Statens vegvesen

Ferry free E39 –Fjord crossings Bjørnafjorden | 304624

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| 01 | 07.12.20 | | JHLN | PLI | ODOL | |
| 00 | 30.11.20 | First edition | JHLN | PLI | ODOL | |
| Rev. | Publish date | Description | Made by | Checked by | Project appro. | Client appro. |

| | |
|---|---|
| Client<br>Statens vegvesen | |
| Contractor<br>COWI | Contract no.:<br>18/91094 |

Document name:

# Bjørnafjorden floating bridge (K12) – Operation, maintenance and rehabilitation strategy

| Document no.: | Rev.: | Pages: |
|---|---|---|
| SBJ -32-C5-COW-23-RE-011-0 | 01 | 93 |

DECEMBER 2020
STATENS VEGVESEN

# Bjørnafjorden floating bridge (K12) – Operation, maintenance and rehabilitation strategy

ADRESSE COWI A/S
Parallelvej 2
2800 Kongens Lyngby
Denmark

TLF +45 56 40 00 00
FAKS +45 56 40 99 99
WWW cowi.com

DECEMBER 2020
STATENS VEGVESEN

# Bjørnafjorden floating bridge (K12) – Operation, maintenance and rehabilitation strategy



| PROJECT NO. | DOCUMENT NO. |
|---|---|
| A205696-002 | A205696-002-D&V001 |

| VERSJON | DATE OF ISSUE | DESCRIPTION | PREPARED | CHECKED | APPROVED |
|---|---|---|---|---|---|
| 2.0 | 07.12.2020 | | PLI/JHLN | HPE/PLI/JHLN | ODOL |

# CONTENTS

# 1 Introduction

This document concerns the operation, maintenance and rehabilitation (in the following named O&M) strategy for the Bjørnafjorden floating bridge concept K12. Figure 1-1 provides an overview of the bridge. This document is based upon phase 5 project documents as delivered to the Norwegian Public Road Administration (Statens Vegvesen – SVV) in august 2019.

The O&M strategy is developed in a phase wise workflow. Phase 1, O&M system description, is part of the VegRAMS process phase 1 - activity 1.4: operation, maintenance and rehabilitation. The activity is detailed in /1/ section 5.5. Phase 2, O&M model, is part of the VegRAMS process phase 2 - activity 2.2: operation, maintenance and rehabilitation model. The activity is detailed in /1/ section 5.9, which has been adjusted to accommodate SVV's focus areas as expressed at meetings 27.09.2020, 03.10.2020 and 23.10.2020.

The workflow is reflected in this document, where items 1-4 are established in phase 1 and items 5-9 are established in phase 2. All items are listed below incl. chapter reference:

1. Overall O&M strategy (incl. spare part strategy), ref. chapter 2
2. Organisation for O&M, ref. chapter 3
3. Operation and maintenance plan, ref. chapter 4
4. Emergency and evacuation plan, ref. chapter 5
5. Risk-based inspection and maintenance analysis, ref. chapter 6
6. Supplementary analyses for 'non-standard' elements
   - Steel pontoons and steel columns, ref. chapter 7
   - Drydock and cofferdam – both being elements for non-scheduled corrective maintenance in case of an incident, ref. chapter 8

› Pontoon mooring lines, ref. chapter 9

7 Access strategy for personnel, equipment and materials, ref. chapter 10

8 Risk-based inspection and maintenance, ref. chapter 11

9 Structural Health Monitoring System (SHMS), ref. chapter 12

According to /1/ the following object boundaries apply:

› From abutment incl. foundation to abutment incl. foundation

The model is based on provided information at project kick-off as well as supplementary information provided by SVV during the work. In addition, the object model developed as part of the VegRAMS process serves as basis for the O&M strategy on element and system level, which then feed O&M information back to the object model.

*Figure 1-1 Overview of K12.*

## 1.1 Abbreviations

AUV: Autonomous Underwater Vehicle
CA: Corrosion Allowance
CRA: Corrosion Resistant Alloy
CP: Cathodic Protection
O&M: Operation and Maintenance
ICCP: Impressed Current Cathodic Protection
SDSS: Super Duplex Stainless Steel
SHMS: Structural Health Monitoring System
SVV: Statens Vegvesen (Norwegian Public Road Administration)
RBI: Risk-based Inspection
RCM: Reliability Centered Maintenance
RC-VAT: Remotely Controlled – Vertical Access Tool

| | |
|---|---|
| ROV: | Remotely Operated Vehicle |
| TSZ: | Thermally Sprayed Zink |
| WIM: | Weigh-In-Motion |
| SUP: | Shared Use Path |

# 2 Overall O&M strategy

## 2.1 Purpose and contents

The Bjørnafjorden floating bridge shall be designed, constructed and maintained so that its function is established and maintained with minimal life cycle costs (LCC).

The main purpose of the O&M strategy is to specify and implement requirements for:

- how to achieve the design service life at minimal costs (LCC)
- how to ensure maximised user availability (overpass traffic, underpass/maritime traffic and O&M personnel)

In order to ensure the above, the requirements are also needed for the following items:

- access facilities and equipment
- staffing (number and qualifications)

In general, all surfaces of all parts shall be easily accessible for inspection (within arm's length) and maintenance (except completely closed steel members). Submerged surfaces shall be inspected using Remotely Operated underwater Vehicle (ROV). Special consideration shall be given to components exposed to water during a possible drainage malfunction. All drainage systems shall be easy to inspect, clean, maintain and replace.

For deformation, fatigue and wear prone details identified during detailed design, the visual inspection shall be assisted by the outcome of a structural health monitoring system (SHMS). Design of the SHMS shall be part of the bridge design.

O&M planning for a bridge like the Bjørnafjorden floating bridge is associated with a large degree of uncertainty. Therefore Statens Vegvesen (SVV) has introduced risk-based methods for O&M analysis. The risk-based approach shall benchmark existing practice (SVV handbooks etc.) and enhance the basis for decision-making during establishment of an O&M strategy. Focus should be on critical and vulnerable elements and systems and where savings in LCC and/or increase in user availability are possible.

Based on the general level of detail of the conceptual design from phase 5, the risk-based approach must be qualitative. Gradually, as the level of detail increases, the risk-based analysis can become quantitative and detailed on a case-by-case basis.

The design service life of the bridge is 100 years, ref. /3/. Elements and systems that expectedly require replacement during the service life of the bridge, shall be replaceable with minimal disturbance of road traffic as well as maritime traffic, ref. /3/ on required uptime. Procedures for replacement of elements and systems shall be planned, described and facilitated as part of the design process, ref. /3/.

This O&M strategy comprise general descriptions and requirements. The O&M strategy can be used as basis for formulation of requirements for the coming project phases, in order to ensure minimal LCC and minimal traffic restrictions during operation.

In parallel with the design and development of a BIM model, an O&M manual should also be established with a description of the bridge, instructions, inspection procedures, maintenance procedures, spare part management etc.

## 2.2 Personnel

The main tasks for an O&M organisation are:

- management incl. planning and evaluation of all procedures
- administration, incl. IT-management and outsourcing
- traffic management (physical work like clearing of roadway, cleaning, establish traffic restrictions, emergency service etc.)
- inspections
- maintenance

In connection with the establishment of the O&M organisation, the ratio between in-house staffing and outsourcing, primarily to consultants and contractors, shall be decided. This subject has not been detailed any further.

Reference is made to chapter 3, where staffing of O&M personnel is detailed.

## 2.3 O&M equipment

Equipment to be provided for performance of O&M activities comprise:

- fixed equipment:
  - permanent installed equipment (fixed ladders, platforms, sensors, surveillance cameras, fixation points for "rope access" etc.)
  - in stock stored equipment – transported to the bridge when needed (scaffolding etc.)
- moveable equipment:
  - service vehicles for road patrol (clearing and cleaning, replacement of

smaller objects etc.)
- emergency vehicles (can be provided by the emergency response contractor)
- boat
- lifts, hoists, sky-climbers etc.

Further considerations related to O&M equipment will be provided in the following chapters.

A major part of all special equipment is access facilities.

Access facilities shall ensure:

- Easy and safe access for inspection and maintenance
- Easy and safe access (incl. evacuation)
- Easy and safe access for regular maintenance with minor consequence for availability
- Easy and safe replacement of elements and systems with a design service life less than 100 years
- Easy and safe maintenance of all pontoon elements and systems
- Easy and safe access to pontoon interior

Access routes, work platforms and other equipment shall be selected and arranged so that restrictions for traffic (vehicles, bikes, pedestrians and maritime traffic) is kept to a minimum. The length of the bridge is decisive for the design of access facilities (e.g. vehicle transport of personnel, materials and equipment in the bridge interior between abutments and use of lift in the tower).

In general doors and stairs are preferred compared to hatches and ladders, which are only to be used when geometry do not allow for doors and stairs.

In case of an emergency, permanent access facilities shall provide for a safe evacuation route and make access for rescue personnel. Permanent facilities, like clearly marked and safe access and evacuation routes and equipment (stretcher, hoists, etc.) shall allow for evacuation in case of an emergency. In addition to an O&M manual, an operation and emergency (O&E) manual should be established.

Detailing of access routes shall be performed as part of the design process. The level of detail shall match design maturity, i.e. handling of materials and equipment that match current design and O&M strategies shall be accounted for.

## 2.4 Special material requirements

There are several factors that affect the service life of the bridge. Some are design detail-oriented choices and others are material-related choices. The latter in particular is detailed for selected elements in the following chapters with due consideration of the exposure.

It is highlighted that material specifications are treated by the Design Basis, see /3/. The material specific requirements in the O&M strategy shall be included in Design Basis requirements.

Detailing of the following above water objects could be performed, e.g. with due reference to /6/:

- Primary steel structures (steel grade, assembly/jointing methods, monitoring, etc.)
- Coating of steel surfaces
- Bearings
- Cable system (stay cables incl. possible dampers)
- Surfacing
- Secondary steel structures
- Concrete structures
- Mechanical and electrical systems

Detailing of the following submerged objects could be performed:

- Prestressed pontoon mooring lines (fairleads, mooring lines that each consists of 50m top-chain, steel wire / fibre rope, 100m bottom chain and suction anchor ref. /6/)
- Primary steel structures incl. coating and sacrificial anodes (incl. use of super duplex SDSS in a 6.5 m high splash zone, ref. /6/)
- Concrete structures
- Secondary steel structures (platforms, fixed ladders etc.)
- Marine systems (ventilation and dehumidification systems)

Detailing of material specifications require strategic considerations, e.g. the following principle of surface protection is recommended (in combination with cathodic protection):

- outside surfaces (external) to be painted
- inside surfaces (internal) to be painted and dehumidified

It means that the outside surfaces shall be without any stiffeners, openings for installation, bolted connections or other protruding elements so that coating can be performed mechanically (e.g. using robots) and with top quality. In addition, all external surfaces shall be "smooth", i.e. without joints where accumulation of water, dirt and eventually corrosion may happen.

Surfaces that are dehumidified do not require repainting after the structure has been erected and the dehumidification system is operating.

## 2.5 Main activities

Table 2-1 summarises the main O&M activities with intervals according to SVV handbook R411. In general, inspection and maintenance intervals could be optimised based on a qualitative risk-based approach. A final O&M plan could be optimised based on a more quantitative evaluation.

*Table 2-1 Main O&M activities according to SVV Handbook R411.*

| Activity | Interval |
|---|---|
| Routine (løpende) inspection and non-scheduled maintenance | Dependant on element/system (ref. chapter 4) |
| Handover inspection | Only once. Before handover. |
| Warranty inspection | Only once. Before end of guarantee period |
| Yearly inspection | Yearly |
| Principal inspection | Every 5 years |
| Special inspection | When needed for a component or a group of components |
| Scheduled maintenance | Individual component frequencies. According to actual needs. |
| Repair | When needed. |
| Replacement | Individual component frequencies. According to actual needs. |

## 2.6 Operation plan

The operation plan shall comprise the following activities:

- Clearing (debris etc.) and cleaning
- Snow removal
- Inspections

- Measurements and surveys
- Material tests
- Structural monitoring

The operation plan has an interface to the object model of Bjørnafjorden K12 as well as integration interface to SVV Bridge Management System 'BRUTUS' and the financial system 'Økosys'.

