex excitation, galloping, buffeting, stall flutter, divergence and classical flutter. Water crossing suspension bridge can achieve a longer span if the aerodynamic stability can be overcome. In the last few decades, the development of long-span bridge deck design can be summarized to three generations (S. Ho 2007).

The 1st generation bridge deck – stiffened truss, has been used for very long time in history and the United States had used it for long span suspension bridges up to 1287m (Verrazano Narrows) in 1964. The 2nd generation bridge deck – close box type, was widely used in Europe for comparatively short spans cable-stayed bridges since 50's. The close box deck is superior to the stiffened truss (1st generation bridge deck) as close box provides better torsional rigidity; hence enhancing the torsional frequency and more streamlined which results in less drag and more flow separation. Figure 8 illustrates the typical sections of 1st and 2nd generation of bridge deck.

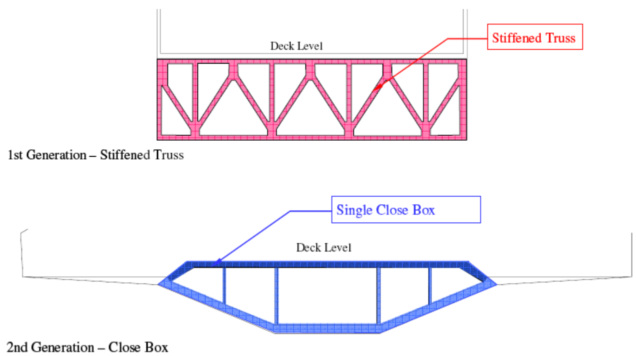

Figure 8 Typical sections of 1st and 2nd generation of bridge deck

The traditional approach in aerodynamic design is that when bridge spans become longer, the deck becomes wider and deeper in order to provide sufficient torsional stiffness. Widening the deck seems more favourable as compared to increasing the depth of bridge as it would create more drag forces. Therefore, for a very long span bridge, deck box may become too wide for a single box and big air gaps between the decks may be required such as the Tsing Ma Bridge. As the deck is getting wider and wider, the 3rd generation bridge deck was developed where the deck could be split into two boxes or multi-box connected by lightweight transverse beams at intervals along the span. In this type of bridge deck, a wider carriageway can be provided where flutter is entirely eliminated without the use of torsion box. In aesthetic point of view, the 3rd generation bridge deck can also provide a slimmer deck with streamlined design which not only enhance the appearance of the bridge but also minimize the visual impact to public. In Italy, there is a suspension bridge of a main span of 3,300m crossing the Messina Strait where the final design was completed by adopting the 3rd generation bridge deck. Figure 9 illustrates the typical section of 3rd generation bridge deck.

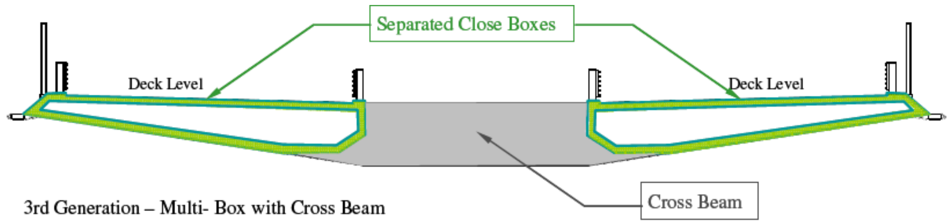

Figure 9 Typical section of 3rd generation bridge deck

The next generation of bridge design would further enhance the simulation and modeling of aerodynamic performance which would give better understanding in determining the shape and span of future long span bridge. Materials development for both cable and deck will bring lighter materials with higher strength which can allow longer and longer span bridge becomes possible. Glass pylons and Carbon Fiber Composite cables are examples for material development. With more understanding in aerodynamic performance and high strength materials, the suspension bridge in the future is able to achieve longer and longer span.

