



# ESFOBB BRIDGE MAINTENANCE PEER REVIEW GROUP

Review Report on Inspection and Maintenance

## ABSTRACT

Peer Review of Proposed Inspection and Maintenance of the new East Span of the San Francisco-Oakland Bay Bridge by an expert group from International Cable Supported Bridge Operators Association

ICSBOA

# Introduction

This report is the result of the peer review on the planned maintenance program for the East San Francisco Oakland Bay Bridge (ESFOBB) carried out by the ICSBOA<sup>1</sup> expert group on 13.-14. October 2014 as requested by BATA<sup>2</sup> on June 30, 2014 by Andrew Fremier, Deputy Executive Director, BATA.

The goal as established by BATA was to review the comprehensiveness of the proposed inspection and maintenance program, and to identify potential best practices or deficiencies in the proposed maintenance program. Specific concerns include corrosion, painting, expansion and seismic joints, maintenance of orthotropic bridge decks, concrete post-tensioning and dehumidification.

The ICSBOA peer review group included the following experts:

- Ewa Bauer, Chief Engineer, Golden Gate Bridge (Participated only in meetings and site visit on 13<sup>th</sup> and 14<sup>th</sup> October)
- Chris Saladino, Facility Engineer, Bronx-Whitestone Bridge, MTA Bridge and Tunnels (Contributing)
- Jim Gibson, Highway Maintenance Manager, Tsing Ma Bridge, Hong Kong (Contributing)
- Barry Colford, Chief Engineer and Bridge Master, Forth Road Bridge, Scotland (Lead Author)
- Leif J. Vincentsen, Managing Director M.Sc., Sund & Bælt Partner A/S, Denmark (Lead Author)

In appendix 1 there is a reference to some of the bridges with which the expert group has experience on and which has informed the group's recommendations.

During the meetings and the site visit on 13th and 14th October 2014, the Review Group met and discussed maintenance topics with, amongst others, the following representatives from BATA, Caltrans, FHWA and the associated consultants:

- Andrew Fremier BATA (Deputy Executive Director)
- Peter Lee, BATA (Principal)
- Rosalynn Chongchaikit, BATA (Associate)
- Tony Anziano, Caltrans (Toll Bridge Program Manager)
- Ken Brown, Caltrans /SMI (Structure Maintenance and Investigations Toll Br)
- Ade Akinsanya, Caltrans (Supervising Bridge Engineer)
- Greg A. Kolle, Federal Highway Administration
- Mazen Wahbeh, Alta Vista (CT consultant material inspection)
- Marwan Nader, TYLin International (Consultant Designer)
- Sajid Abbas, TYLin International (Consultant designer)
- Ali H. Ahbas, NorCal Structural
- Dan McElhinney (Chief Deputy District Director, District 4)
- Ken Terpstra (SFOBB Project Manager)

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<sup>1</sup> ICSBOA is the International Cable Supported Bridge Operators Association

<sup>2</sup> BATA is the Bay Area Toll Authority

During the site visit the Review Group had the opportunity to visit the following areas of the bridge:

- The Skyway - interior of steel box girder, seismic joints with pipe beam connection, interior of concrete box girder, anchorage of main cable
- The SAS (Self Anchored Suspension Bridge) – Piers and girders from water level, pylon foundation and pylon tower at lower platform.

Various topics were discussed during the meetings and these discussions provided detailed information on the structural components as well as organizational structures and each agency's responsibility. Included in the discussions were descriptions of the various elements of the bridge, including but not limited to roadway joints, hinge pipe beams, orthotropic deck segments, concrete segmental sections, shear keys, bearings, suspender ropes, main cable and dehumidification systems.

Also mentioned during the meeting was the need for a 10-20 year rolling Major Maintenance Program to address cyclical efforts including joint cleaning/joint seal replacements, bridge painting, dehumidification system maintenance and monitoring, traveller maintenance and overlay replacement/repair.

Before and during the site visit a number of documents were made available for the Review Group as background documentation. More documents were made available for the Review Group using a Drop Box.

The Review Group did not study all these documents in detail as several relate to construction matters and problems encountered during construction, which were considered outside the brief of the Review Group.

Plans for inspection and maintenance in these very specific areas, however, were examined closely, especially those concerning components or elements which are unique to the ESFOBB. The Review Group stresses that the maintenance or warranty period of the ESFOBB and the obligations that the Contractor must fulfil during this period need to be clearly identified. If these works have been carried out, the records and documentation of any remedial works must be recovered and recorded. If there are elements or components with varying warranty periods then these need to be established.

The Inspection and Maintenance Manuals for the Skyway Bridge and for the SAS Bridge are commented in this report in section 3.9 and in appendix 2.

# Executive Summary

## Summary of Observations

- During the review meetings in Oakland, the Review Group was met by very open and professional representatives from the client, Caltrans and the agencies' consultants.
- There is a significant body of experience with the inspection, operation and maintenance of bridges within the Caltrans organisation.
- Caltrans staff with experience in the inspection, maintenance and operation of existing bridges was involved during all phases of the design and construction of these bridges, which is of great benefit to the future maintenance of the bridges.
- Major defects from the construction phase (regarding rods and bolts, welding quality and other topics) have been addressed separately by other expert groups. This Peer Review Group presumes the necessary inspection, monitoring, testing and maintenance plans on these issues have been defined and recorded within the as-built documents.
- Inspection and Maintenance Manuals are nearly finalised, and these manuals appear to cover all important items that would be expected for these unique bridge structures. Comments on two of the three manuals are included in this report.
- A durability strategy has been defined, and is in place for the critical structures in the splash zone of the bridge. This includes extended concrete cover and epoxy coating of reinforcement, and is followed-up by sealing of cracks from concrete shrinkage during construction. A sacrificial thickness of 20 mm has been allowed for in the design of the steel piles.
- Baseline Inspections have been performed and documented, and will be the basis for the forthcoming inspections. The Review Group has not seen these Baseline Inspections but has been informed that the results are satisfactory.
- The traffic at the ESFOBB counts up to 280,000 vehicles per day. Such a heavy traffic is a challenge for the planning and execution of the inspection and maintenance activities to be performed. Because the percentage of heavily loaded trucks within the traffic mix is low, there is a lower risk of fatigue causing problems with the orthotropic deck. However, the deck plate thickness is noted as being 14 mm which is not ideal when considering the long term robustness of the deck.
- The environmental conditions for the bridge show relatively small variations in temperatures during the year (from 10° to 27°C) and with low wind speeds (average between 7-14 mph and during winter storms up to 50-75 mph).
- Facilities and equipment are in place from existing maintenance and operation of the old bridges, and a new facility is being built on the Oakland landing specifically dedicated to the Bay Bridge Maintenance. The O&M centre is housed in the Caltrans District 4 Headquarters in Oakland.

## Major Recommendations:

- It is acknowledged that there is often a division between those tasked to carry out inspection and routine maintenance works, and staff involved in the engineering side of large bridge maintenance (efforts which include major retrofitting projects and structural assessments). In addition, there is often conflict with the operational aspects of running a large and high-profile facility such as these bridges, where disruption to traffic can cause serious reputational issues for the managing authority. Experience has shown that the most efficient method of organizing the management of a large cable supported structure is if all the main elements – inspection, routine maintenance, engineering and operation – are overseen by one individual, preferably a professional civil or structural engineer with relevant experience. It is recommended that the Authority consider such an appointment.
- There is no access provision to enable inspection and minor maintenance work on the main cable. This should be addressed. There is a similar issue with the suspenders. Given the unique geometry of the suspension system and the fact that it crosses over the carriageways, providing this access while also minimizing the risk to bridge users to an acceptable level will be challenging. A plan should be developed and put in place for the inspection and maintenance of the suspension system.
- It is recommended that the case for retrofitting a Structural Health Monitoring (SHM) system be considered.
- The structural integrity of the deck relies on the post tensioning system, which consists of high tensile steel tendons within grouted ducts located in the deck boxes. There is no access to the tendons and no means of carrying out future inspections. This is a standard way of utilizing post tensioning. But it has caused issues within other bridges where corrosion of tendons has gone unnoticed and failures have occurred. A recent case at Hammersmith Viaduct in London, UK resulted in the retrofitting of an acoustic monitoring system to the post tensioning to pick up wire breaks within the strands. Consideration should be given to the merits of retrofitting an acoustic monitoring system which would form part of a SHM system on the post-tensioning within the deck.
- Recent work has shown that the conventional methods of protecting main cables of suspension bridges using paint systems alone are not effective. In order to prevent future corrosion and deterioration of the main cable of the SAS, it is recommended that the retrofitting of a dehumidification system to the main cable of the SAS be considered and, unless there are overwhelming difficulties that prevent such a system from being fitted, it should be installed as soon as possible.
- It is becoming more common for owners and operators of large cable supported bridges to utilize risk-based inspection frequencies. An assessment of the criticality, vulnerability and current condition of each bridge component (or group of components) is carried out to determine the frequency of inspection based on the risk of failure. This approach not only reduces the risk of failure but helps optimize resource management. It is recommended that such a system of risk-based inspection is implemented on these bridges.
- It is recommended that a program is developed to manage the maintenance needs of the infrastructure to cover a period of 20 years, which would establish a platform for justifying

yearly maintenance funding needs. However, it is also important to have sufficient funding and procedures to ensure that acute remedial needs can be met.