The operation plan is further detailed in section 4.1.

The maintenance plan comprises routine maintenance (day to day activities) and scheduled maintenance and/or replacement.

The maintenance plan is further detailed in section 4.2.

## 2.7 Spare part strategy

The spare part strategy shall support efficient, safe and cost-optimal operation, which at the same time minimise traffic restrictions for vehicles, bikes, pedestrians and maritime traffic.

Spare part requirements shall be part of the O&M manual. Requirements shall be based on:

- O&M strategy
- Differentiated needs across elements/systems based on their criticality (risk), vulnerability and the economic impact of having/not having the spare part available. If economic feasible, Reliability Centered Maintenance analyses can be appropriate for spare part requirements especially for mechanical and electrical elements and systems.
- Flexible process considering work orders
- Are spare parts off the shelf or a specialised product (with long delivery time)?
- Is it possible to store the spare parts? – with due consideration of storage space and possible deterioration during storage

A spare part example may be pontoons and their moorings, which both are critical and vulnerable when considering ship impact. Therefor it shall be considered to have a complete mooring line in stock, emergency contract with ROV and AHTS (Anchor Handling Tug Supply vessel) contractor and possibly establishment of a local drydock so that downtime in case of a ship impact with a pontoon or anchor is minimised.

Other spare parts which would be beneficial, if economic feasible, are:

- Pumps and other equipment for ballast water
- Moveable ladders
- Scissor lift
- Hoists
- Truck Mounted Attenuator (TMA)
- Bearings
- Lighting equipment
- Equipment for traffic restrictions

# 3 O&M organisation

## 3.1 Overall considerations

Statens Vegvesen (SVV) will handle management (primarily) of the Bjørnafjorden floating bridge and outsource inspection, maintenance and rehabilitation of elements and systems to contractors. The same principle is used on the Hålogaland bridge and internationally on bridges such as the Great Belt Bridge in Denmark, the Øresund Bridge between Denmark and Sweden and many others where no concession agreement is established. On this basis, it is assumed that the same principle is also valid for the Bjørnafjorden floating bridge.

## 3.2 Organisation

Requirements for the O&M-organisation, number and qualifications, are described in Table 3-1. The structure of the organisation is based on similar organisations that manage other international bridges of similar size (without a toll station that increases the operational setup). It is recommended that the organisation is adjusted according to SVV's needs and plans.

It is noted that certification of special components like lifts, "rope access" systems, UAV's and mechanical inspection equipment shall be performed according to their own provisions.

It is assumed that external consultants and contractors design and execute maintenance and rehabilitation projects.

*Table 3-1: O&M-organisation. *)Part time/full time depends on whether or not an O&M-organisation for several fjord-bridges is established.*

| Number | Title | Task | Qualification | Comments*) | Outsourcing? |
|---|---|---|---|---|---|
| 1 | Manager | Management Administration | Management of bridge maintenance | Part time | No |
| 1 | IT-manager | Maintenance of BIM, BRUTUS database, GIS systems and Økosys. | Experienced in use of BIM, BRUTUS, GIS and Økosys | Part time | No |
| 2 | Bridge Patrol, 2 persons | Routine maintenance of roadway and structures | Experienced in inspection, cleaning and remedy of simple defects, incl. coating repair | Part time | Yes |
| 1 | Electrical technician | Periodic maintenance of electrical systems | Experienced in maintenance of electrical systems | Part time | Yes |
| 1 | Mechanical technician | Periodic maintenance of mechanical systems, incl. ballast (water) systems, possibly firefighting systems, lifts and other access facilities | Experienced in maintenance of mechanical systems | Part time | Yes |
| 1 | Maritime supervision/technician | Periodic inspection/verification of status/stability of pontoons incl. mooring lines | Experienced in control and inspection of ballast systems and mooring lines | Part time | Yes |
| 1 | SHMS specialist | Test, maintenance and use of SHMS | Experienced in maintenance and use of SHMS | Part time | Yes |
| 1 | Structural engineer | Activities according to the results of the SHMS | Experienced in structural assessments initiated by the SHMS | Part time | Yes |

# 4 Operation and maintenance plan

## 4.1 Operation plan

Operation of elements and systems above water is performed according to the plan in Table 4-1.

*Table 4-1 Operation plan for elements and systems. Frequencies based on international best practice and SVV handbooks.*

| Inspection type | Description | Frequency | First time | Derived actions |
|---|---|---|---|---|
| Routine inspection (løpende inspeksjon) | Clearing (debris etc.) and cleaning | Daily | Before taking bridge in operation | |
| | Snow removal | As needed | | |
| | Primary steel and coating | Yearly | Before taking bridge in operation | *) |
| | Roadway and footway/bicycle track. Incl. drainage and barriers/railings | Weekly | Before taking bridge in operation | *) |
| | Cable system | Weekly | Before taking bridge in operation | *) |
| | Overhead sign structures and signs | Monthly | Before taking bridge in operation | *) |
| | Mechanical installations | Weekly | Before taking bridge in operation | *) |
| | Service roads | Daily | Before taking bridge in operation | *) |
| | Critical electrical system incl. lighting | Daily | Before taking bridge in operation | *) |
| | Non-critical electrical system incl. lighting | Weekly | Before taking bridge in operation | *) |
| | Dehumidification system | Monitoring | Before taking bridge in operation | *) |
| | Access facilities incl. inspection and maintenance equipment | Weekly | Before taking bridge in operation | *) |
| | Structural Health Monitoring System (SHMS) | Test as appropriate | Before taking bridge in operation | *) |
| Hand-over inspection (Ferdigbefaring) Entire bridge | Visual inspection. Registration of defects and deficiencies | One time | Before handover of project | **) |
| Guarantee inspection (Reklamasjonsinspeksjon) Entire bridge | Visual inspection related to remedy of defects and deficiencies | One time | Before end of agreed guarantee period | **) |
| General inspection (Enkel inspeksjon) Entire bridge | Visual inspection | Yearly | Within 1 year after handover | **) |
| Principal inspection (Hovedinspeksjon) Objects above water | Visual inspection | 5-year interval | Within 5 year after handover | **) |
| Principal inspection (Hovedinspeksjon) Objects below water | Visual inspection using special methods and equipment (see the following text) | As needed | As needed | **) |
| Special inspection (special inspeksjon) On selected bridge parts/components | Extended visual inspection, surveys and material tests | As needed according to outcome of SHMS and/or visual inspection | As needed according to outcome of SHMS and/or visual inspection | **) |

*)
- instantly remedy of some of the observed defects
- description of needed inspection and maintenance actions

**)
Preparation of inspection and maintenance action list

The strategy for inspections below water is:

- Inspections of external surfaces to be carried out by ROV from a certain depth specified by the contractor (not splash zone). Divers are only allowed to a certain depth. Special splash zone inspection tools to be applied.
- Replacement of sacrificial anodes to be carried out by ROV (requires manufacturing of special equipment/tools).
- As much as possible of the under-water equipment shall be monitored.
- To facilitate inspection of internal surfaces it shall be possible to empty all ballast tanks. In addition, platforms and ladders shall be installed.
- In case of an incident (e.g. ship impact) the manager shall rely on the results of the risk analysis (that specify any operational measures) and qualified inspections and assessments in order to minimise downtime.

There is normally no need for detailed inspections of external surfaces of pontoons. Leakage control of tanks are carried out from inside during regular tank inspection.

The inspection program of the O&M manual should (in line with SVV current steps towards a risk-based inspection approach) be based on a risk-based approach. This should lead to considerable savings on operation, when compared to handbook-based inspection approach, especially when considering inspection of surfaces not readily accessible.

The structural health monitoring system (SHMS) shall be used, among others, for monitoring on non-visible load response from deformations, fatigue and wear. SHMS can be divided in two main parts:

- Monitoring part (sensors etc.)
- Evaluation part (analyses which provide relevant information – including information for O&M)

Figure 4-1 presents an overview of a SHMS. The SHMS can be used, among others, for verification of bridge design during the first years of operation. In addition, it can be assessed whether it should be used in connection with special elements and systems where the remaining service life needs to be evaluated (e.g. fatigue or wear). It is expected that the mooring line prestress shall be monitored continuously.

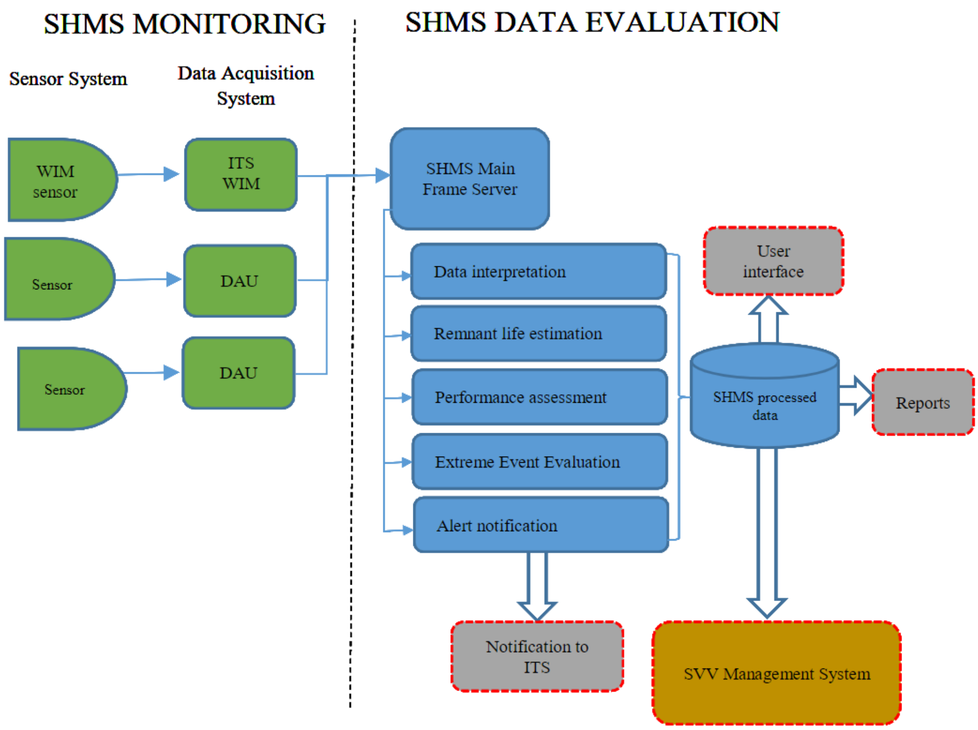


*Figure 4-1: SHMS concept. Abbreviations are WIM: Weigh In Motion, ITS: Intelligent Traffic System, DAU: Data Acquisition Unit.*

The O&M-strategy can detail which components that needs monitoring.

## 4.2 Maintenance plan

A maintenance plan shall consist of:

- Routine (løpende) maintenance
- Periodic maintenance/replacements

Routine (løpende) maintenance is carried out according to standard procedures – as based on routines. Routine maintenance is normally carried out by the in-house contractor (operation contractor) along with routine inspections. Routine maintenance comprises, but not limited to:

- vehicle damage repair
- lighting check and maintenance (bulb exchange etc.)
- graffiti removal
- pothole repair
- check and maintain functionality of doors, hatches, locks, sensors, signs, lifts, weather stations, drainage etc.

- ballast system in pontoons

Periodic maintenance/replacement of components with a service life less than 100 years is drafted in Table 4-2. It is based on the Design Basis /3/ and recommended materials for the floating suspension bridge anno 2017, see /4/ and /5/. Non-periodic maintenance can always be expected. Periodic maintenance shall be described in a LCC model. A LCC model shall be based on the object model of the project.