3.2 Sustainable Design of Water Crossing Tunnel

In the design of tunnel crossings, length is an important factor. Long underwater tunnel will make the tunnel ventilation and recues operation difficult. These may require additional ancillary facilities such as artificial island and/or ventilation/recue tunnels.

The geology and tunnel alignment also play important parts in selection of construction method. Soft ground conditions impose extra constraints to the tunnel construction. Shallow cover to tunnel limits the use of bored tunnel or Tunnel Boring Machine (TBM) construction method as these methods require adequate ground cover to ensure ground stability.

With the advancement of technology, solutions are now available to overcome these challenges. For instance, application of engineering techniques in construction of the tunnel crossing over Shanghai Yangtze River (上海長江隧道) connecting the Pudong (浦東) and Changxing Island (長興島) has successfully overcome these challenges. The tunnel is situated on soft ground composed of clayey materials. TBM using large slurry shield method was deployed to cater the soft ground condition. Sophisticated ground movement and ground water monitoring and control scheme were also formulated and implemented to ensure the settlement are within limits and retain an historic seawall, buildings and highways above the tunnel. The construction also deployed a temporary stockpile and grouting to provide sufficient ground cover and strength during construction to ensure stability. These engineering innovations successfully eliminate the need to demolish the seawall and highways and minimize the social impact arising from resumption of the residential housings.

4 CHALLENGES AND OPPORTUNITIES - SOCIAL

4.1 Enjoyment of Waterfront

There has been criticism that the existing bridge structures aligning along the shoreline are in fact acting as massive barriers inhabiting the public accessing the waterfront areas as well as the open sea view. In addition, there has been an outcry for public's enjoyment to waterfront areas. To overcome this challenge, it requires holistic planning for the water crossing and improvement to the adjacent areas. On the other hand, opportunity exists to align and design the bridge to enhance the view and connectivity with the promenade by incorporating a pedestrian walkway and/or bike lane to bridge crossing. Brooklyn Bridge is a solid example. By enhancing the leisure value of the bridge, it will have positive socio-cultural benefit.

Chi Feng Bridge, Tianjin is also a good example of holistic urban planning and bridge design by incorporating shopping centre and viewing platform at the bridge to provide services and enhance experience to tourists and sightseers while maximizing the structural performance.

4.2 Sense of Place

Bridges are most commonly being criticized to have significant visual impact usually due to the bulky structure in an open sea view and damage to the natural shoreline. Mitigation by greening will need to be maximized on bridges. It is also recognized the potential for a bridge to enhance the townscape and being a landmark should it be suitably designed. Bridges like Tower Bridge in London, Brooklyn Bridge in New York, Golden Gate Bridge in San Francisco and Harbour Bridge in Sydney are well recognized tourist spots and successfully create a sense of place of these cosmopolitan cities.

The appearance of the bridge crossing should not only be aesthetically pleasing, but also need to promote the uniqueness of a city or create a sense of place through its interaction with the surrounding townscape. Chi Feng Bridge, Tianjin is a recent successful example by adopting this principle to produce a people-oriented design. Chi Feng Bridge of 175m will span over the Haihe River carrying dual 3-lane carriageway with segregation of motor, bicycle and pedestrian traffic. It is featured with a 71m high main support tower resembling the mast of traditional junks.

The bridge deck is curved that the bridge tower has to be located outside the deck envelope. Junk bow feature incorporating a viewing platform and shopping arcade is therefore designed to provide counterweight, instead of tensile piles, which are not favourable in China. There are 10 pairs of stay cables resembling ropes attached to the mast of the junk.

Locating a sailing junk like viewing platform and shopping arcade with a perfect view of the city and waterfront, which also act as a counter-weight to the bridge structure for enhanced structural performance, has produced an outstanding and sustainable design for water crossing. It is expected that the bridge will be one of the tourist spots of Tianjin with the enhanced view to the waterfront.

Figure 4.7 Architectural Impression of Chi Feng Bridge

Signature bridges will not only provide closer linkage to separated communities and traffic improvement, but also can inspire public's sense of ownership and civic pride for the benefit of the society as a whole.