- It is the experience from many large bridges that repair and remedial work carried out during construction often has a lower quality and service life. It is therefore vital to have all information on such repairs during construction phases present in order to prepare more intensive inspection plans in these areas.
- It is recommended that as-built drawings be available in an electronic format at the bridge site for easy access during inspections; and that these drawings and other documents are kept updated based on inspection regime and all maintenance activities. It is essential that procedures and instructions for activities either performed in-house or by contractors/consultants are updated yearly where necessary. It is of great importance that a quality control system for this is established from the outset.
- Procedures for replacement of important parts of the bridge that are expected to have a shorter service life than the bridge itself (pavement, expansion joints, suspenders, etc.) are recommended to be established early, as long as the relevant suppliers are still available.
- Based on experience from a truck fire close to main cable and suspenders at the Little Belt bridge in Denmark in 2013 it is recommended to perform a risk evaluation of a possible fire close to the main cable and suspenders at ESFOBB due to the special geometry at this bridge.

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the bridges, including the projects mandated by Regional Measure 1 and the Toll Bridge Seismic Retrofit Program. BATA has joint oversight of the toll bridge seismic construction program, including the ESFOBB, with Caltrans and the California Transportation Commission.

## **1.2. Description of Operations and Maintenance Staffing**

**Investigations and Inspection** – Caltrans Structure Maintenance and Investigations is responsible for managing the department's transportation structures. This includes performing bridge inspections in accordance with federal regulations on over 12,000 state highway bridges and approximately 12,200 bridges owned by local government agencies. Caltrans Structure Maintenance and Investigations makes repair recommendations, determines the safe load capacity of all bridges, reviews and approves encroachment permits and air space lease proposals involving structures, delivers plans, specifications and estimates for bridge maintenance projects, and coordinates the protective coating work on over 800 state highway steel bridges.

Given the importance and history of the ESFOBB and six other toll bridges, the Office of Structure Investigation - Toll Bridges is located in Oakland and is responsible for the investigation, evaluation, work recommendations, repair design and documentation of all major toll crossings (except the Golden Gate Bridge) and toll plaza bridges in the Bay Area. The unit has approximately 20 dedicated licensed professional engineers and technicians. Typically one engineer is assigned to each toll bridge, serving as a single focal point with flexibility for engineers to support and work on other toll bridges as needed.

**Maintenance** – Caltrans Division of Maintenance maintains the ESFOBB along with the entire state highway network. District 4 maintenance staff in Oakland provides general roadway, electrical, mechanical, landscape maintenance, maintenance and bridge engineering, tow services and painting. The ESFOBB has maintenance facilities and equipment located around the east and west spans. There are paint facilities both in Oakland and San Francisco. A new maintenance complex for paint, equipment maintenance, and storage recently was completed just off the span in Oakland.

**Operations** - The Caltrans Division of Traffic Operations staff monitors traffic operations on the bridge and on the entire state highway network from the Transportation Management Centre in Oakland.

## **1.3. Comments from Review Group:**

It is of prime importance when establishing an organization to operate and maintain a new bridge infrastructure that the full scope of all the work involved is determined and that a risk register is established to identify the most critical tasks. This will ensure the most effective use of staffing resources and will assist in setting up the organization.

### **Organization and Oversight**

It is acknowledged that there is often a division between those tasked to carry out inspection and routine maintenance works, and staff involved in the engineering side of large bridge maintenance (which includes major retrofitting projects and structural assessments). In addition, there is often

conflict with the operational aspects of running a large and high profile facility, where disruption to traffic can cause serious reputational issues for the managing authority. Experience has shown that the most efficient method of organizing the management of a large cable supported structure is if all the main elements making up the management requirements – inspection, routine maintenance, engineering and operation – are overseen by a single individual, preferably a professional civil or structural engineer with relevant experience.

A secondary level of manager or supervisor can be appointed to supervise each of the three elements. However, to ensure efficiency and minimize technical and financial risk, one controlling mind with budgetary responsibility should manage all three elements. This structure should minimize the risk of unforeseen traffic disruption, misinformation being issued to users and duplication of efforts with resulting financial cost. The maintenance activities can be divided into civil maintenance and electrical and mechanical (E&M) maintenance.

The civil maintenance team will take care of the inspection, maintenance, repair and upgrade of civil structures, drainage, signage, guardrails and buildings, while the E&M team will be responsible for inspection, servicing, repair and upgrade of electrical, mechanical, and electronic equipment.

A technical control room or a help desk function is often necessary to centralize service and repair requests. The above mentioned Operation Center and the Technical Control Room should be in close contact in order to coordinate activities and make priorities regarding influence on traffic.

It is normally necessary for the organizations responsible for Operation and Maintenance to have easy access to IT-support, a public information officer, and legal and HR staff. In addition, staff functions dealing with environmental matters, health and safety, QA/QC and audit topics also will be required.

In Appendix 2 a short description of the O&M-organizations for some other bridges is included.

In appendix 4 examples on numbers of persons involved in service, inspection and maintenance of other bridges are included.

## **2. Design Review**

The design of the SAS Bridge is unique in many ways, and the inspection and maintenance regime should recognize the uniqueness of the design of the suspended structure.

The geometry of the cable and suspenders makes access for both inspection and maintenance, without causing disruption or increasing risk to users, very challenging.

Anchoring the cable to the deck is very innovative, but results in imparting extremely high compressive forces into the deck. Special care has to be taken at these highly stressed elements. The removal of bearings in the approach spans is recognized as contributing to a reduction in future maintenance. However, this means that the piers must flex to accommodate longitudinal movement and are susceptible to cracking. The mix design and the quality of the concrete; and the cover and compaction achieved on site will be crucial to achieving the design life of the concrete in the piers in this relatively aggressive environment. It is important to ascertain whether any changes were made to the design or specification during construction of the piers. The issue of potential excessive cracking should be noted for the future.

The issue of the A354 Grade High Strength Holding Down Rods is of obvious concern. Although remedial actions have been taken to try to prevent a recurrence of the rod failures, some doubt over their long term service life remains. In addition, it is understood there were initial concerns over the quality of welding in some of the deck boxes. If a risk-based inspection regime is adopted, the rods and affected weld areas may be identified as being more vulnerable or critical than other elements, and thus inspected more frequently.

## **2.1. Additional Design Elements for Consideration**

### **a. Additional Access**

Access is essential both for inspection and to carry out maintenance on all parts of the bridge, and should have been considered at the design stage. An underdeck traveller has been provided to the soffit of the deck and should ensure good access for inspection and minor maintenance, provided in the traveller itself is maintained.

The traveller is unlikely to provide the containment necessary for a major or complete repainting of the structure. However, this is usual with this form of access.

Careful consideration should be given to the operation, inspection and maintenance of the travellers themselves. That can be quite onerous, especially if there is complex electrical and mechanical equipment involved.

The protection from deterioration by the environment for this equipment should be carefully considered. Experience has shown that deterioration of this type of equipment can be quite rapid if it is not used regularly. A schedule for the use of the system should be maintained, thus ensuring its availability when necessary. Adequate training in the use of any access equipment is essential and must be carried out on a regular basis. Helpful advice on the use of travellers is given in the Institution of Structural Engineers' publication "The Operation and Maintenance of Bridge Access Gantries and Runway Beams (Second Edition, October 2007)".

In general, all long span bridges usually have various access facilities incorporated into their design and take the form of:

- Permanent underdeck gantries for bridge soffit inspection
- Permanent/temporary cradles/suspended working platforms in various configuration such as curved and straight units
- Gondolas for main cables, suspenders and cable stays
- Access ladders and platforms distributed throughout main structures for general access
- Internal lifts in tower legs
- Other – mobile hydraulic hoist platforms are used to provide access to above or below deck structures

There are always going to be shortcomings with some of the provided access. Enhancement, modification and/or addition of new means of access will need to be designed and procured. This could take the form of steel scaffolds for temporary use, purpose-designed platforms, or the procurement of

bridge inspection equipment such as cradles, hydraulic platforms or bridge inspection vehicles for permanent access. The basic design philosophy should be to ensure that the bridge inspector can get to most places by the simplest methods. One example would be if there is a high level area, then a high level walkway would allow easy access to view the initial structural condition or act as a starting point for a scaffold platform. A second could be to provide permanent platforms to those areas where access is required on a regular basis due to the criticality of the element (e.g. main cable wires in the anchorage) or for maintenance needs (such as the underside of wide expansion joints). It is always much easier to incorporate access into the structure during the design stage.

There is no access provision to enable inspection and minor maintenance work on the main cable to be carried out. It does not appear to have been provided and this should be addressed. There is a similar issue with the suspenders. However, given the unique geometry of the suspension system and the fact that it crosses over the carriageways, providing this access while minimizing the risk to bridge users to an acceptable level will be challenging. A plan should be developed and in place for the inspection, maintenance and painting of the suspension system. It should be noted that minor works may include work on the handstrand cables; resealing cable bands and checking cable band bolt tensions. Inspection and maintenance carriages for main cables on other international bridges have been installed after opening of the bridges based on functional specifications.

Such specifications (eg. Storebælt Link) typically contain requirements on:

- Ease of erection and operation
- Safety requirements and approval procedures
- No damages to cable or adjacent structures and equipment
- Robustness and durability
- Access to all critical areas of cable, cable clamps, hangers, etc.
- Functionality for inspection, repair of surface treatment on cable and cable-clamps and for re-tensioning of bolts at clamps
- Functionality ensuring always horizontal floors
- Running on wheels on main cable with limited contact pressure
- Pulling wire system allowing at least 100m before shift of fix-point.
- Load capacity and operation speed
- Equipment in the carriage and spare parts.
- Commissioning and instructions
- Operation and Maintenance Manual for the carriage.

Proper storage for platforms and carriages is important in order to keep them in good condition for a long service life and low maintenance costs. It is equally important that the equipment be properly tested before use and operated by trained personnel.