*Table 4-2: Periodic maintenance/replacement of elements and systems with a service life less than 100 years. *) Further detailing if the surface is exposed to de-icing salt spray.*

| Element/system | Service life | Maintenance | Replacement |
|---|---|---|---|
| Coating of primary steel structures, superstructure above water | 50 | After 25 and 40 years *) | 50 years (total replacement) |
| Waterproofing of bridge deck (isolation) | 40 | None | 40 years |
| Wearing course | 40 | As needed | 40 years |
| Safety barriers and railings | 50 | As needed | 50 years |
| Permanently installed access equipment | 50-100 | As needed | 50-100 years |
| Drainage | 50 | As needed | 50 years |
| Stay cables | >100 years | As needed | > 100 years (total replacement) |
| Dehumidification systems | 30 | As needed | 30 years |
| Bearings | 100 | After 30 years (wear parts) | 50 years (coating) |
| Systems:<br>- Electrical<br>- Mechanical | 30 | As needed | 30 years |
| SHMS | 10-20 (sensors: 10, infrastructure: 20) | As needed | 10-20 years |
| Lifts | 30 | see LCC | 30 years |
| Coating of primary steel structures, substructure above splash zone | 40 | After 30 years (spot repair) | 40 years |
| Coating of primary steel structures, interior surfaces in permanent ballast tanks | 15 | - | 15 years |
| Mooring lines (50m top chain, 124mm steel wire) | 50 | As needed | 50 years |
| Mooring lines (other components) | 100 | As needed | 100 years |
| Cathodic protection system | 30-40 | None | 30-40 years |

# 5 Emergency preparedness

An emergency preparedness plan shall be prepared in parallel with the design of the Bjørnafjorden floating bridge. Among others, risk analyses shall form basis for development of the plan. It shall be updated as the design matures. This process shall ensure the involvement of the relevant authorities, so that the final design is optimal considering the input from the authorities.

The overall purpose of the emergency preparedness plan is, among others:

- ensure a fast and efficient warning of relevant authorities
- ensure a clear and distinct division of tasks and responsibilities between the emergency preparedness stakeholders
- ensure clear and unambiguous communication between the parties and between the emergency response organizations and public bodies
- ensure a fast and safe recovery of the normal traffic situation

The contents of the emergency preparedness plan can be:

- Introduction (purpose and boundaries, basic principles, authors, revision log)
- System description and access conditions (incl. evacuation routes, possibility of crossing traffic, 'marching areas', traffic restrictions, any possible permissions for special events)
- Emergency preparedness stakeholders
- Incident management (alerting, verification and disposition, effort, clean-up and termination of effort)
- Safety for rescue personnel
- Communication and information
- Significant risk scenarios (wind, ice, fire, ship impact, terror)
- Education, drills and evacuations
- List of contacts

# 6 Risk-based inspection and maintenance analysis

As part of the operation, maintenance and rehabilitation model a risk-based inspection and maintenance analysis has been performed. The analysis concern bridge elements and systems that are described by the Bjørnafjorden phase 5 project. The applied methodology is detailed in Appendix A. The result is enclosed in Appendix B. Based on the risk-based inspection and maintenance analysis and the focus areas of SVV, certain elements have been selected for a further O&M-based study, including attention towards:

- design and execution
- inspections
- maintenance and rehabilitation

## 6.1 Criticality and vulnerability classes

An components criticality class is a measure related to the risk of failure of the component developed in the operation period of the bridge.

The risk is in principle a summation of all risks related to all (identified) possible failures that may occur for the component in the operation period. A risk is defined as the product of the likelihood of the failure to occur and the consequences of the failure.

An components vulnerability class is a measure of the time period that is expected for the failure to develop after the failure has been observed to initiate. The vulnerability class is determined by considering all failures as identified for the component.

As part of the Bjørnafjorden floating bridge, critical and vulnerable elements and systems have an impact on service life and maintenance requirements. For each element/system a criticality class and a vulnerability class are evaluated.

Evaluated classes are shown in Appendix B. In Table 6-1 elements and systems with non-acceptable (C3, C4, R3, R4) criticalities and/or vulnerabilities are summarised. It is expected that all non-acceptable criticalities and vulnerabilities will be mitigated during design incl. establishment of operation and maintenance procedures.

*Table 6-1 Elements with non-acceptable criticalities/vulnerabilities.*

| Element/System | Criticality | Vulnerability | Detailed as part of this report | Detailed in a later phase |
|---|---|---|---|---|
| 2.04 Steel girder - weldings | C4 | R2 | | x |
| 3.01 Concrete column – reinf. concrete | C3 | R1 | | x |
| 4.01 Steel columns, interior surfaces | C3 | R1 | x | |
| 4.03 Steel Columns, exterior surfaces | C3 | R1 | x | |
| 4.04 Steel columns, weldings | C4 | R2 | x | |
| 5.01 Concrete towers – reinf. concrete | C3 | R1 | | x |
| 5.02 Posttensioning elements | C3 | R1 | | x |
| 6.01 Tower foundation – reinf. concrete | C3 | R1 | | x |
| 7.01 Abutment, concrete – reinf. concrete | C3 | R1 | | x |
| 8.01 Stay cables, cables | C3 | R1 | | x |
| 8.06 Stay cables, anchors | C3 | R1 | | x |
| 8.07 Stay cables, damping system | C3 | R1 | | x |
| 9.01 Steel pontoons, interior surfaces | C3 | R1 | x | |
| 9.03 Steel pontoons, exterior surfaces | C3 | R1 | x | |
| 9.04 Steel pontoons, weldings | C4 | R2 | x | |
| 9.05 Steel pontoons, coating system | C3 | R1 | x | |
| 9.06 Steel pontoons, top coat | C3 | R1 | x | |
| 11.01 Roadway, surfacing, friction | C4 | R4 | | x |
| 11.02 Roadway surfacing, protec. | C3 | R1 | | x |
| 13.01 Lighting, critical | C3 | R4 | | x |
| 14.01 Lighting, non critical | C2 | R3 | | x |
| 17.01 Drainage system | C3 | R4 | | x |
| 18.01 SHMS system | C2 | R3 | | x |

In Table 6-2 the maximum criticality class and the maximum vulnerability class are shown for every element/system class. According to the RBI/RCM approach, an analysis of design requirements (e.g. reliability, durability/service life and resilience) and O&M (inspection, maintenance and rehabilitation) shall be performed for elements/systems that have an estimated value 3 or 4 (C3, C4, R3, R4). In many cases the optimal solution is known. In other cases, an analysis shall be performed as part of the design process incl. preparation of O&M procedures.

In agreement with SVV focus areas, the following element groups are analysed in the following chapters:

- Steel pontoons and steel columns
- Mooring lines

In addition, SVV has requested an O&M analysis of drydock and cofferdam facilities as a 'third element group' – both being elements for non-scheduled corrective maintenance in case of an incident.

The above 3 element groups are all unusual elements for major cable supported bridges.

*Table 6-2 Criticalities and vulnerabilities of elements and systems classes.*

| Class no. | Element/system | Maximum criticality / vulnerability | Comments |
|---|---|---|---|
| 1.00 | Concrete girder | High (C3) / Robust (R1) | Known challenges |
| 2.00 | Steel girder | Very high (C4) / semi robust (R2) | Known challenges |
| 3.00 | Concrete column | High (C3) / Robust (R1) | Known challenges |
| 4.00 | Steel column | Very high (C4) / semi robust (R2) | To be analysed |
| 5.00 | Concrete tower | High (C3) / Robust (R1) | Known challenges |
| 6.00 | Tower foundation | High (C3) / Robust (R1) | Known challenges |
| 7.00 | Abutment | High (C3) / Robust (R1) | Known challenges |
| 8.00 | Cable system | High (C3) / Robust (R1) | Known challenges |
| 9.00 | Steel pontoons | Very high (C4) / semi robust (R2) | To be analysed |
| 10.00 | Moring | Medium (C2) / Robust (R1) | To be analysed |
| 11.00 | Surfacing | Very high (C4) / Very vulnerable (R4) | Known challenges |
| 12.00 | Road sign | Medium (C2) / Vulnerable (R3) | Known challenges |
| 13.00 | Electrical systems - critical | High (C3) / Very vulnerable (R4) | Known challenges |
| 14.00 | Electrical systems – non-critical | Medium (C2) / Vulnerable (R3) | Known challenges |
| 15.00 | Railings | Inconsiderable (C1) / Very robust (R0) | Known challenges |
| 16.00 | Bearings | Medium (C2) / Robust (R1) | Known challenges |
| 17.00 | Drainage system | High (C3) / Very vulnerable (R4) | Known challenges |
| 18.00 | SHMS | Medium (C2) / Vulnerable (R3) | Known challenges |
| 19.00 | Permanent access facilities | Medium (C2) / Robust (R1) | Known challenges |

# 7 Steel pontoons and steel columns

The pontoons are situated in a particular aggressive environment that has been investigated intensively in previous stages of the project Bjørnafjorden floating bridge. This section is based on the previous analyses e.g. ref. /2/ "Preferred solution K12" and /8/ SINTEF, "Material selection, surfaces treatment and corrosion protection for floating bridge Bjørnafjorden".

## 7.1 Materials for pontoons and columns

In the K12-concept the pontoon steel is a combination of carbon steel S420 N/NL and super duplex stainless steel (SDSS).

In the splash zone the pontoons are made of SDSS in full material thickness. The top and bottom plate as well as the side plates below the splash zone (equivalent to 6,5 m from the top plate), are constructed in carbon steel S420. Bulkhead, diaphragm, stiffeners etc. inside the pontoons as well as the columns are also constructed in carbon steel S420.

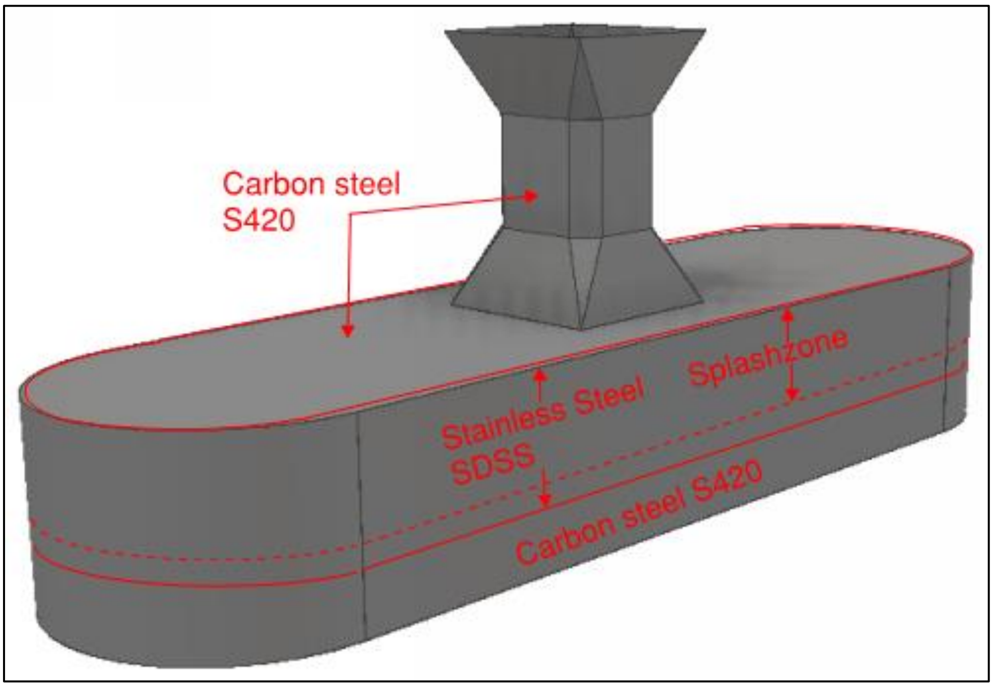


*Figure 7-1 Pontoon and column*

Several transitions and joints between different steel types will occur, which require special handling to guarantee a sufficiently high quality, see /8/. The same issues will apply for different types of surface treatments in different zones.

Reference /8/ describes a number of recommendations for material and fabrication requirements as well as recommended requirements for corrosion protection of the steel structures.