In case of tunnel, there may not be a "signature" effect to the city compared to bridge, but there still exists opportunity to maximise and enhance the quality leisure space for public enjoyment. Pedestrianed landscape decks over depressed road near to portals will have positive effect on the social life. In a congested city like Hong Kong, ventilation buildings may unavoidably be located near to residential areas. However, the design of ventilation buildings can incorporate greening measures, such as landscaping deck, and the provision of recreational facilities which could definitely create more leisure space for public enjoyment and enhance the vibrancy of environment.

5 CHALLENGES AND OPPORTUNITIES – ECONOMIC

In recent years, the closer ties between Hong Kong and the nearby Pearl River Delta Regions necessitate more and more strategic cross-boundary transport links with between Hong Kong and the Mainland China including the Hong Kong Shenzhen

Western Corridor and Hong Kong-Zhuhai-Macau Bridge. These are essentially long span bridges and impose significant burden on tax payers and the Government. Financial viability and economic internal rate of return of these projects are always subject to questions in the deliberation of funding approval for these projects.

5.1 Life Cycle Costing Design

In the design of a sustainable water crossing, life cycle costing approach has to be considered. Balance need to be strike between the initial capital cost and recurrent cost. For instance, Application of LED light in tunnel lighting, which forms an important part of recurrent cost in tunnel operation, is one of the examples to achieve energy efficiency of tunnel.

The modern technology of LED lighting can achieve high energy efficiency, currently ranging from 0.01 to 25 lm/W, and long service life (35,000 to 50,000 hours). The LED lamps are more environmental friendly light compared to traditional ones as these lamps are lead-free and mercury-free. Though these lamps involve a higher per-unit capital cost at present, savings from its higher energy efficiency and longer lifespan offer a balance to the initial cost. Furthermore, the technology is currently under rapid development and expansion in applications, with its increasing popularity and advancement in the technology, the initial cost would likely to decrease. The possibility to adopt such technology will need to be reviewed from time to time. Other possible use of renewable energy to support tunnel lighting by wind turbine or photovoltaic cells installed on bridge deck may be considered. In particular, technology of solar panel has been developing rapidly making installation of solar panels on noise barriers to support irrigation system feasible. This technology could be further applied in water crossing where large exposed surface is available. These could be part of the electricity support to the TCSS devices and lightings on the bridge forming a self contained system.

Other than the recurrent energy cost, the maintenance cost is also a major issue. For the long span bridges in Hong Kong such as Tsing Ma Bridge, Wind and Structural Health Monitoring System (WASHMS) are implemented. The system includes an array of monitoring devices including GPS receivers to provide real time measurement to the 3D motion of the bridge. Finite element model is also set up to identify the global dynamic characteristics of the bridge. These findings are used to form an advance evaluation model for predicting bridge responses under extreme events, such as severe typhoon and earthquake as well as for fatigue assessment. The findings are important to the strategic planning for predictive and condition-based maintenance further to the conventional preventive and corrective maintenance. Also, as discussed earlier, understanding of the aerodynamic behaviour of long span bridge will be helpful to the development of cost effective bridge deck design (ie. The 4th generation bridge deck).

6 CONCLUSION

The paper has briefly identified the challenges and opportunities in water crossings developments with focuses on the environmental and social expectations. There are challenges to achieve cleaner air, using more sustainable construction materials and achieve minimal dredging and reclamation in protection of water quality and marine life of our Victoria Harbour. Engineering solutions such as air cleaning system, development of high strength construction materials in complementary with more sophisticated structural analysis modeling and more advanced construction technology are available to address these challenges. It is also recognized the opportunities lie in holistic planning and creating a sense of place in bridge crossings in enhancing the townscape and public enjoyment of leisure areas. The last but not the least is to adopt a life cycle costing approach in the design of water crossings to improve the cost effectiveness of the crossings.

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