Example from Tsing Ma Bridge:

On Tsing Ma Bridge, the underdeck gantries extend only part way up the underside of the external fairing. So a special purpose hydraulic platform is used for paint repairs to the splitter rail at the apex of the fairing. Despite the machine being capable of setting itself up within a single closed lane, progress is still rather slow.



Figure 2 Bridge Inspection Vehicle

Currently, there is no land access, to the Tsing Yi Tower base area of Tsing Ma Bridge. Access is available only by water or by using the tower lift. Clients/owners and designers should look at the long-term access requirements for certain critical elements of the structures at design stage, to ensure that access is not restricted by local conditions.

#### **b. Structural Health Monitoring**

Structural Health Monitoring (SHM) of cable supported bridges is becoming increasingly common. A number of recently constructed bridges as well as those currently under construction have extensive SHM systems fitted. These systems include GPS sensors, corrosion sensors, accelerometers, strain gauges and anemometers. Apart from the monitoring of the dehumidification system within the deck boxes, no other SHM appears to have been installed on the ESFOBB and it is recommended that the case for retrofitting a SHM system at least be considered.

With the enormous developments in information technology, the installation of sophisticated SHM systems has increased in general on large bridges. In each case, it is important to define the objectives for application is important for the specific bridge. Important questions that need to be addressed include: is the system installed for design verification; trouble shooting; user safety or maintenance planning? Economic considerations must be taken into account as well, covering both direct construction costs and indirect operational costs of the SHM system. It is also important to consider how a SHM system can be integrated with the overall Bridge Management and Maintenance System.

On large bridges, 24/7 operators monitor the SHM system in real time and are able to take immediate actions based on the warnings and alarms, especially those influencing the traffic on the bridge. Regarding maintenance planning, SHM systems can provide information on degradation rates of material and wear inclusive accumulated movements of mechanical installations such as bearings, hydraulic buffers or dampers and expansion joints, as well as the fatigue levels of critical structures. A bridge rating system is often necessary to include as a basis for prioritisation, planning and cost evaluation of inspection and maintenance, and to initiate of actions based on proactive risk evaluations.

A comprehensive Structural Health Monitoring System is being installed during construction of the new Queensferry Crossing, a 2.7-km long, three-tower cable stayed bridge being built across the Firth of Forth in Scotland. The purpose of the system is to monitor performance, give advanced warning of structural problems, and allow the planning and programming of a targeted inspection. It comprises thousands of sensors which will monitor, archive and process environmental conditions, bridge loads and the structural response to these loads. It is designed to allow the diagnosis of structural problems and a prognosis of the future service life of the bridge. The system includes wind and weather sensors, temperature sensors, corrosion sensors, dynamic weigh-in-motion sensors, accelerometers, global positioning receivers, tilt meters, displacement transducers and strain gauges.

The sensors are to be positioned to ensure that the system will monitor, archive and process environmental conditions, bridge loads and the structural response to these loads and allow the diagnosis of structural problems and a prognosis of the future service life of the bridge.

The operation and maintenance of both the new Queensferry Crossing and the existing Forth Road Bridge will be carried out from a bridge control room, adjacent to the existing bridge. This control room is being established to operate both bridges. In addition, the security systems, CCTV coverage, System Control and Data Acquisition (SCADA), fire detection and alarm systems, and architectural lighting control also will be operated from this control room.

Whether SHM monitoring data is collated by the owner or by a third party, it is important that the data be made available to the operator. The operator at Tsing Ma Bridge is responsible for maintaining the SHM system, but is rarely issued the data obtained through the SHM system and is therefore unaware of any detected anomalies. This type of arrangement is clearly unsuitable and should be avoided.

The expected service life of a SHM system is likely to be no more than 15 years. There are examples of older systems, such as at Tsing Ma where the current system is now over 17 years old and parts of it will be due for replacement in the next few years. One issue that is often encountered with older systems is that certain electronic parts become unavailable or are no longer manufactured.

Experience shows that an additional issue with any form of sensor is that there is a disconnect between the robustness and life span claimed by the manufacturer or supplier and the actual reliability and life cycle when the sensor is installed in the usually aggressive environment found on big bridges.

Owners have reported significant issues with sensors misreading or being damaged. Unfortunately, as sensors often are located in difficult areas to access, trouble shooting and fault discovery can be both time consuming and expensive.

On the next page you will find examples of content of Structural Health Monitoring Systems for bridges.

<b>STRUCTURAL MONITORING SYSTEMS</b>	<b>Storebælt Road link</b>	<b>Forth Road bridge/ Queensferry Crossing</b>
Corrosion monitoring	X	X
Cathodic protection	X	X
Pore water- pressure under anchor blocks	(X)	
Inclination of piers and anchor blocks	X	X
Position of bearings	X	X
Displacement of superstructure	X	X
Movements of expansion joints	X	x
Fatigue in orthotropic steel deck	(X)	X
Position of hydraulic buffers	X	
Tuned mass dampers	X	
Accelerometers on hangers	(X)	
Acoustic Monitoring		X
Dehumidification Monitoring	X	X

(X) Active during campaign periods

Figure 3 Examples on Structural Health Monitoring Systems

Issues with fitting SHM systems to cable supported bridges have included bridge owners receiving a surfeit of data that is difficult to process and store, and a questionable need for all this data. The need to have 24-hour or even full working day monitoring is doubtful, and the use of an ‘alarm system’ based on threshold levels output from the system (which could be monitored by non-engineering staff) would be a more cost effective approach. A protocol could be put in place to inform engineering staff of breaches of thresholds or unusual events. Work on existing cable supported and long span bridges has shown that the most important part of a SHM system may be to evaluate movement and strain with transient loads over time in order to assist in a future assessment of the bridge when loads or other parameters are changed.

### c. Deck Post Tensioning System

The structural integrity of the deck relies on the post tensioning system, which consists of high tensile steel tendons within grouted ducts located in the deck boxes. There is no access to the tendons and no means of carrying out future inspections. This is a standard way of utilizing post tensioning, but one that

has caused issues within other bridges where corrosion of tendons has gone unnoticed and failures have occurred. A recent case at Hammersmith Viaduct in London, UK resulted in the retrofitting of an acoustic monitoring system to the post tensioning to pick up wire breaks within the strands. Consideration should be given to the merits of retrofitting an acoustic monitoring system, which would form part of a SHM system on the post tensioning within the deck.

#### **d. Main Cable Dehumidification**

Dehumidification systems are installed at ESFOBB at the tower base, at the anchorage and at the saddles, and will be connected to a SCADA system. No dehumidification system is installed at main cable.

There have been significant issues with the deterioration of the main cables of suspension bridges throughout the world over the past 20 to 25 years. It is becoming clear that the traditional method of protecting the galvanized wires which make up the cables — by applying red lead or zinc paste, then wrapping circumferentially with round or s-shaped wire and finally painting the external surface of the wrapping wire — has not been effective on large numbers of these bridges around the world. Cracks in wires and wire breaks have been found within the cables of a significant number of suspension bridges. It would appear that there is now serious doubt on whether the traditional method of painting to provide protection to the main cables of these bridges is sufficient to provide a service life similar to the full design service life of the bridge.

Efforts have been made within the industry to try to find an alternative method of providing protection to the main cables of suspension bridges. Two methods have been used. One is oiling the cable which involves opening up the cables and pouring oil into the voids to provide protection. This method has been used on only a relatively small number of bridges in the USA, and little research has been done on the long-term effectiveness of this method. The cost and potential disruption to users caused by oiling also can be significant, as the work involves opening up the cable over a significant part of its length.

The other method of preventing deterioration is by installing a dehumidification system to blow dry air under a low pressure into the voids within the cable in order to keep the relative humidity below the level at which corrosion can occur.

Dehumidification systems have now been fitted to the cables of a number of existing suspension bridges (among many others Storebælt Bridge in 2014-2015) and now appear to be being fitted to almost all new suspension bridges. (Hardanger in Norway; Yavuz Sultan Selim and Izmit in Turkey and the Yingwuzhou Bridge, Wuhan, China).

In Appendix 3 you will find an overview of many of the big cable supported bridges that have implemented cable dehumidification systems.

The effectiveness of dehumidification in preventing further deterioration in main cables that have already suffered corrosion wire cracks and wire breaks is still to be determined due to the relatively recent adoption of the technique. However, evidence is now beginning to show that the deterioration and loss of strength of main cables on existing bridges that have been dehumidified is significantly

reduced or even halted. There is little doubt that the greatest benefit and lowest cost of installing a dehumidification system on the main cables of a suspension bridge will be gained if the system is fitted during construction of the bridge, and prior to any significant deterioration occurring.

It is understood that the fitting of a dehumidification system was considered during design for the SAS main cable, but at that time the concept was felt to be as yet untried.

Taking all of this into consideration, it is recommended that the retrofitting of a dehumidification system to the main cable of the SAS should be considered and, unless there are overwhelming difficulties that would prevent a system being fitted, it should be installed as soon as possible.

With regard to the retrofitting of an acoustic monitoring system on the main cable, given the relatively young age of the cable, and the expected service of such a system, it is not considered that there would be great benefit in installing an acoustic monitoring system at this time.

### **3. Bridge Manual**

It is extremely important that all the information relating to the management, operation and maintenance of a large cable supported bridge be retained within a single document. This document can be called a Maintenance Manual or Engineering Manual. However, if this document is to be all encompassing a more suitable title would be Bridge Manual.

This Bridge Manual would include all the information relating to the design and construction of the bridge. Ideally this should include design calculations, certification, contract documents and drawings, as-built drawings and resident engineers' reports. Material certification and all quality documentations also should be included, along with warranty information.