### 7.1.1 Welds

The documents /2/ "*Preferred solution, K12 – Appendix O*" and /8/ "*Material selection, surface treatment and corrosion protection for floating bridge Bjørnafjorden*", describe amongst other requirements for welding of SDSS and carbon steel. It is concluded in /8/ that the welding of the different steel types is manageable if sound qualified welding procedures are established and restrictions on critical material parameters are introduced. In /8/ the possibility of a pre-treatment of the carbon steel by buttering in order to avoid hot or cold cracking is described. An example of buttering before welding is shown in Figure 7-2.

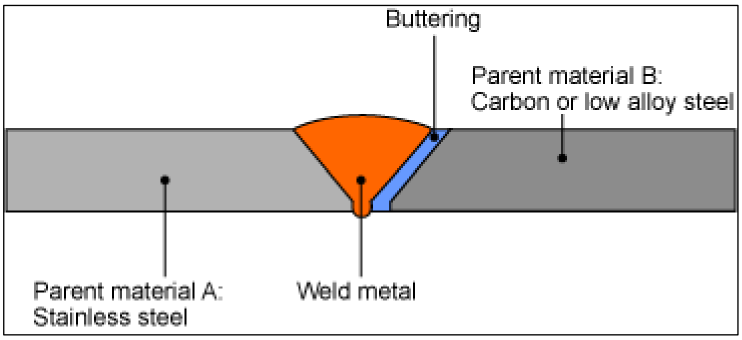


*Figure 7-2 Pre-treatment of welds in form of buttering*

In the Design Basis, it should be maintained that the design of welds must take the greatest possible account of execution and future maintenance.

Now, possible critical areas and details that are not considered in the documents /2/ and /8/ are assessed, where there may be special requirements for the execution of welding joints or the execution can have special effect on durability and hence on the extent of O&M.

*Figure 7-3 Typical type of corrosion on welding*

Figure 7-3 shows a typical example of a corrosion damage to a weld seam. Corrosion as shown can occur due to several reasons, but often the reason is a combination of roughness and unevenness of the surface. The weld seam is difficult to clean adequately and to apply the surface treatment in correct layer thickness. Even on a relatively easily accessible area and on a simple rectilinear weld seam, corrosion can occur if adverse conditions are present.

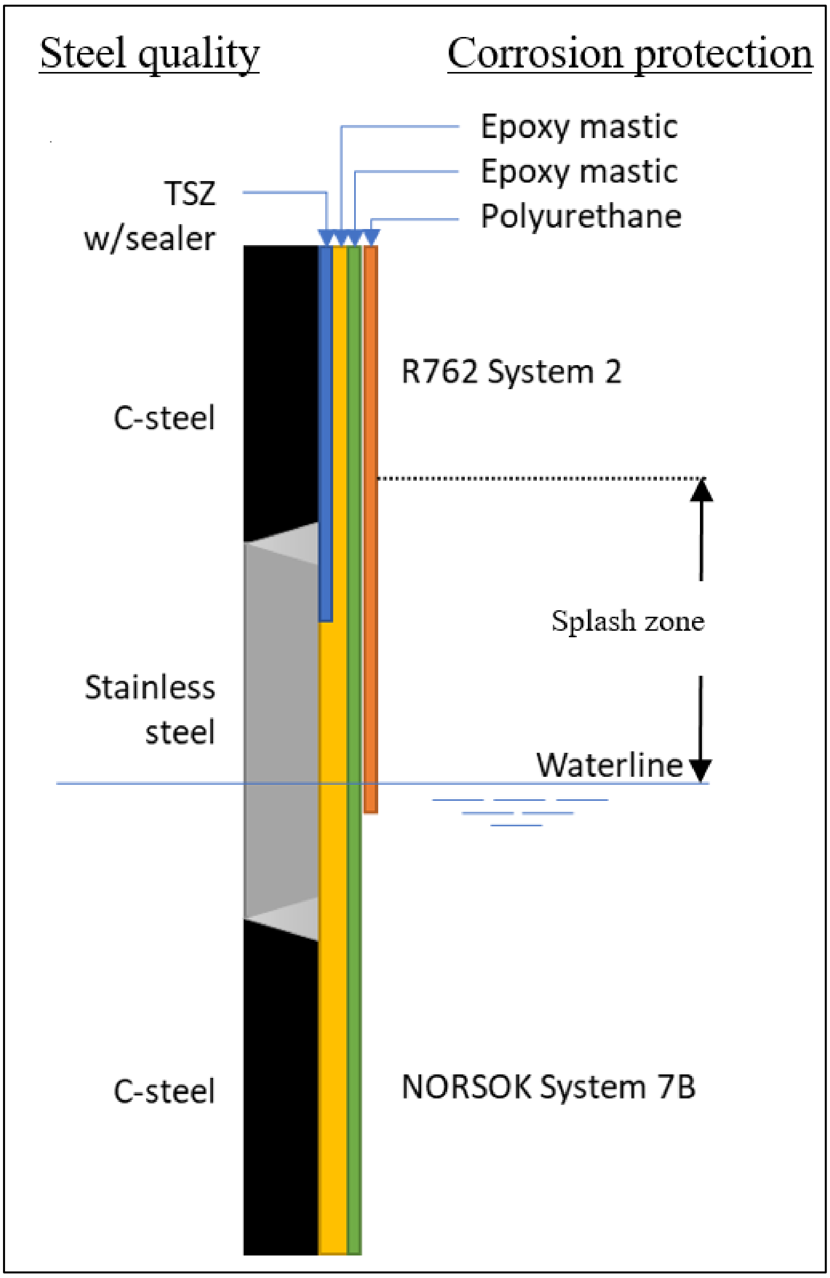


*Figure 7-4 Proposed surface treatment on pontoon according to /8/*

A proposal for the design of a surface treatment on the pontoons is shown in Figure 7-4, which is described in document /8/.

In the figure a buttweld is shown with the root of the weld facing the interior surfaces of the pontoon. The exposed surface of the weld root is much smaller than the opposite side of the buttweld and the surface of the root side is also much more even than the opposite side (especially with an x-shaped weld seam). Since the environment inside the pontoon is expected to be less aggressive than the outside, it should be investigated whether welding seams can be turned so that the root is situated on the outside of the pontoon. It should be clarified which environment (internal or external surfaces) will be the most aggressive before the design of the welds are finally determined. In that way, the most vulnerable parts of the welds will be exposed to a less aggressive environment. It is probably not possible to turn all buttwelds for production reasons (safe and healthy working environment etc.), but there should be focus on the continuous horizontal and vertical welds.

At joints between top and side plates on pontoons, there will occur a transition between stainless steel (upper side plates) and carbon steel (lower side and top plates). The joint between horizontal and vertical plates is marked with a red circle in Figure 7-5.

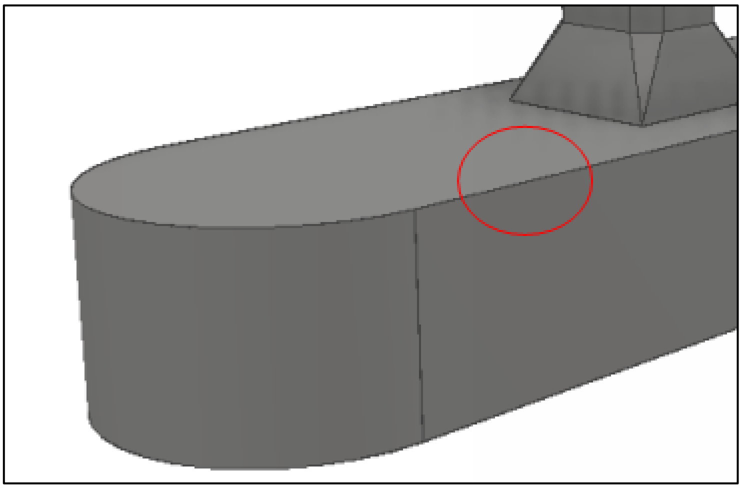

*Figure 7-5 Joint between top and side plates*

Consideration must be given to how the joints of horizontal and vertical plates are to be designed. Some principal assembly types are shown in Figure 7-6 and assessed for maintenance and service life issues, but not from a structural capacity or execution point of view.

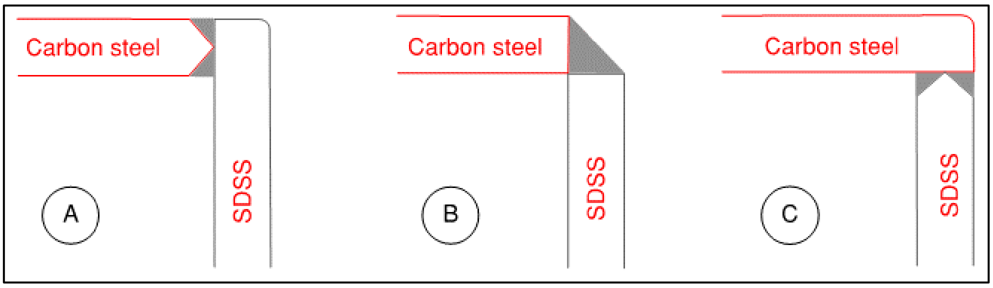


*Figure 7-6 Examples of weld types between top and side plates*

The top plates must have a slope towards the sides, which shall ensure drainages of the surface. The recommended slope for a self-draining surface should be no less than 25‰. At the joint detail shown in Figure 7-6-A, it is likely that the weld will form an edge (groove or dent) that prevents free drainage of water from the pontoon surfaces.

At the weld shown in Figure 7-6-B the risk for forming a groove or dent along the edge will be less. However, the surface area of the weld will become much larger and require extensive finishing work in order to ensure a smooth surface that does not collect debris and ensures good drainage from the top of the pontoon.

At the joint in Figure 7-6-C the weld is placed on the side plate, whereby water from the top of the pontoon has a free flow to the outside of the vertical side plate.

For all three variants shown in Figure 7-6 the water and with this is debris from the surface of the top plates will run directly down the side plates. It is good practice to design a drip mould at the edge of the surface that is drained so that underlying surfaces are not unnecessarily contaminated, see Figure 7-7. The Design Basis should require that vulnerable details must be designed with respect for good drainage conditions. Horizontal surfaces should be fabricated with a slope no less than 25‰.