In essence, all information relating to the bridge should be available through a single portal. Experience has shown that if this is not done then records and documents relating to the management of the bridge is much more difficult to retrieve.

The Manual must be a 'live' document and should be amended as changes are made over the service life of the structure.

Users of the bridge are best served if all parts of the infrastructure are covered by the same Manual. For example the power, lighting and communications systems and other mechanical and electrical equipment (including signing and toll plaza infrastructure) should be included within the Manual.

Experience from a number of bridges has shown that carrying out maintenance works without quality controlled records can be a safety concern as well as a cause of increased costs. For example the site records of loading and geometry during erection of Kap Shui Mun Bridge in Hong Kong were incomplete. The stressing records were missing and the loads within some hold down stays have to be verified by testing in order to design temporary works for bearing replacement.

Records must be detailed. For example, the method statements used to assemble an item are very important for carrying out repairs at a later date. They show how a part was constructed, which makes it easier to do the reverse and disassemble.

### **3.1. Document Control and Records Management**

The adoption of a formally controlled documentation and records system to maintain the quality of existing and future records relating to the bridge is vital.

Such a system would ensure that all records are managed within legal and professional requirements; and that the records will meet operational effectiveness and information needs. It would also ensure best practice of Documentation and Records Management and offers benefits including:

- Improved control of valuable information and documentation
- Compliance with legislation and standards
- Consistency and accuracy in the creation, archiving and storage of documentation and records
- Reduced costs in the retrieval of documentation and records

One of the keys to ensuring a well-managed records management system is the management of the drawings. Experience has shown that the adoption of a single numbering system for all the differing drawings will simplify the management of the drawing system in the future.

It would also be of great benefit if all the construction drawings (design and as-built) were provided in electronic format. It is much preferable that the drawings are not scanned PDF copies, but are provided in a format where all the original coordinates of all the elements are given.

It also will be beneficial if the computer models of all the structural modelling work are provided. Even if there is an issue over liability for use of the models, the element information contained within can save a considerable amount of rework at some future date.

### **3.2. Service Life of Components**

It is important to recognize that although the bridge structure has been designed for a notional 150-year life, elements and components making up the bridge have differing and lesser design life spans.

For example, experience has shown that the electro/mechanical and computing equipment likely will have a service life of only 10 to 15 years. The pavement may only have a 20- to 25-year life, and it is not uncommon for the suspenders of suspension bridges to be replaced at least once in the life of a bridge.

The paint systems used on the deck, cable and suspenders also will require replacement or refurbishment during the life span of the structure. A strategy should be developed to determine how this will be done while minimizing disruption to the users and ensuring minimal environmental damage.

It is crucial that these differing service life spans are set out in the Bridge Manual, and that a strategy for their replacement is provided. This strategy will have to consider the replacement of above deck components while minimizing risk to bridge users.

### **3.3. Spare parts, tools and equipment**

Any specialized or bespoke tools or equipment used in the construction of the bridges should be identified and an assessment carried out to determine the cost/ benefit of procuring these items from the Contractor. Examples include items such as access equipment, the cable compactor and wrapper, bolt and rod tensioning equipment, and tension measuring devices.

Items such as temporary access and equipment for repair and replacement of the most critical and vulnerable elements also should be considered. For example, if a suspender is damaged (either by accident or maliciously) and needs to be replaced, a procedure and the necessary equipment (should be readily available. Replacement suspenders (or at least the rope and sockets) also could be kept in store.

Instructions and training on how to use the equipment and tools is important and shall be prepared.

Trial replacement of critical spare parts under very controlled conditions in order to learn and test is recommended.

### **3.4. Defects, non-conformances, changes etc.**

It is the experience from many bridges that repair work done during construction (after defects have been discovered) often have a lower quality, and that new repairs can be expected earlier during the operation phase of the bridge. It is therefore vital to have all information from the construction phase on such repairs present in order to prepare a more intensive inspection plan on these areas.

For any defects that remain un-repaired or closed out, it is essential to undertake follow up inspections of these areas until a decision is reached on whether to repair or to do nothing. These inspections could take the form of a simple visual inspection where crack patterns or growth are recorded on a drawing year by year, or where a steel crack is inspected with UT to establish if there has been any growth. If access is easy then the frequency can be higher or more regular. However, if access is difficult, then more care must be taken in deciding what has to be done, how the item is to be accessed, and how often. It should not be an onerous burden to the inspection group, just because a decision on the repair is pending.

Reports on specific technical problems during construction have been presented to the Review Group on orthotropic bridge decks, concrete post-tensioning and bolts. Further corrosion, painting, expansion and seismic joints and dehumidification have been mentioned and will be issues to be faced during the service life of the bridges.

### **3.5. Guaranties / warranties from construction**

Any Contractor guarantees or warranties for material, equipment and plant, and systems should be identified, and any special inspection and maintenance requirements noted to ensure that compliance

with any warranty conditions is maintained. Special Inspections and monitoring can be planned based on such information.

### **3.6. Observations from supervisors during construction**

Any site diaries from the Resident Engineers Staff, or any special reports commissioned during the project relating to the design and construction of the bridges, should be retained as part of the ‘As-Built’ information.

### **3.7. Maintenance and Inspection Manuals**

In this section, comments have been made on the planned maintenance manuals for ESFOBB and in the end of the section a proposal based on experience from Sund & Bælt’s infrastructure is described. The Sund and Bælt experience shows certain advantages in dividing the manuals into Procedures, Instructions and Electronic Forms in order to transform the information in the manuals to a more operational platform and make them easier to update.

#### **3.7.1. ESFOBB Manuals:**

In total three Maintenance and Inspection Manuals have been planned for the East SFOBB. They are:

1. “San Francisco Oakland Bay Bridge – Skyway Project. Bridge Maintenance and Inspection Manual” of December 12, 2007.
2. “San Francisco Oakland Bay Bridge – Self Anchored Suspension (SAS) Bridge. Maintenance and Inspection Manual.” Table of Contents of June 10, 2014.
3. “San Francisco Oakland Bay Bridge – East Spans Seismic – Safety Project. Maintenance and Inspection Manual for Yerba Buena Island Transition Structures & Oakland Touch Down.” Table of Contents of September 8, 2014.

Only the first two of those three manuals were prepared in a draft format and made available for the Review Group, Which comments on these manuals in the following sections. The Review Group has no comments on the list of contents for the third manual.

Detailed comments have been submitted from the Peer Review Group and the comments have been responded by the Design JV and Caltrans Maintenance organization. The two next sections contain some of the essential topics from the performed review.

#### **3.7.2. Skyway Project. Bridge Maintenance and Inspection Manual:**

The review of this Manual by the Review Group was based on a draft version from December 2007. It is recommended that this Manual now be finalized with the outstanding topics mentioned in the Manual (inclusive baseline inspections) and further updated based on the gathered experience since 2007,

including results of performed inspections or follow-up on defects and repairs from the construction phase. The following should be noted:

- The durability of the concrete structure in the splash zone is recommended to be inspected with extra care and frequency in all areas where cracks or defects are observed during construction or after handing over.
- The results of planned survey activities in 2008, 2009, 2010 and 2014 are important to analyze, as they provide information on developments over time, which is vital for evaluating “the health of the structure,” especially in the first decade after construction of the bridge.
- The inspection and maintenance plans, procedures and inspections should be reviewed and updated where necessary, every year, based on all observations and collected experience during the year.
- It is our experience that all movable parts such as bearings and joints must be inspected more frequently. In addition, special thought must be given to the frequency of inspecting elements such as roadway pavement and drainage. Items which can suffer deliberate or accidental damage, including crash barriers, should be inspected more frequently (and always after accidents). In summary, a risk-based inspection regime is recommended for this structure in order to prioritize the most critical and vulnerable parts of the structure and to optimize the use of scarce resources.
- “Significant submittals and revisions made to the original design and details during construction” shall be collected and the consequences for inspection and maintenance determined and described.
- Photo documentation from the construction phase, especially for complicated structural parts or for parts of structures not visible after finalization of the bridge, is likely to be of great value for maintenance staff at a later phase and should be stored with informative comments.

### **3.7.3. Self-Anchored Suspension (SAS) Bridge. Maintenance and Inspection Manual**

In general, this is a well written manual which has to be used by different staff in the organization looking after and maintaining this important bridge infrastructure. Keeping the manual updated and with easy access for all necessary parts is vital if it is to remain relevant in the future.

- It is recommended that as-built drawings are available at the bridge site in an electronic format for easy access during inspections; and that these drawings and other documents are kept updated based on the inspection regime and all maintenance activities. It is our experience that it is essential that procedures and instructions for activities either performed in-house or by contractors/consultants are updated yearly where necessary. It is of great importance that a quality control system for this is established from the outset. The baseline inspection data is of importance as reference for the first inspections performed by the maintenance organization.
- Access for inspection, maintenance and future replacement of all parts of the bridge must be determined. Access must be suitable for carrying out one or more of these activities. A cable traveler is strongly recommended for inspection of the main cable bands and bolts, and top portions of the suspenders. It should also be robust enough to enable the tension within the cable band bolts to be checked. The traveler should be provided with suitable propulsion and sufficient containment to allow it to be used when traffic is running on the bridge, while

minimizing risk to the public. Performing maintenance on the cable (such as re-tensioning cable band bolts) may require a different form of access and containment. Established gantries and travelers shall be well protected when not in use in order to reduce maintenance expenses. Operation and maintenance manuals must be available for all this equipment and it is important that only trained staff is allowed to operate and use this equipment.