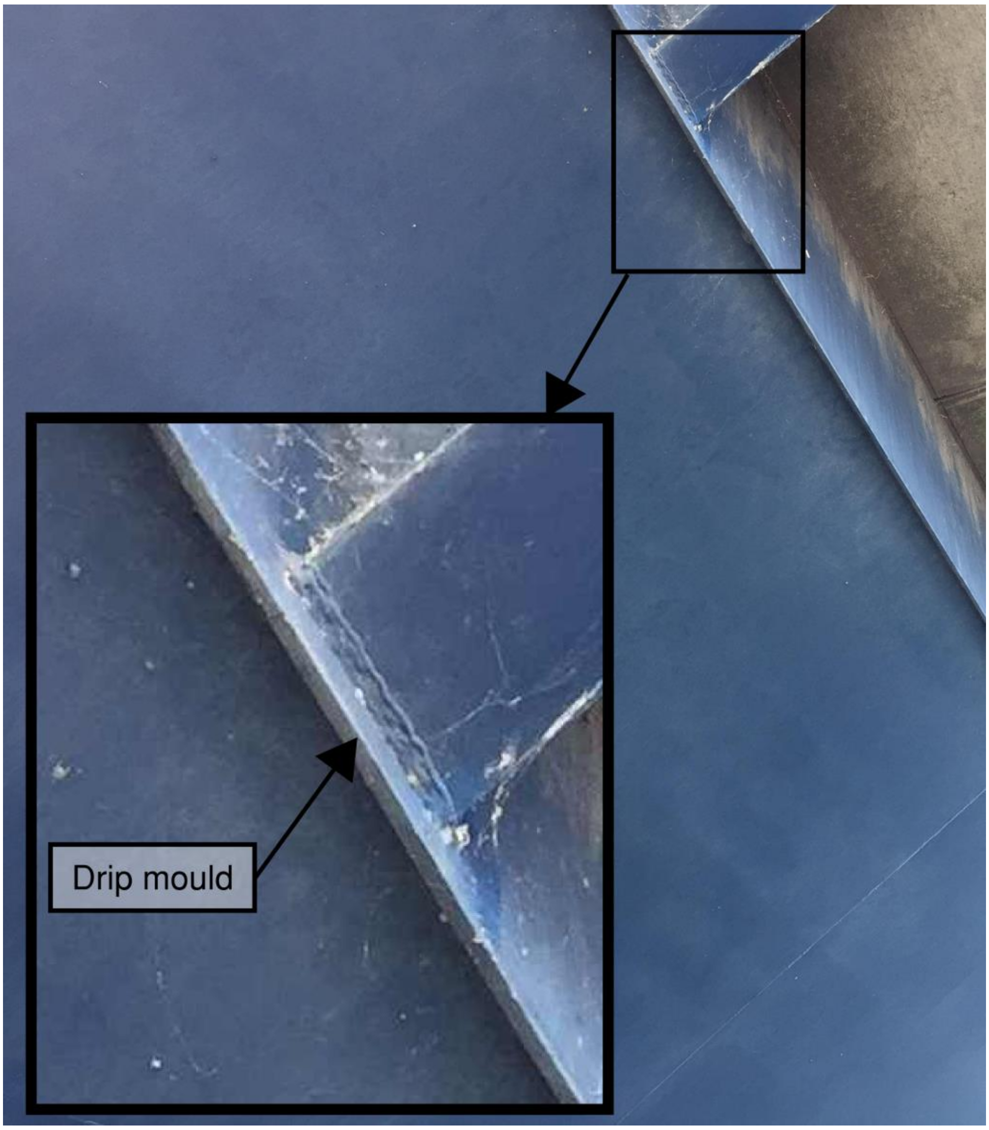


*Figure 7-7 Example of a drip mould*

If the top plate is designed as shown in Figure 7-7 the overhang will act as a drip mould and the weld is located in a less exposed zone.

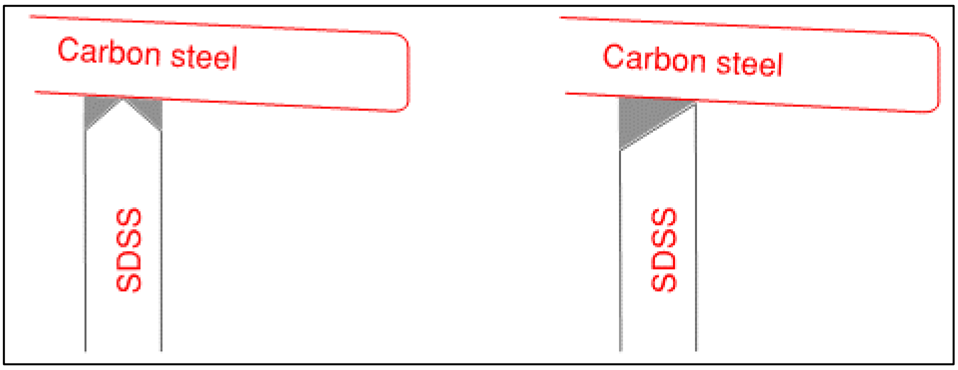


*Figure 7-8 Weld between top and side plates designed with an overhang.*

Type and location of welds along with a possible drip mould should be designed with focus on the production.

The joint between the bottom and side plates are below the waterline and are therefore outside the splash zone. The plates are therefore all designed in the same type of carbon steel S420, but the problems with regard to surface treatment and location of welds are to a certain extent similar, however a drip mould is not relevant.

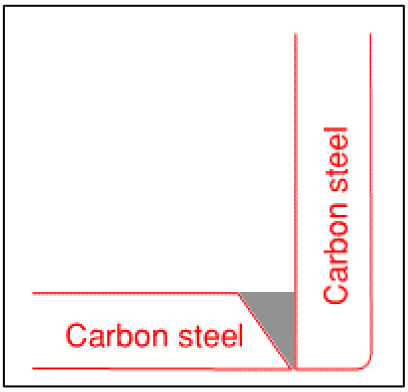


*Figure 7-9 Joint between bottom and side plates*

Joints between columns and pontoons are also located outside the splash zone, so the materials will presumably be designed as carbon steel S420 with a surface treatment. The same recommendations apply to the design as described in the previous section.

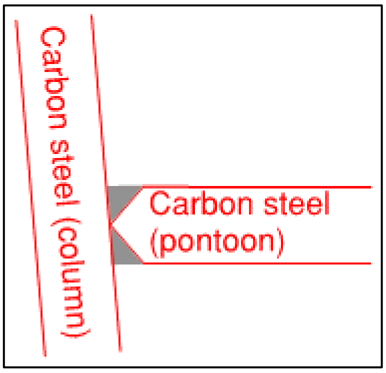


*Figure 7-10 Weld between column and top plate (pontoon)*

The joints between columns and pontoons should be detailed in a future phase with special focus on drainage and cleaning of the joints.

### 7.1.2 Corrosion protection

In order to achieve the desired service life of the steel elements in different environments, the carbon steel must be protected against corrosion. Based on ref. /8/ where different surface protection systems were evaluated, various transition zones on the structure are subsequently examined, which must be in focus during the detailed design, including specification of requirements for the execution.

In ref. /2/ and /8/ a number of topics are described that must be in focus when the surface treatments are applied, emphasising on good workmanship and best practice:

- Layer thickness
- Rounding of edges
- Cleanliness of surfaces
- Surface roughness
- Chloride contamination on surfaces
- Conditions during application: temperature, dew point, relative humidity
- Workmanship: Operator knowledge and experience, equipment and QC inspection

In addition to the above listed topics the design shall emphasize that all surfaces shall be easy to paint and clean. This means that during the design e.g. it must be taken into account that water can easily run off surfaces and that edges and chambers are created so that no water and debris can accumulate.

*Figure 7-11 Unpractical details where debris accumulates.*

According to the recommendations in /8/ all components above the splash zone must be fabricated in carbon steel S420 with a coating type *SVV System 2* (standard surface treatment system in accordance with SVV Handbook R762).

Figure 7-12 shows the recommended build-up of the surface protection system over a weld on a flat SDSS-surface from ref. /8/.

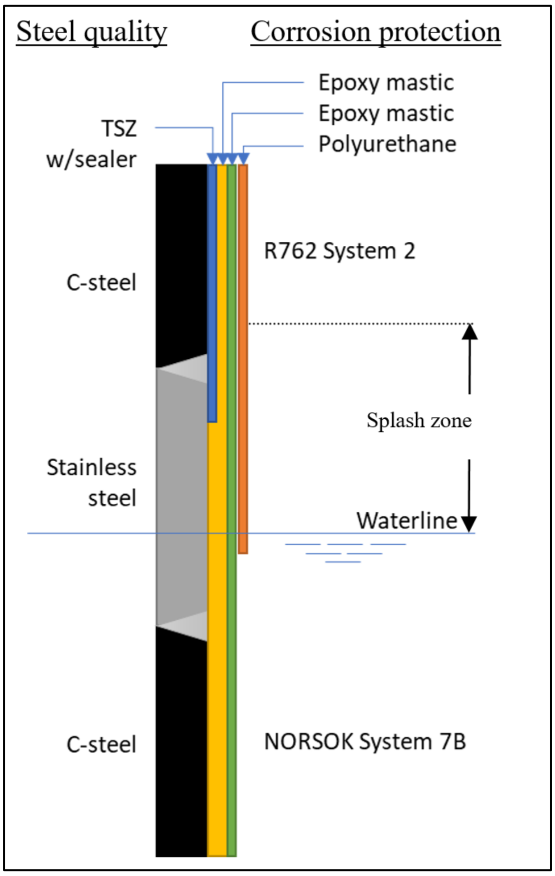


*Figure 7-12 Example of corrosion protection build-up over a weld in accordance with /8/*

Submerged elements shall be fabricated in carbon steel S420 with a coating type NORSOK System 7B together with cathodic protection.

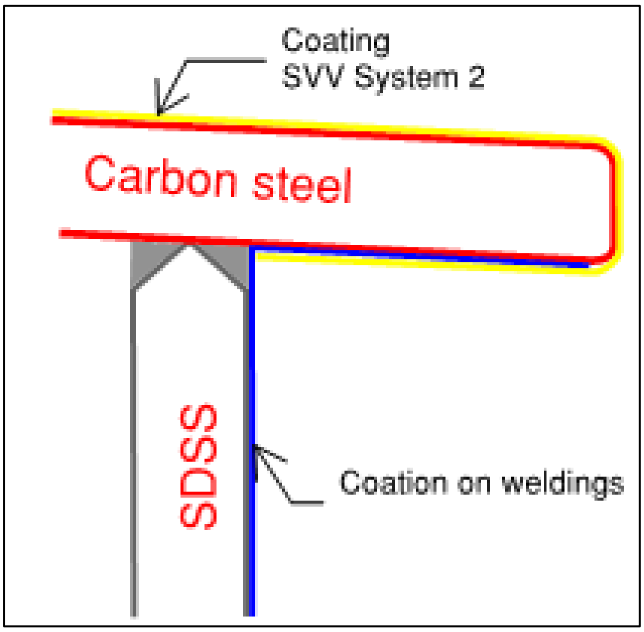


*Figure 7-13 Transition between different materials and coating systems.*

In principle it is more complex to perform a good coating in transition zones on non-plane surfaces. First the joint details/welding are more difficult to perform and secondly the pre-treatment is more difficult to produce. Hence these are items that require special attention during design and fabrication.

Interior surfaces in columns and all inactive ballast tanks are protected against corrosion by dehumidification. Interior surfaces in active ballast tanks of the pontoons are protected from corrosion by a combination of coating and cathodic protection. Recommended coating systems and cathodic protection are described more detailed in ref. /8/.

### 7.1.3 Cathodic protection

According to the Design Basis /3/ all submerged steel elements must be protected against corrosion by a cathodic protection system. That also applies to interior surfaces in active ballast tanks inside pontoons if seawater is used as ballast. The use of seawater or other chloride-containing materials as ballast in the active ballast tanks is currently not planned. In the splash zone cathodic protection cannot be expected to be fully efficient, therefore selection of material and coating systems must be robust, especially in critical areas like the splash zone.

Cathodic protection is a recognized and well proven method of corrosion protection of steel members and the degree of efficiency can be measured and monitored. The size, numbers and location of the sacrificial anodes must be designed on a principle that takes into account the frequency of inspections and replacements, as well as access conditions.

As a part of the cathodic protection systems, sensors are installed to monitor the potential differences in the steel between anodes and sensors. If the potential difference is below a threshold value, the corrosion protection in the area is no longer fully ensured and therefore indicate that replacement of anodes is due. The number of sensors to be installed should be chosen to cover a representative section of the structural parts to be cathodic protected without necessarily monitoring the entire pontoon. It must also be considered whether all pontoons should be monitored, or a representative selection would be sufficient.

If the anodes are designed for an expected service life of 30-40 years, anodes should typically be inspected the first time after 15-20 years. The intervals of the inspection can be based on the monitoring in a combination with inputs from inspections. The extent of inspections can be adjusted according to experience with the system.

The OceanTech document "Methodology for dry access to pontoons of floating bridge Bjørnafjorden" /10/ describes a concept for dry access that may be used for inspection, cleaning, maintenance and replacement of anodes on the outside of pontoons.

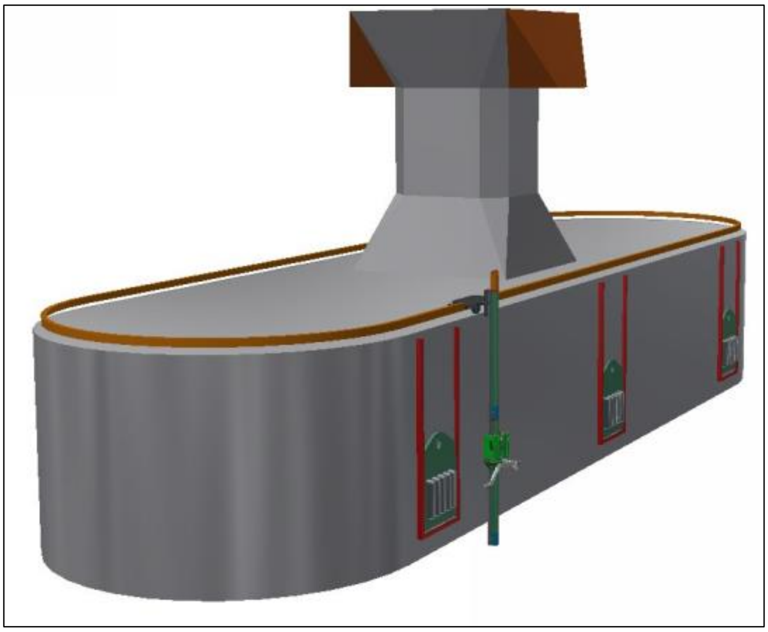

*Figure 7-14 Access equipment for CP, copied from /10/*

In Figure 7-14 the anodes are shown installed on bespoke plates in a rail device, in which the anodes can be pulled up to the upper side of the pontoon and handled. A remote-controlled tool, attached to a rail on top of the pontoon, can be used to clean and/or replace anodes on the pontoon exterior.

There are several items concerning the access equipment tool shown that could be problematic and should be investigated further as detailed below.

The anodes are arranged in a rail device which is connected to the pontoon. The rail thereby passes over zones with stainless steel SDSS and carbon steel S420. It is assessed that there will be a very high risk of corrosion problems in the form of galvanic corrosion when different materials are connected. The rail device is also located in the splash zone, which increases the risk of developing corrosion around the connections (welds, bolts or similar), as shown in Figure 7-15.

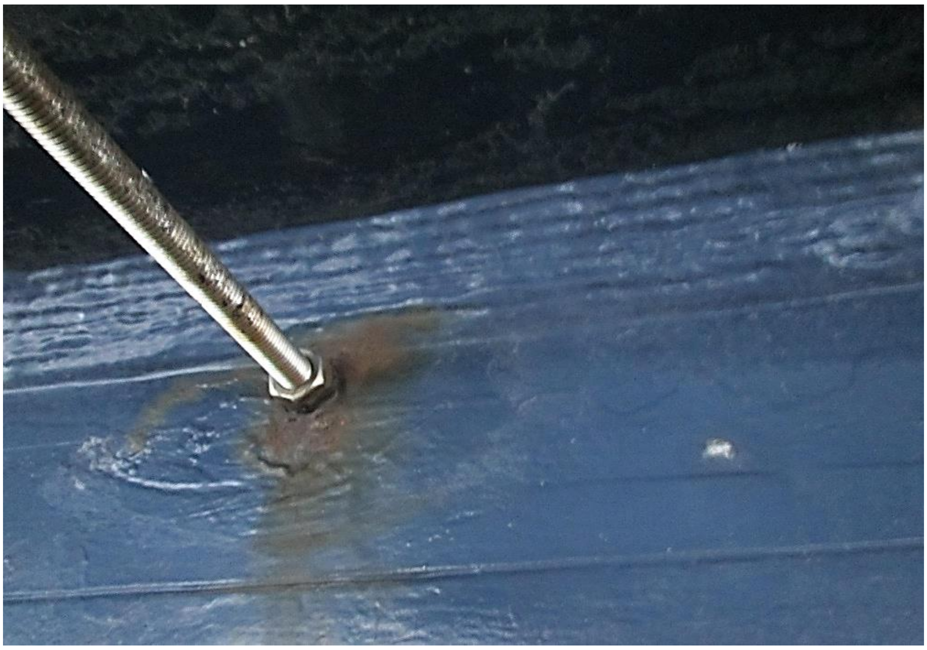

*Figure 7-15 Typical example of corrosion between different materials. The dark colour indicates corrosion*

Furthermore, it is desirable to have as few penetrations of the steel surface and coating as possible, which will be compromised by the connection of a rail device.

There is a high risk that marine growth will build-up on and around rails and spread out on adjacent surfaces. In order to ensure full functionality of the rail devices cleaning and maintenance of the system will be required to some extent. That could become extensive before the system comes into use after approximately 15 years.

Anodes on the underside of the pontoons are likely to be required. These anodes cannot be reached by the proposed rail devices and therefore a different form of access will be required.

Based on the concerns described above the advantages of a permanently installed equipment for maintenance of anodes are estimated to be less than the disadvantages that comes with the system in terms of general maintenance of the system.

## 7.2 Operation and maintenance

There will be a number of general operation and maintenance tasks that must be performed for columns and pontoons. Subsequently four of the probably most frequently occurring tasks with different intervals and character are described.

- General cleaning

General cleaning must be performed on the outside of the column exterior and on the top of pontoons. General cleaning means removal of debris and contamination, that over time could lead to damages of the coating. General cleaning is considered a part of the normal operation that is organised and performed by the operation organisation.

- Removal of marine growth
Elements submerged and in the splash zone are subject to marine growth to a degree that over time can damage the coating and eventually the steel. In accordance with the Design Basis /3/ marine growth must be taken into account during the design. However, removal of the marine growth can be required for instance during inspection and maintenance. To the largest extent possible the cleaning must be performed by a remote-controlled or autonomous ROV robot, although in the upper parts of the splash zone it may be necessary to supplement with manually operated equipment. The cleaning requires special equipment and trained personnel for the operation and is considered to be a maintenance task. During inspections marine growth must be removed in the area under examination.

-Spot repairs on coating
Minor damages to the coating on columns and top side of pontoons are repaired in appropriate intervals, in order to diminish the development of corrosion on the steel and deterioration of the coating. Spot repairs of the coating is a typical maintenance task and must be performed by skilled workers.

- Replacement of sacrificial anodes for the cathodic protection
The time for replacement of sacrificial anodes for cathodic protection on the pontoons is determined from the results of inspection and cathodic potential differences monitored. The replacement of anodes is a task for specialists, whether performed by ROV robots or professional divers.

## 7.3 Accessibility

The operation and maintenance tasks described in section 7.2 require access facilities that suit the frequency and duration of the individual tasks. In section 10 an access strategy is described.

As described in section 10 there should be access from the columns to the top side of the pontoons. From the pontoons, inspections, cleaning and spot repairs of coating on columns and top side of pontoons are performed. Safe access on the upper side of the pontoons can be guaranteed by the use of harnesses in combination with fall protection equipment or by installing permanent guard rails at the perimeter of the pontoon. The extent of maintenance on guard rails is considered to become unacceptably large in relation to the benefits of restriction-free access on the pontoons. Hence rails should come in use when all other solutions are exhausted. Permanent anchor points for rope access require to some extent maintenance and with the number of inspections and other tasks to be performed from the top of the pontoons a permanent safety guardrail in combination with rope access/fall protection equipment should be considered in special situations. Access from the column to the edge of the pontoon can be established by guardrails, which create a more easily accessible evacuation route on the pontoons. The guardrail should be placed at a suitable distance from the edge, so that a safe platform is established from which access on and off a mooring boat can be created. In addition, bollards for mooring of vessels can be installed in the space between the railing and pontoon edge. Access to the pontoons from the waterside is still under evaluation and a solution without guard rails is preferred.

Access to the external surfaces on the columns can be established using ladders, lift, scaffold or rope access. Visual routine inspection and general cleaning can primarily be performed from the top of the pontoons. Access by ladder is limited to low heights and cannot fully cover the access to the columns. Lifts or scaffolding must be lifted from the bridge deck to the top of the pontoon, which can cause interference with traffic to a certain extent. Alternatively, equipment could be transported by boat to the pontoons. This will require more planning and mobilisation. Rope access would not disturb the traffic on the bridge and can be mobilised at short notice, however it requires access in form of hatches from the bridge girder at the columns. Alternatively rope access could be created from a self-propelled inspection gantry. The gantry will in that case be parked adjacent to a column and be occupied during the inspection periods and therefore not available for other tasks. The access strategy to the external surfaces of the column should preferably be a combination of measures. Inspections and cleaning of columns are in general performed from the pontoon top and only in special cases or on high columns inspections must be performed by rope access from the inspection gantry. Spot repairs of the coating are preformed from scaffolding that can be transported inside column and bridge girder. It requires equipment for transportation inside the bridge and all hatches must be designed for general access. Sizes of hatches for access must be specified in the Design Basis.

The bridge girder inspection gantry must be opened in the middle when passing the columns. The open gantry must be stabilized during the column passage e.g. on gantry beams as shown in Figure 7-16. From the open gantry there will be surfaces on the bridge girder that are inaccessible for inspection or maintenance works. Therefor access to these surfaces must be established in another way (e.g. by a lift) when maintenance or inspection is required.

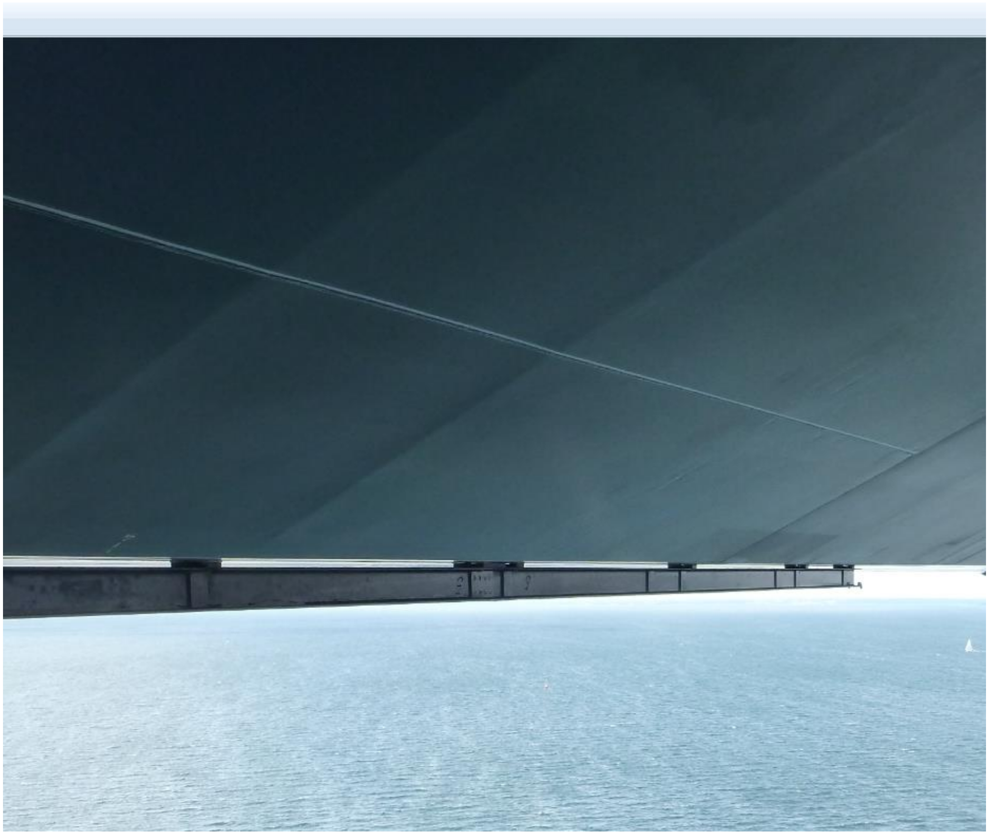

*Figure 7-16 Gantry rail for inspection gantry*

Access to the sides of the pontoons above water must primarily be performed from boat or barge. The sides of the pontoon are fabricated in SDSS in the splash zone and any spot repairs on the coating are primary for esthetic reasons. Should the pontoon be completed with a drip mould as shown in Figure 7-8 spot repairs may be required. The works could be accomplished from the top of the pontoons. Inspection and removal of marine growth can be performed form a boat or barge.

Inspection and removing marine growth below water should preferably be carried out using ROV equipment.

# 8 Optional tools for corrective maintenance

In this section concepts for dry access to the pontoons for O&M tasks are reviewed. The reviews are based on OceanTech´s documents for dry dock and cofferdam /9/ and /10/ regarding concepts and economic considerations.