- It is our experience that problems faced during the construction phase, and areas with repairs or defects are often the cause of increased inspection and maintenance during the early life of the structure. These problems must be highlighted in the documentation for the maintenance organization and inspected with extra care during the first few years based on clear guidance from handing over from the construction phase.
- It is important to decide at an early stage whether or not to install a SHM-system to verify design assumptions (engineering feedback) or to support the inspection and maintenance of the bridge (condition evaluation of the bridge). We recommend a system for the latter purpose and one that is suited to the actual structure rather than relying on the suppliers' standard SHM-products. Corrosion monitoring of the lower part of the bridge is a subject that should be included in a SHM-system for ESFOBB.
- A risk-based inspection regime also is recommended for this unique and complex bridge. An inspection plan (combined with a service and maintenance plan) should be established based on the criticality and vulnerability of each element or family of elements in order to prioritize inspection based on risk, and to make the best use of inspection resources.
- An Asset Management Plan using a risk-based inspection regime that generates follow up work packages for repair and construction is recommended.
- Procedures for replacement of important parts of the bridge which are expected to have a shorter service life than the bridge itself (pavement, expansion joints, suspenders, etc.) are recommended to be established early as long as the relevant suppliers are still available.
- Special attention should be placed on the cleaning and inspection of expansion joints, as they are highly vulnerable and any possible defects are likely to have a big influence on traffic.
- The dehumidification system installed within the box girder appears to be operating at an RH Level less than 20%. This is a very low value, which over time should be possible to increase. It is noted that there is a proposal to review the system.
- It is further recommended that a cable dehumidification system is installed on the main cable of the SAS. The technology is now well proven and is the only protection system that will prevent deterioration and strength loss within the main cable, which arguably is the most critical element of the whole structure. Main cable dehumidification has been installed on a large number of existing suspension bridges and is being installed on new suspension bridges all over the world.

#### **3.7.4. Proposal for alternative Manual —Solution from Sund & Bælt Infrastructures.**

The Inspection and Maintenance Manual as reviewed could be organized in another way. It is the experience during 17 years of operation of the Great Belt Bridge (The Storebælt Link) that the management documents for operation and maintenance are best used and updated if they are separate

documents made easily accessible in an electronic format, and with clearly appointed persons or functions responsible for preparation, checking and approval of each single document.

The documents, all accessible on the organization's intranet, are structured in five levels:

Level 1: Mission, vision, strategic objectives and additional yearly operational objectives and focus areas.

Level 2: Strategy for Operation and Maintenance of the Infrastructure

Level 3: Operational strategy within each function (e.g. M&E-installations, Concrete or Steel structures)

Level 4: Technical Procedures and Technical Instructions

Level 5: Specific forms in easily accessible electronic format during planning, execution and reporting (e.g. inspections of all parts of the infrastructure).

The Level 4 and Level 5 documents are substituting for a Maintenance and Inspection Manual.

The Technical Procedures (TP) and the Technical Instructions (TI) are the basis for maintenance and inspection activities. For each technical system or structural part, there is a TP and one or more TIs. These documents are written at such a level that a new Technical Manager can easily get an overview of the system or the structural part, and in this way perform his/her job efficiently from the first day.

The TPs are the tool for the Technical Manager to manage the maintenance and inspection activities within his/her area of responsibility.

The TP typically will contain the following information (e.g. for a technical system):

- Purpose and coverage of the procedure
- Functional description of the system, including
  - Design Basis
  - Interface description to other systems
  - Criticality Evaluation (result of a FMECA analysis if prepared)
  - Asset Management (division in assets)
  - IT safety
  - Access
- Strategy for the maintenance of the system
- Obtained experience
- References (eg. to specific user manuals, other TP's, standards, rules and regulations)
- Appendices
- Change log

The TIs are written for the operational staff to perform the activity and can be included in contract documents if the activity is outsourced. It is in this way the basis for pricing of the activity by external parts.

The TIs typically have this content:

- Purpose of Instruction
- Description of the System
- Materials and equipment to be used during the activity
- References
- Activity description (e.g. preventive service and maintenance or basis for acute remedial maintenance) and special conditions
- Reporting and documentation
- Change Log
- Appendices

It is important that the TPs and TIs are kept as live documents, and that they are improved on a running basis in order to optimize operation and maintenance activities.

The numbers of Technical Procedures at the Storebælt Road Link in 2014 were:

Administrative activities:	10 general TPs
Concrete and steel structures:	1 general and 14 specific TPs
Electrical installations:	1 general and 30 specific TPs
Mechanical installations:	10 specific TPs
Land works, buildings, coast protection:	10 specific TPs
Operational procedures:	1 general and 14 specific OPs

For each Technical Procedure (TP) you will find from 1 to 10 Technical Instructions (TI).  
For the Operational Procedures you will find in total 52 Operational Instructions.

#### **4. Inspection Review**

An inspection of any highway structure should, as a minimum requirement, ensure that the structure is safe for use and fit for purpose. In addition, the inspection should provide the data required to support effective maintenance management and planning.

Inspections provide information on the current condition, performance and environment of the structure. This enables the safety, functionality and durability of the bridge to be continually assessed, and ensures the long-term structural integrity of the bridge.

Standards for bridge inspection which are set at national or state level are rightly determined to suit the needs of an owner with a large stock of bridges, the majority of which will be small, span simple structures.

These standards are based on inspecting at set frequencies, usually one or two years, with a more rigorous inspection every five or six years. However, such a program of inspections is not considered best suited for the inspection of large cable supported or other signature bridges such as the ESFOBB

bridges. Consideration instead should be given to implementing a bridge inspection program that takes account of the unique nature of the ESFOBB bridges.

It is becoming more common for owners and operators of large cable supported bridges to use risk-based inspection frequencies. An assessment of the criticality, vulnerability and current condition of each bridge component or groups of components is carried out to determine the frequency of inspection based on the risk of failure. This system not only reduces the risk of failure but helps optimize resource management.

The vulnerability of each bridge component is assessed based on its failure mode, likelihood of detection and the probability of this failure occurring. The criticality of each bridge component is also assessed based on the effect such a failure would have to the structure and to the bridge users. The actual condition of each component is also important, and has must be considered as some deterioration may already have occurred.

The overall assessment can then be carried out in the form of a Failure Mode, Effects and Criticality Analysis (FMECA), whereby each component is assigned a quantitative score based on defined criteria. The result of the assessment can be used to determine a Risk Priority Number (RPN) to highlight components of concern.

#### **4.1. Scheduling of Inspections**

While scheduling inspections, consideration should be given to the following:

- Inspection Categories – (Type of inspection/objective of the inspection)
- Inspection Frequency – (Minimum standard inspection frequency of component determined from statutory requirements, feedback from inspections, or vulnerability and criticality assessment of bridge component)
- Inspection Program – (takes into account resource availability, co-ordination with maintenance and capital work projects to seek efficiencies in the programme)

The program for inspection has to be carefully considered and should take into account the following:

- Time to undertake specific type of inspection
- Efficient use of resources
- Efficient use of access systems
- Traffic management requirements
- Weather conditions
- Coordination of concurrent works
- Scheduling tolerances

#### **4.2. Defects Type Categories**

There is a wide range of potential defects and defect categories to be considered on large cable supported bridges. Different materials for which defects may be detected are:

- Reinforced concrete elements

- Pre-tensioned concrete elements
- Post-tensioned concrete elements
- Steel elements
- Aluminium elements
- Pavement materials
- Steel wire in cables
- Electrical and mechanical systems equipment

In addition to recording the type of defect, extent of defect, and severity of defect, the purpose of any inspection regime should be to record any maintenance that is required to correct the defect.

In addition to the recommended repair works, the priority rating of the repair works to be carried out should be formally recorded.

## 5. Maintenance Review

A maintenance program is a coordinated and updated plan for all inspection-, service- and preventive maintenance-activities with additional remedial activities (included on a running basis) which are not acute. The maintenance management system should be the place where the program is accessible for planning, execution and reporting on the activities. Based on the obtained experience and risk evaluations regarding criticality and vulnerability, the strategy and the frequencies of activities should be adjusted.

It is recommended that a program be developed to manage the maintenance needs of the infrastructure to cover a period of 20 years, which would establish a platform for justifying yearly maintenance funding needs. It is, however, important to have procedures for solving acute remedial needs. For example, minor maintenance painting should be performed every seven to 15 years or as necessary based on inspections. Ultimately, paint coatings' life expectancy is 25-30 years depending on the level of exposure to corrosive environments. It is good practice to carry out minor maintenance regularly. This will not only greatly assist in achieving the maximum service life of the paint system but also may reduce the amount of preparation required at the end of the coatings' service life, which reduces containment requirements.

The same thought needs to be employed for overlays. Generally, the life expectancy for full replacement is about 10 years, depending on traffic volume and weights of vehicles. However, this would likely only be achieved if a maintenance effort to ensure that all minor deteriorated areas are addressed over the prior period. This same philosophy should be prescribed for other known maintenance work.

Topics of Special Interest which need to be included in the MM Program:

- Traffic management
- Painting and corrosion protection
- Waterproofing/deck sealing and roadway re-surfacing
- Expansion joints/bearings
- Seismic program

- Main cable and suspender rope painting every 7-10 years with water based elastomeric acrylic coatings#(Noxyde, Isoclad, Polynox), including inspection coating of socket boxes.
- Joint maintenance/cleaning
- Cable band tightening
- Cable retrofit dehumidification
- Bridge cleaning/washing
- Other

## **6. Operations Review**

The operation activities often will play a more visible and dominating role, as they impact directly with the users of the bridge. These activities cover mainly traffic management, motorway assistance service, customer service and communications (call center), toll operation and operation center (variable message signs, weather monitoring, etc.).