A floating dry dock could come into use if a large very extensive repair is required on a pontoon e.g. after a ship collision. The dry dock will create dry access to all exterior surfaces of the pontoon and form an enclosed space in which the climate can be controlled for optimal working conditions, minimizing downtime due to weather. A cofferdam is used to establish dry access to the outside of the pontoon in the event of more local damages that require repairs.

A dry dock or a cofferdam are not needed in the construction period of the bridge and would not be fabricated until a requirement occur in the operation period of the bridge.

The use of a dry dock is expected to be primarily a safety tool in relation to a major ship collision. Damages in relation to a minor ship collision and local repair requirements in the splash zone are expected to be remedied more economically using a cofferdam (shown in Figure 8-4).

## 8.1 Concept for dry dock

OceanTech have developed two primary concepts for access to the surfaces of the pontoons from the dry dock construction:

- Grillage
- Gantry

The concepts have been developed with the aim of creating fully access of the submerged surfaces of the pontoon so that inspection and maintenance can be performed.

Dry dock with grillage is shown in Figure 8-1.

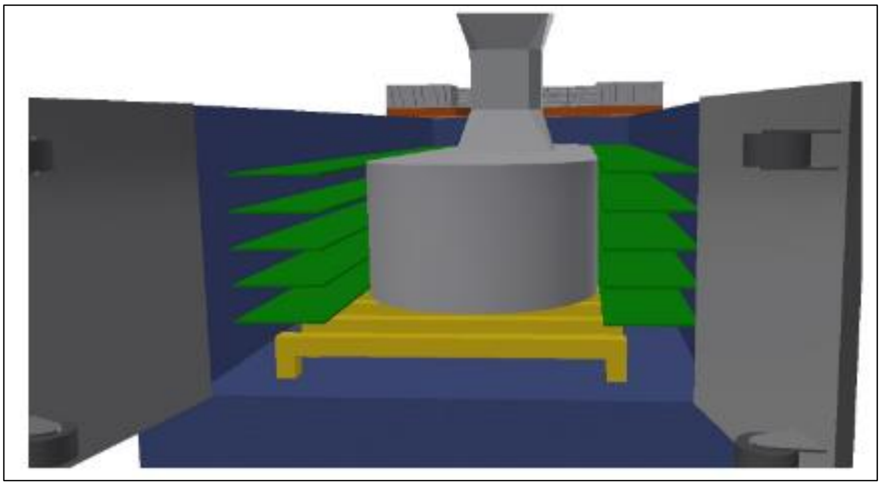

*Figure 8-1 Drydock with grillage (yellow) and scaffold (green)*

Dry dock with a gantry is shown in Figure 8-2.

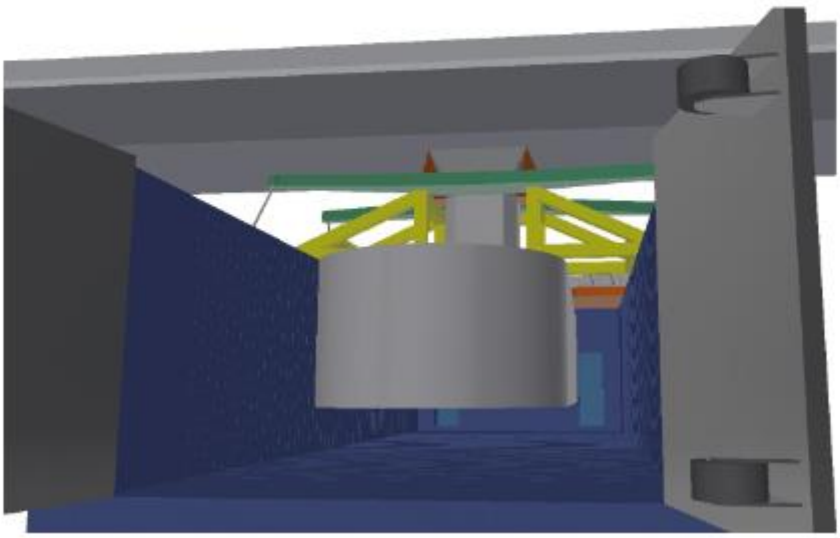

*Figure 8-2 Dry dock with gantry*

OceanTech recommends that consoles are installed at the side of the column underneath the bridge girder as shown in Figure 8-3.

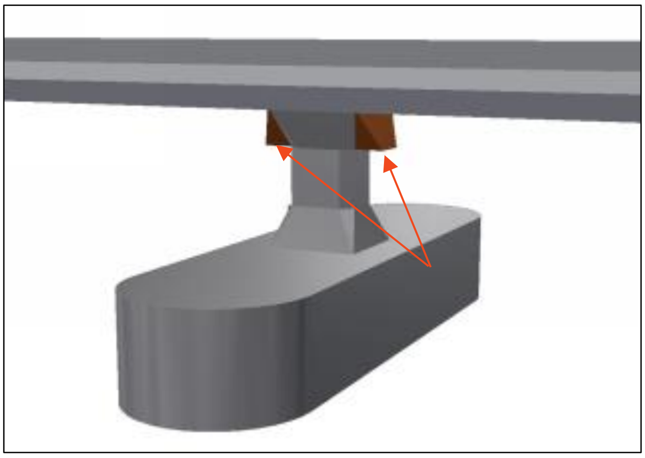

*Figure 8-3 Consoles at column for dry dock*

As the consoles will restrict the passage of the inspection gantry and therefor also restrict access to the soffit of the bridge girder, the size and location of the consoles should be assessed in more detail.

OceanTech states that there is no suitable dry dock on the market and therefore it must be manufactured from scratch if required. OceanTech estimates that a dry dock can be acquired for approx. NOK 99 million and approx. NOK 6 million for mobilisation, 20 days operation and demobilisation.

In ref. /10/ OceanTech describes the required temporary relocation of mooring lines when a dry dock comes into use. This operation must be performed before the dry dock arrives at the pontoon. Different locations for the mooring lines have been analyzed. One with the anchor of mooring lines situated central on the pontoon and another where the anchorages are positioned at the side of the pontoon.

For safety reasons the mooring lines cannot be anchored to the dry dock. Therefore, mooring lines must temporary be anchored to buoys or the adjacent pontoon. On the basis of the technical and economic analysis in ref. /10/ this work must be performed using tugboats and anchor vessels.

Before the mooring lines can be relocated to buoys or an adjacent pontoon it must be prepared for the anchoring of the mooring lines with fairlead chain stopper etc. The mooring lines must be returned to the original pontoons when repair works has been completed and the dry dock is removed.

## 8.2 Operation and maintenance

The Bjørnafjord project has in servals documents (e.g. /2/ and /8/) analyzed and recommended the best combination of materials and corrosion protection (cathodic protection and coating) which should not require maintenance for the required 100 years of service life for the bridge. Corrosion protection by dehumidification is in operation in all interior chambers that are not in use as active ballast tanks. Removal of marine growth and inspection of submerged elements should be done using ROV robots. Inspection of submerged elements are further described in ref. /11/.

Recommendations regarding fabrication of a dry dock (as a spare part) must be motivated by a quantitative risk analysis which analyses safe requirements for downtime and economic aspects. From an O&M aspect there should be no need for a dry dock for the first 100 years and it will only be used in the event of an unusual and special event. This should be evaluated in detail when the risk analyses for ship collision are completed. Ref. /16/ RAM-analysis refers to an earlier risk analysis that concluded the risk for a ship collision to be very low, which also is accepted to be the outcome of the pending risk analysis.

From an O&M aspect it will be a technical and economic advantage to include preparation of the structure for a dry dock concept for maintenance as well as the design of the dry dock itself. This should be a part of the bridge design from an early stage. Experience from other major bridge projects shows that technically and economic optimal access facilities will be ensured by involvement early in the design.

## 8.3 Cofferdam

OceanTech have worked with a technical and economic concept for a cofferdam to provide dry access to the side of pontoons. This concept is illustrated in Figure 8-4.

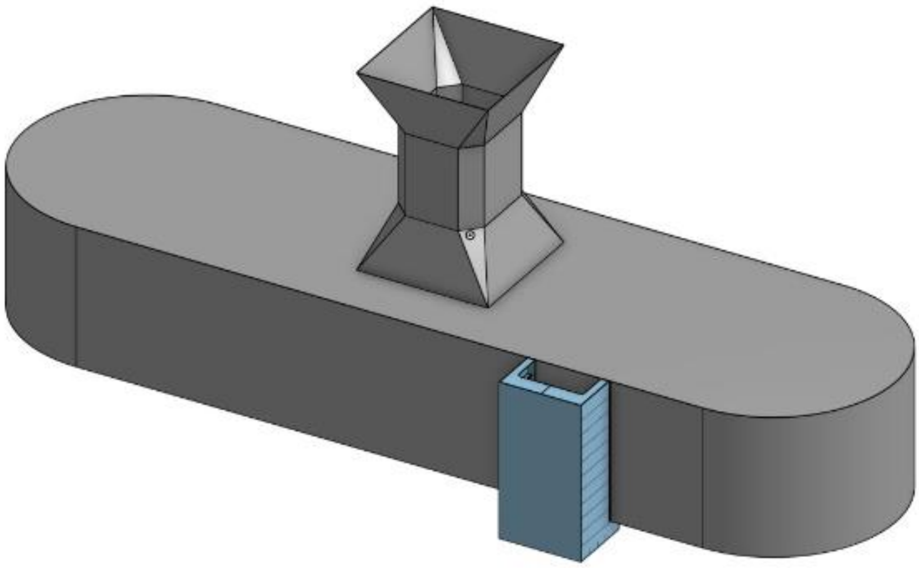

*Figure 8-4 Cofferdam as shown in ref. /9/.*

OceanTech estimates that a cofferdam can be acquired for approx. NOK 7 million and mobilization is estimated to approx. NOK 6 million for operation in 10 days and subsequently demobilization.

The cofferdam will be an appropriate tool for repairing minor but significant damages in the submerged and splash zone of the pontoons.

From an O&M aspect it will be a technical and economic advantage to include preparation of the pontoons for a cofferdam for maintenance tasks. The design for a cofferdam should be included in the bridge design and commence in an early staged of the design. Experience from other major bridge projects shows that technical and economic optimal access facilities will be ensured by involvement early in the design. The design of a cofferdam should be a flexible solution that can be operated in as many locations on the pontoons as possible.

The size of the cofferdam is not only given by O&M considerations, but the layout must in coming stages also be analyzed based on a quantitative risk analysis which amongst other describes the consequences of a ship collision. The frequency of a ship collision is expected to be very low, however this should be evaluated when the pending risk analysis is finalized.

OceanTech consider that it is possible to design a single type of cofferdam to operate on the complete set of pontoons as they are sufficiently monotonous, whether they are fabricated with or without anchorages for mooring lines. OceanTech recommend that the cofferdam is designed to cover an entire ballast tank on the inside of a pontoon and the pontoon frame must be situated so that horizontal loads are led directly into the bulkheads and stiffener of the pontoon.

It is assumed that the cofferdam is only fabricated when an incident or damage arises, so that the design and layout of the cofferdam can be adjusted to best suit the given location on the pontoon in question. Fabrication cost of a cofferdam will to some extend depend on the required delivery time. This should be evaluated when the final risk analysis is completed.

In the transverse direction of the pontoons, bulkheads, diaphragms and stiffeners are situated with a uniform distance of 2.5 m. In the longitudinal direction the bulkheads etc. are in the center arranged with a spacing of 800 mm and 862 mm towards the edges.