Experience has shown that a technical control room and operation center located on the site of the new crossing would be very beneficial for the future operation and maintenance of the ESFOBB. A technical control room normally would house the structural health monitoring system and SCADA while the operations center deals with traffic and tolling, security, communications and customer service. In addition, the operations center staff can monitor the SCADA and SHMS out of hours.

Ideally, the two can be combined within one office or, if this is not possible, they should be as close to each other as possible to enable close cooperation in the daily work of operation and maintenance. Activities should be planned with as little disturbance to traffic as possible. At the same time, they should secure the right quality of inspection, maintenance and repair work.

## **7. Reinvestment Review**

The Peer Review Group has experience inspecting and monitoring the conditions of large bridges and other miscellaneous parts of highway infrastructure. This knowledge of the remaining life of structures leads to the Group recommending that a reinvestment plan be established for the ESFOBB. This plan should detail when the different parts of the infrastructure are going to be replaced (partly or in total); the expected direct and indirect costs; and the timeframe for the planning to start. The reinvestment plan should be reviewed and, if necessary, updated every year based on new information collected during the year.

The service life of bridges is often defined to be 100-150 years. The duty of the owner/operator is to ensure that during this service life the bridge's structural integrity and functionality is not compromised, and that it remains fit for purpose. However, this can only be achieved with adequate resources to ensure a suitable inspection, maintenance and repair program is carried out in a planned manner. Further, individual sections and installations have to be replaced due to wear, damages, deterioration, missing service support or spare parts, reduced functionality, uneconomic operation, excessive energy consumption, or new rules and requirements.

The cost of construction of the ESFOBB is reported to be \$6.2 billion, and the budget set aside for maintaining the ESFOBB and six other large bridges is reported to be \$8 million per year (with a plan to

increase to approximately \$20 million in the future); and \$60 million per year for rehabilitation of all toll bridges over both 10-year and 20-year periods.

BATA will be responsible for funding all operations, inspections and maintenance with toll funds, and has authority to raise tolls for this work. BATA collects approximately \$750 million per year in tolls across all bridges.

### **7.1. Comments by Peer Review Group**

It is very encouraging to note that funding has been set aside specifically for the inspection, maintenance and operation of the bridge. However, it is difficult to comment on the adequacy of the funding without knowing the sum allocated to the ESFOBB and the scope of work the funding has to cover.

Clarification would be required to determine whether this funding is to cover maintenance, inspection and operations, and if staff costs are included. Further clarification on funding for any future capital works would be required to complete the review, including the following:

- The extent of facilities, equipment, availability of access and requirements on inspection has a significant impact on costs, and these costs would have to be evaluated.
- Costs related to procuring professional consultant firms to perform hands-on inspection. In-house resources, based on the meeting discussions, are not available to provide needed inspection services. These costs should be established and added to cyclical costs.
- Major Maintenance Cyclical Program is required to oversee and track each effort. This assists in establishing and justifying required funding.

The decision to start planning a reinvestment strategy should be based on a cost-benefit analysis where alternative solutions are compared. However, new technology, new rules and regulations, environmental requirements, and missing spare parts or support can determine an earlier time for replacement.

In the following paragraphs, some strategies on reinvestment planning are described.

The planning of reinvestments for the Storebælt link is done every year, covering in detail the next year and in more general terms for a five-year period. Every fifth year, the result of five years of planning is re-evaluated and plans for a 50-year reinvestment are updated.

The MTAB&T has a five-year Capital Program and a yearly Major Maintenance Program. Project funding is determined based on need, scope of work and life expectancy of the investment. A 20-year Capital Program is also prepared, updated every five years. The biennial inspections, along with other inspections, provide a platform for upcoming Capital and Major Maintenance programs development.

The level of reinvestment depends on many factors. Among these are the extent and quality of maintenance and repair work, and the defined operations and maintenance strategy.

In appendix 4 an example of external service, inspection and maintenance costs as well as reinvestment costs for a 5 year period for a large infrastructure project is included. The example is taken from the Storebælt Road Link and covers a period from 13 to 17 years after opening of the fixed link. In the same appendix the manning of the O&M organization is shown.

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## Appendix 1

### Bridges representing the ISCBOA Peer Review Group

#### Golden Gate Bridge (San Francisco, USA) - Main span 1280 m



The Golden Gate Bridge is a suspension bridge spanning the Golden Gate strait, the mile-wide, three-mile-long channel between San Francisco Bay and the Pacific Ocean. The structure links the U.S. city of San Francisco, on the northern tip of the San Francisco Peninsula, to Marin County, bridging both U.S. Route 101 and California State Route 1 across the strait. The bridge is one of the most internationally recognized symbols of San Francisco, California, and the United States. It has been declared one of the Wonders of the Modern World by the American Society of Civil Engineers. Open to traffic 1937.

#### Bronx-Whitestone Bridge (New York, USA) – Main span: 701 m



The Bronx–Whitestone Bridge (colloquially referred to as the Whitestone Bridge or simply the Whitestone) is a suspension bridge in New York City that crosses the East River and connects the boroughs of Queens on Long Island, and the Bronx on the United States mainland via Interstate 678. The bridge was designed by Othmar Ammann and opened to traffic with four lanes on April 29, 1939.

The Bronx–Whitestone Bridge is owned by New York City and operated by the MTA Bridges and Tunnels, an affiliate agency of the Metropolitan Transportation Authority.

### **Tsing Ma Bridge (Hong Kong, China) – Main span: 1377 m**



Tsing Ma Bridge is the world's ninth-longest span suspension bridge, and was the second longest at time of completion. The bridge was named after two of the islands at its ends, namely Tsing Yi and Ma Wan. It has two decks and carries both road and rail traffic, which also makes it the largest suspension bridge of this type. The bridge has a main span of 1,377 m. The span is the largest of all bridges in the world carrying rail traffic.

The 41-metre wide bridge deck carries six lanes of automobile traffic, with three lanes in each direction. The lower level contains two rail tracks and two sheltered carriageways, used for maintenance access and traffic lanes when particularly severe typhoons strike Hong Kong and the bridge deck is closed to traffic.

**Forth Road Bridge (Scotland) – Main span: 1006 m**



The Forth Road Bridge is a suspension bridge in east central Scotland. The bridge, opened in 1964, spans the Firth of Forth, connecting Edinburgh to the North Queensferry. It replaced a centuries-old ferry service to carry vehicular traffic, cyclists, and pedestrians across the Forth; rail crossings are made by the adjacent and historic Forth Bridge.

**Storebælt Bridge (Denmark) – Main span: 1624 m**



The Storebælt Fixed Link runs between the Danish islands of Zealand and Funen. It consists of three structures: a road suspension bridge and a railway tunnel between Zealand and the small island Sprogø located in the middle of the strait, and a low level concrete bridge for both road and rail traffic between Sprogø and Funen. The suspension bridge, officially known as the East Bridge, has the world's third longest main span. The fixed road link was opened to traffic in 1998.

**Øresund Bridge (Denmark/Sweden) – Main span: 490 m**

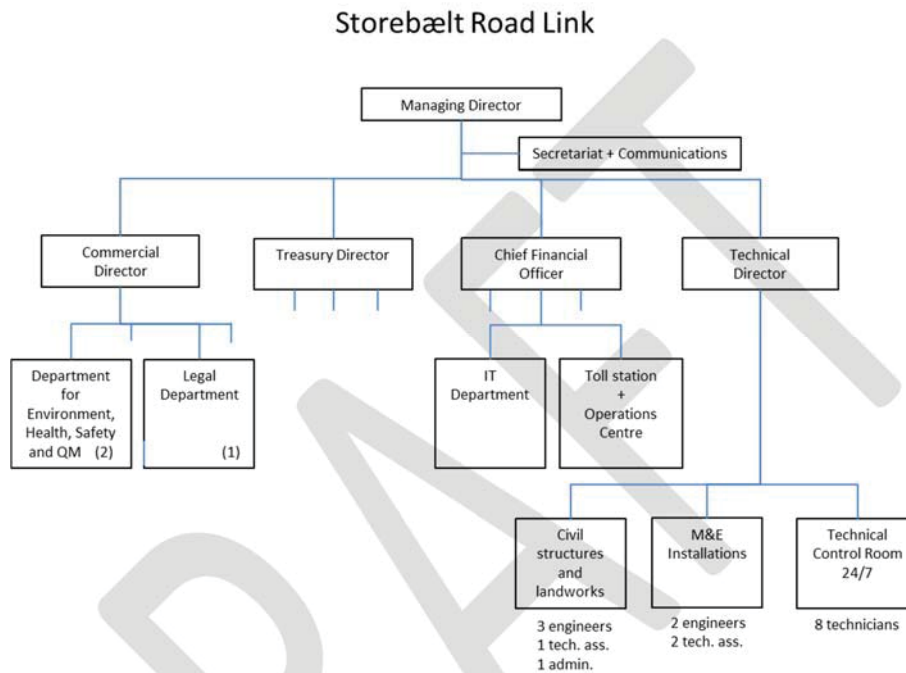


The Øresund fixed Link for road and rail traffic connecting Sweden and Denmark consist of a 4 km immersed tunnel, an artificial island and a cable stayed bridge with two approach bridges. The bridges have a railway line at lower level and a 4 lane motorway at the upper level. The fixed link was opened to traffic in 2000.

## Appendix 2 – Examples of Bridge Organization and Staffing

### Storebælt link:

The organisation for Storebælt Road Link is shown on the following illustration:



The management level in the shown organization also is responsible for the railway link and some other infrastructure. The number of employees indicated in the technical division includes the persons directly involved in the operation and maintenance of the road link, except for the Control Room, where the staff also takes care of the railway line.

As mentioned in appendix 5, the resources in the O&M organization are determined by the outsourcing strategy selected by the operator and owner A/S Storebælt. This strategy has been chosen in order to get access to specialist, with updated knowledge on specific technical topics, to increase flexibility, to get access to new technology, and to benefit from economic scale, including the possibility of absorbing variations in workload and man activities with special time restrictions.

In general A/S Storebælt is outsourcing activities to consultants and contractors. However this is not the case for management tasks in A/S Storebælt. If outsourcing will increase the vulnerability for the company, if the outsourced activities are very expensive compared with using own resources or if there will be a big risk for loss of image for the company in case of non-performance outsourcing is not used.

There are no Danish requirements on qualifications for inspectors of large bridges. A/S Storebælt has defined specific requirements for consultant engineers performing such inspections related to years of experience with inspection on the actual structures or installations.

### **Bronx Whitestone Bridge:**

Created in 1933 by Robert Moses, the Triborough Bridge & Tunnel Authority (TBTA), aka MTA Bridges and Tunnels, serves more than 800,000 vehicles each weekday — over 280 million vehicles each year — and carries more traffic than any other bridge and tunnel authority in the nation. MTA Bridges and Tunnels bridges are the Robert F. Kennedy (formerly Triborough), Throgs Neck, Verrazano-Narrows, Bronx-Whitestone, Henry Hudson, Marine Parkway-Gil Hodges Memorial, and Cross Bay Veterans Memorial; its tunnels are the Hugh L. Carey (formerly Brooklyn-Battery) and Queens Midtown. All are within New York City, and all accept payment by E-ZPass, an electronic toll collection system. The Bronx Whitestone Bridge opened on April 29, 1939. The bridge spans the East River with Bronx connections to the Hutchinson River Parkway, the Bruckner Expressway and the Cross Bronx Expressway.

The Bronx-Whitestone Bridge is used by commuters and weekend travelers, and also serves as an economic engine, providing a crucial link in the transportation of goods in the Tri-State area. Nearly 1115,000 vehicles use the bridge on an average weekday.

MTA Bridges and Tunnels has spent \$737 million in capital improvements on the bridge since 1992 to ensure that it meets modern standards and is in a state of good repair for the millions of customers who use it each year. Among the major capital projects were the addition of aerodynamic wind fairings in 2004; a new, lighter-weight steel orthotropic deck in 2007; reconstruction and widening of the Bronx approach roadways in 2012; and a similar reconstruction and widening project that is ongoing on the Queens approach roadways and is scheduled for completion in 2015.

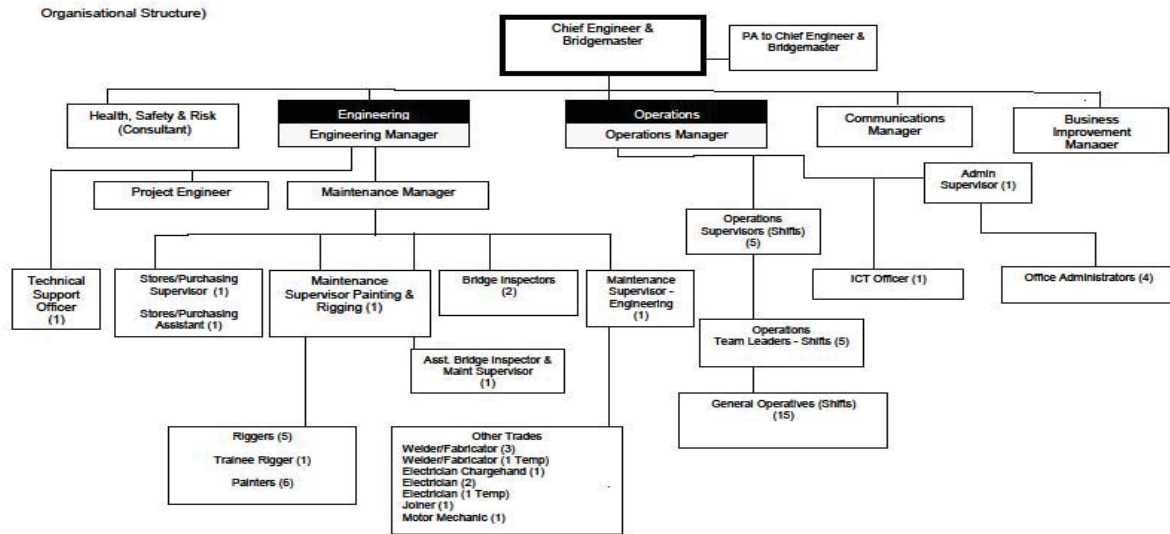
There is a dedicated on-site staff at the bridge, the Director of Bridges South, who also manages the neighboring Throgs Neck Bridge as well as all toll collection and maintenance duties, and a Facility Engineer responsible for carrying out the bridges' Capital and Major Maintenance programs.

### **Forth Road Bridge**

The Forth Road Bridge is owned and operated by the Forth Estuary Transport Authority (FETA). The main function of FETA is to operate and maintain the Forth Road Bridge. The bridge was tolled until 2008 when the Scottish government removed the tolls from all the tolled bridges in Scotland following an Act being passed in the Scottish Parliament.

The FETA Board is made up of local politicians from either side of the Firth of Forth and they have governance over all matters relating to the bridge. Funding for all maintenance and operations now comes directly from the Scottish government. There is a full-time staff of 72 people working on maintenance, operations and administration. The staff members are all FETA employees. The chief operating officer is the Chief Engineer and Bridge-master who has to be a Chartered (Professional) Civil or Structural Engineer. The Chief Engineer and Bridge-master is responsible for the structural certification of the bridge including all refurbishment or improvement works.

The Forth Road Bridge staff structure is shown below:



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Most small remedial or improvement works are carried out by the FETA maintenance staff. For larger improvement works, a consulting engineer is employed to design the works to a FETA brief and then a contractor is appointed to carry out the works on site. Recent works have included dehumidifying the main cables ( £11.5 million ) and replacing all the viaduct bearings ( £18.4 million).

The operations staff carry out traffic management and recovery of breakdowns; security and suicide prevention; and building and grounds maintenance.

One benefit of the organization at Forth is that the entire decision making is held within the one organization, and that organization is based at the bridge site.

### Tsing Ma Bridge

The Hong Kong Government specifies a minimum number of staff that shall be employed within the Tsing Ma Control Area on the Manage, Operate and Maintain contract. The operator supplements this with additional staff in order to fulfill the requirements of the contract.

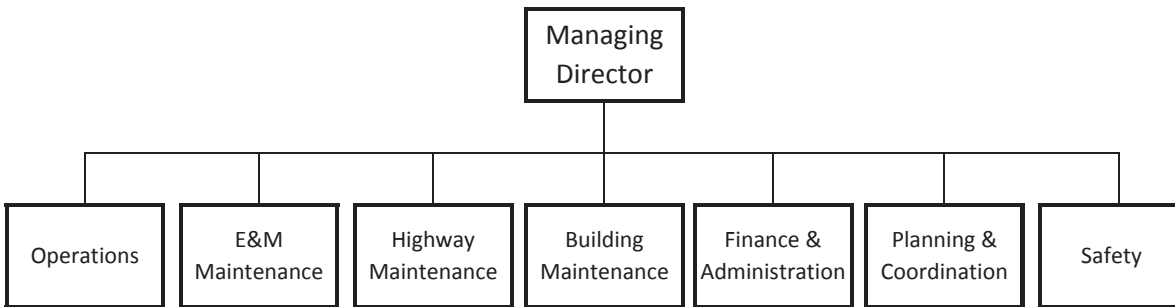


Figure TML Organisation Chart.

The company at present employs approximately 650 staff who are assigned to the various operating sections.

The Highway Maintenance Department of TML is tasked with the job of inspecting, reporting and maintaining the bridges, structures, slopes and roads within the TMCA. One of the sections within this department is responsible for the inspection and maintenance of the three long span bridges.

The Building Department is responsible for monitoring the upkeep of all buildings, cleansing and the gardening of the planted beds.

E&M maintains some 140 vehicles, all the electronics, software and services within the TMCA.

Operations have within their scope of work traffic control and surveillance, vehicle recovery, security control, toll collection, lane enforcement and operation of various E&M systems.

Both E&M and Operations operate around the clock on a 3-shift roster basis.

Lastly, the F&A Department has responsibilities for personnel, general administration, canteen services, purchase and supplies, accounting and the toll money.

It is TML's policy to undertake inspection and maintenance in-house as far as possible in order to achieve better control of work quality as well as response and completion times. For those works that fall beyond TML's own expertise or those of an infrequent nature or perhaps not economical, then TML engages specialists to carry out the work under TMML supervision.

Such examples would be any carriageway resurfacing, surveying or engineering inspections of slopes.

The HM department is divided into five sections: roadworks, geotechnical works, structures, long span cable supported bridges and works.

Each of first four sections is led by an experienced professional engineer who reports to the Highway Maintenance Manager. Depending on the workload, each technical section has a number of deputy engineers, supervisors and inspectors. There has been a very limited amount of staff movements between sections and it cannot be considered as significant, the main reason being the vast variation in skills that are required in each discipline. Currently there are:

Deputy Engineers	6
Technical Supervisors	8
Inspectors	26
Works Supervisors / Inspectors	3
Labour	30
Senior Drivers	12

The last item above - that of Senior Drivers - requires further explanation.

Due to the low levels of car ownership in Hong Kong, not every person has either the confidence or a driving license and to guarantee driving resources additional staff has been employed. In addition within the Highways section there are several vehicles that require special licenses to operate, such as the bridge inspection vehicle, tunnel washing vehicle, road sweepers, crane lorry, gully emptier, hoists. In total there are some 25 vehicles.

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### Appendix 3 Examples of Suspension Bridges with Main Cables Dehumidified

#### Retrofitted to existing operational suspension bridges

Bridge	Location	Main Span ft (m)	Year opened	Year Dehumidification Installed
Ohnaruto Bridge	Japan	2874 (876)	1985	1997
Ohshima Bridge	Japan	1837 (560)	1988	1998
Innoshima Bridge	Japan	2526 (770)	1983	1998
Kita Bisan-Seto Bridge	Japan	3248 (990)	1988	1998
Shimotsui-Seto Bridge	Japan	3084 (940)	1988	1999
Minami Bisan-Seto Bridge	Japan	3609 (1100)	1988	1999
Hakucho Bridge	Japan	2362 (720)	1998	2000
Littelbelt	Denmark	1969 (600)	1970	2003
Aquataine <sup>1</sup>	France	1292 (394)	1967	2003
Hoga Kusten	Sweden	3970 (1210)	1998	2005
Hirado Bridge	Japan	1509 (460)	1967	2008
Severn	UK	3241 (988)	1966	2008
Forth	UK	3300 (1006)	1964	2009
Humber	UK	4626 (1410)	1983	2010
Rainbow	Japan	1870 (570)	2000	2015
Chesapeake Bay EB Bridge	USA	2950 (899)	1951	2015
Chesapeake Bay WB Bridge	USA	2951 (899)	1973	2015
Storebealt	Denmark	5328 (1624)	1998	2015
Delaware Memorial Bridge 1 <sup>2</sup>	USA	1951 (595)	1951	
Delaware Memorial Bridge 2 <sup>2</sup>	USA	1952 (595)	1968	
10th Street Bridge <sup>2</sup>	USA	725 (221)	1933	
Ben Franklin <sup>2</sup>	USA	1750 (533)	1926	
George Washington <sup>2</sup>	USA	3500 (1067)	1931	

### Appendix 3 Examples of Suspension Bridges with Main Cables Dehumidified (Continued)

#### Installed at time of construction

Bridge	Location	Main Span ft (m)	Year opened	Year Dehumidification Installed
Akashi-Kaikyo Bridge	Japan	6532 (1991)	1998	1997
1st Kurushima Kaikyo Bridge	Japan	1969 (600)	1999	1999
2nd Kurushima Kaikyo Bridge	Japan	3347 (1020)	1999	1999
3rd Kurushima Kaikyo Bridge	Japan	3379 (1030)	1999	1999
Akinada Bridge	Japan	2461 (750)	2000	2000
Runyang (south bridge) <sup>3</sup>	China	4888 (1490)	2005	2005
Toyoshima Bridge	Japan	1772 (540)	2008	2008
Hardanger	Norway	4298 (1310)	2013	2013
Yingwuzhou Bridge	China	2 x 2789 (850)	2014	2014
Halogand	Norway	4643 (1415)		under construction
Yavuz Sultan Selim	Turkey	4620 (1408)		under construction
Izmit	Turkey	5086 (1550)		under construction

#### Proposed New Bridge Projects

Messina <sup>4</sup>	Italy
Lusail	Qatar

#### Notes:

1. cables replaced in 2003 and dehumidification installed.
2. scheme being considered by Client Authority
3. assumed installed at construction
4. dehumidification is included in initial designs

#### Appendix 4. Examples on numbers of employees in O&M organizations at other large bridges.

The number of employees in the Operations and Maintenance organization for the ESOBB is difficult to estimate as this bridge is managed together with the western part of the Bay Bridge and six other bridge infrastructures. Furthermore, the selected outsourcing strategy will have a big influence on the size and role of in-house organization. If a significant amount of work is outsourced, it is very important to keep the knowledge on the conditions of the bridge in-house. In addition, it is crucially important to have personnel available who can keep the documentation (drawings, procedures and instructions) updated all the time.

In case of outsourcing (partly or total) to consultants and contractors, the in-house bridge engineers (civil as well as E&M) must have sufficient knowledge and experience to plan, supervise and evaluate the quality of external partners' work.

TABLE SHOWING THE SIZE OF THE TECHNICAL ORGANIZATIONS FOR SELECTED INTERNATIONAL BRIDGES (staff at Toll station not included):

NB: Managers are not included in the table:

Bridges: O&M Organisation:	Storebælt Road link DK  Note 1)	Forth Roadbridge UK  Note 2)	Tsing Ma Bridge HongKong  Note 3)	MTA Bronx Whitestone Bridge USA  Note 4)
Engineers Civil structures:	3	2	11	7
Engineers E&M installation	2	-	4	*b)
Technical assistants	3	2	35*a) & c)	*b)
Technical Control room	*a)	1	0	*c)
Operation centre	*b)	2	24 *b)	*c)
Staff on QA/QC, environ- ment/ H&S/CSR	*c)	1	4	*b)
Administrative Staff	1	4	30	*b)
Others:			650 *d)	

**Note 1):** 25 km motorway with a low level concrete bridge (7 km) and a suspension bridge with approach bridges (7 km). The link opened to traffic 1998. Inspection, maintenance, repair and upgrading is out-sourced to consultants and contractors.

Note a): Technical control room managed 24/7 and shared with rail link. Staff 8 technicians

Note b): Operation Centre shared with toll station. 24/7 with 2-3 persons on duty.

Note c): 4 specialists.

**Note 2):** Although there are now no tolls at Forth Road Bridge, a 24/7 Control Room is maintained to supervise traffic management, security and other operational issues.

**Note 3):** 22 km highway with a suspension bridge (road & rail), two cable stay bridges, a tunnel, containing 70% of elevated roadway. First part opened in 1997. Inspection and maintenance is generally performed in-house with the larger maintenance tasks out-sourced to contractors and consultants.

Note a): For E&M, highway maintenance and buildings

Note b): Two main control rooms, one of which monitors the toll plaza; 4 staff on duty in each control room

Note c): E&M and operations staff on shift 24/7

Note d): Total numbers in TMCA

**Note 4):** 3,770 ft. suspension bridge (side spans – 735 ft. each and main span 2,300 ft.) along with the Bronx Approach 1,800 ft. and Queens Approach 1,150 ft. The Bronx Whitestone Bridge first opened in 1939. Inspection, Maintenance and Construction projects are designed and constructed by in-house staff, and external consultants and contractors. The MTAB&T organization has a dedicated Engineering, Operations, and Maintenance staff located at the Bronx Whitestone Bridge Facility.

Note a) Facility Engineering Staff is housed at the Bronx Whitestone Bridge Facility. Seven Engineers (disciplines may vary).

Note b) Technical assistance is provided by Structural, Mechanical, Electrical, Architectural, Civil, QA/QC, and Environmental Engineering groups at the HQ location. Construction Safety and H&S groups are also at that location. Professional Engineering Consultants are procured and issued contracts to provide Biennial Inspection, Design Services and Construction Inspection and Management Services as necessary.

Note c) Operations and Maintenance Department is a 24/7 operation.

**Specific information on manning and costs for service, inspection and maintenance and for reinvestments costs at Storebælt Road Link is presented in the next page as an example:**

<b>Storebælt Fixed Link. Inspection, Maintenance and Reinvestments Costs for the Road Link (exclusive toll station):</b>					5 Oct.2015
<b>External Costs in million USD (running costs). Internal costs for own staff is not included.</b>					
Note: 1 USD = 6.66 DKK					
	2015 *	2014	2013	2012	2011
Inspection and maintenance Structures:	2.608	2.531	2.548	2.384	2.366
Inspection and maintenance E&M:	2.864	2.104	2.076	2.074	2.452
Road-service and road-works:	1.374	1.348	1.308	1.366	1.419
Winter service:	0.754	0.772	0.712	0.730	0.686
<b>Total service, inspection and maintenance:</b>	<b>6.846</b>	<b>5.983</b>	<b>5.932</b>	<b>5.824</b>	<b>6.237</b>
Reinvestment costs:	15.700	19.429	10.930	6.952	5.796
<b>Total Costs per year:</b>	<b>22.546</b>	<b>25.412</b>	<b>16.862</b>	<b>12.776</b>	<b>12.033</b>
*) planned costs in budget					
<b>General remark:</b> The East Bridge inspection and maintenance costs is about 75 % of the indicated total costs for the Road Link.					
For the Road- and Winterservice the costs related to the East Bridge is about 33 %.					
For reinvestments about 90 % can be related to the East Bridge for the last few years					
<b>Number of persons involved in operation, inspection and maintenance (exclusive reinvestments) of Road Link:</b>					
(Toll station staff and management level is not included)					
<b>In-house resources:</b>					
Engineers (structures):			3		
Engineers (E&M-installations):			2		
Technical assistants, secretary:			3		
<b>Total direct in-house staff O&amp;M:</b>			<b>8</b>		
Technical Control Room with SCADA System (Road and Rail Link):			8 **	**)	24/7 with 12 hours shifts
Operation Center Road Link:			6 ***	***)	24/7 with 8 hours shifts
General company staff on QA/QC, Environment, H&S, CSR, legal:			6 ****	****)	Shared with Rail Link
<b>General staff and manning Control rooms:</b>			<b>20</b>		
<b>External resources (mainly through 4-5 years contracts):</b>			<b>Contractors:</b>	<b>Consultants:</b>	
Inspection & Maintenance Structures:			9		2
Inspection & Maintenance E&M:			8		2
Road-service and road-works:			11		
Winter service:			7		
<b>Total external resources for service, inspection and maintenance:</b>			<b>35</b>		<b>4</b>