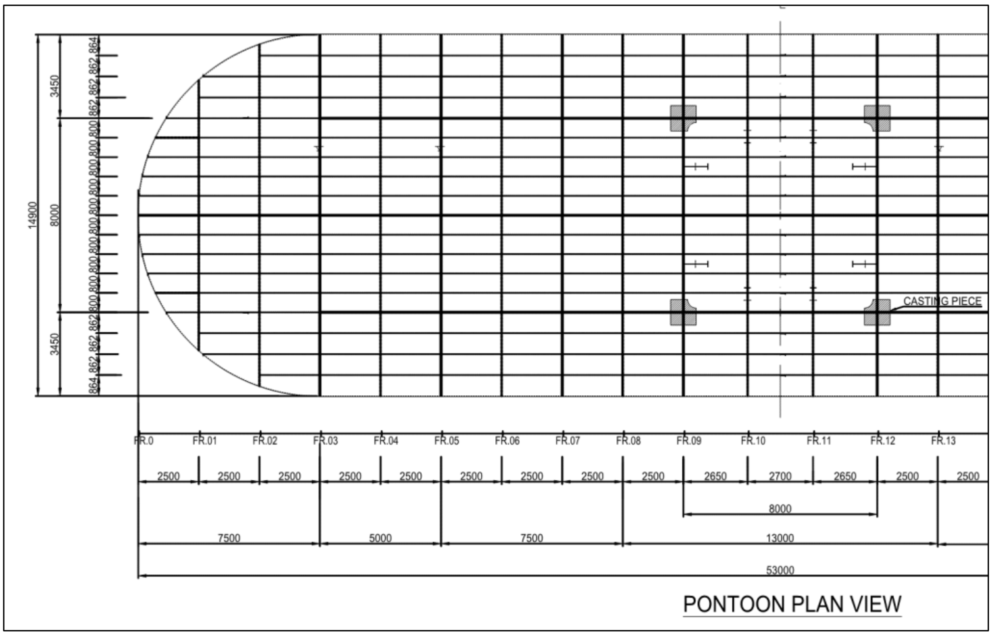


*Figure 8-5 Section of pontoon, plan view*

The size of the ballast tanks varies in width (ballast tank A and B) and shape (ballast tank C) as shown in Figure 8-6. In particular the rounded sections (ballast tank C) at the ends of the pontoons require a robust concept for the cofferdam if it should be able to cover all types of ballast tanks and all shapes of the pontoon.

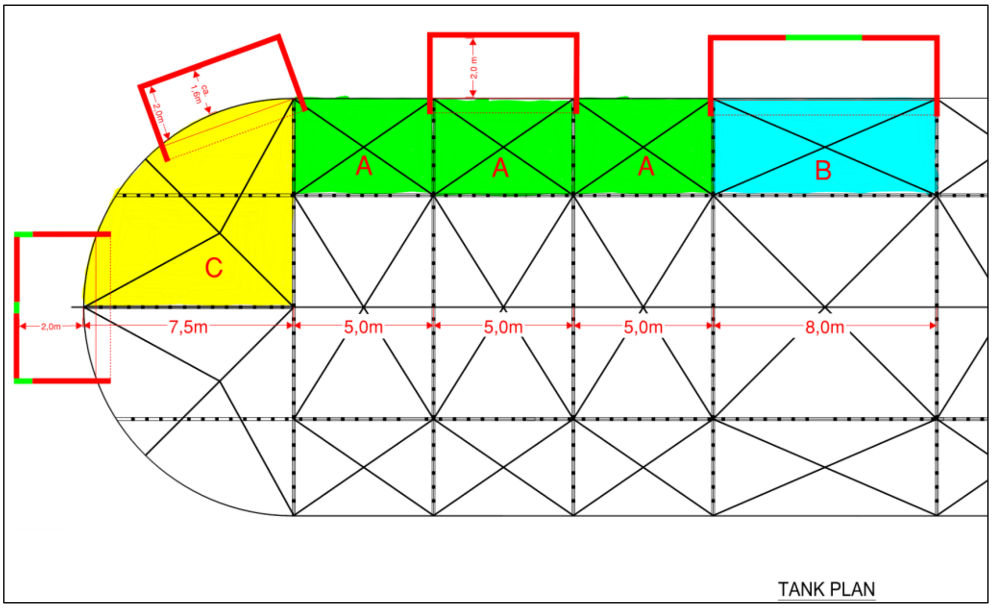


*Figure 8-6 The cofferdam situated at different locations on the pontoon.*

When a cofferdam is installed on the pontoon, according to /9/ there must be a working space inside the cofferdam of minimum 2.0 m to create sufficient space for a self-moving scissor lift or platform. The working space cannot be established if a cofferdam designed for installation on the plane surface of the pontoon is installed on the rounded section of the pontoon, as shown in Figure 8-6.

In the cofferdam design an extent of flexibility should be incorporated e.g. in form of modules that can take the rounded sections of the pontoon and the variable sizes of ballast tanks into account.

In ref. /9/ a brief description on how to seal the joint between pontoon and cofferdam is include. However, it is not described how the cofferdam is attached to the pontoon. This should be investigated further including a procedure for reestablishment of the coating on the pontoon after the cofferdam is demobilized.

# 9 Mooring of pontoons

## 9.1 Concept

The two consortia that in the conceptual stage 5 have worked with a floating cable stay bridge solution over Bjørnafjorden, have described two concepts for anchoring the mooring lines to the pontoons:

- Anchoring to the sides on the pontoons (AMC concept)
- Anchoring to the centre of the pontoons in mooring pools (OON concept)

Anchoring at the side of pontoons (described in ref. /7/ App. A, drawing 701) is shown in Figure 9-1.

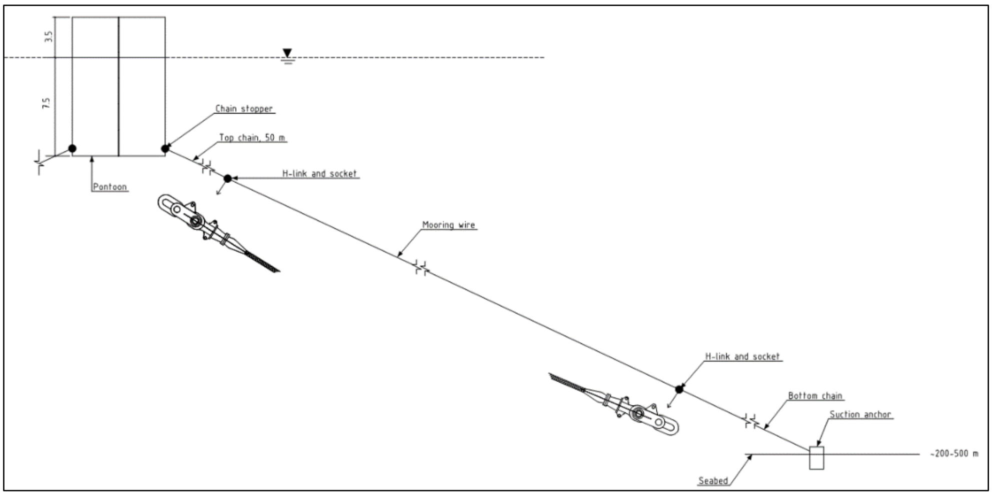


*Figure 9-1 Concept of mooring system (ref. /7/ appendix A, drawing 701)*

Anchoring to the centre of the pontoons in mooring pools (ref. /15/) is shown in Figure 9-2.

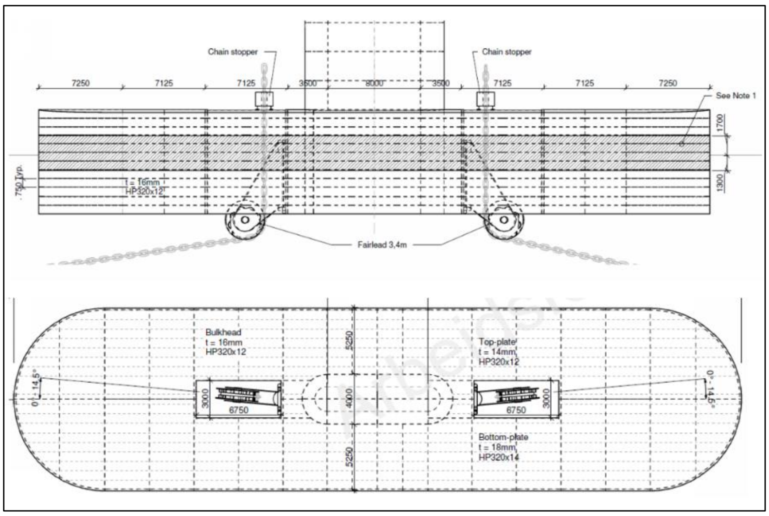


*Figure 9-2 Anchoring to the centre of the pontoons in mooring pools*

## 9.2 Materials

SINTEF recommends in a preliminary conclusion after comparing AMC and OON design that the following material, corrosion protection and other protection systems are used (see ref. /8/):

| Description | Material | Surface treatment | Other corrosion protective measures |
|---|---|---|---|
| Submerged chain stopper and fairlead | C-steel | NORSOK System 7B in submerged zone | CP in submerged zone |
| Atmospherically exposed chain stopper | C-steel | System 2 duplex coating in atmospheric zone | Alternatively, make chain stopper in CRA |
| Moonpool | C-steel with CRA in splash zone | NORSOK System 7B in submerged zone System 2 duplex coating in atmospheric zone | Alternatively, CRA in the entire moonpool |
| Top chain | R4 | None | Corrosion allowance, 0.8 mm/year in splash zone and 0.2 mm/year in submerged zone. |
| Sheathed steel wire rope | HDG coated steel wires | Hot dip galvanizing | Lubricant and external sheath |
| Fibre rope | Polyester | None | Design against abrasive wear |
| Bottom chain | R4 | | Corrosion allowance, 0.2 mm/year |
| Suction anchor or gravity anchor | C-steel | NORSOK System 7B | Cathodic protection |

It is noted that the two consortia estimate different service lives for top and bottom chains. Top chain materials and dimensions are similar in the two consortia, whereas there is a difference in the dimensions for bottom chains. The latter obviously gives a different lifespan. From an O&M perspective a solution with a longer service lifespan is recommended.

## 9.3 Operation and maintenance

The central anchoring of mooring lines to the pontoons could probably result in a material reduction and thus an economic saving. Whether the savings can compensate for the extra costs due to mooring pools should be assessed separately. The mooring pool solution will be an advantage if there is a need for the installation of a cofferdam, where a side anchoring of mooring lines would otherwise be situated.

From an operation and maintenance aspect mooring pools will cause a number of challenges. The solution with the central anchoring of the mooring lines creates several surfaces and transitions zones on the pontoons which must be inspected and possibly maintained. Furthermore, considerations must be given to provide safe access to the mooring pools during inspection and maintenance. From the cathodic protection hydrogen gases can develop and accumulate in the mooring pools and they must therefore be ventilated before workers can access the cavity safely.

On the top of the pontoons, mooring pools must be secured so that there is no danger of falling into the hole. If a railing would be installed around the mooring pools, it must be assessed whether access to the columns will be restricted.

In the side anchoring solution, the chain stopper and fairled will to an extent be protected by the cathodic protection installed on the pontoons. In the mooring pools chain stopper and fairled cannot benefit from the cathodic protection and the elements therefore require a separate corrosion protection.

Further analyzes must be performed to determine whether sheated steel wire rope or fiber rope should be used on the central parts of the mooring lines between top and bottom anchor chains.

As pointed out above there are a number of O&M disadvantages to the current OON concept, but it should be further investigated whether the concept can bring savings that outweigh the disadvantages.

The top and bottom chains are recommended in ref. /8/ to be designed with a corrosion allowance of 0.8mm/year in the splash zone and 0.2 mm/year for fully submerged items. Should the corrosion rate turn out to be higher than expected or service lifespan of the element is to be extended, the possibility of implementing a cathodic protection system should be considered. Since cathodic protection using sacrificial anodes are likely to have only a limited effect on chains, it could be considered to use impressed current cathodic protection (ICCP).

## 9.4 Spare parts

In order to minimise downtime of the bridge service due to unforeseen events, there should be components for the mooring system in stock if these items are not standard components or have an unacceptably long delivery time. It is assumed that documentation of downtime will remain part of the future design process. The design of mooring lines and related components are still in a phase where component are not designed and therefor delivery times cannot be estimated.

The failure of one or two mooring lines and the acceptable replacement times are assessed in the AMC document ref. /12/. The design is considered to be a relatively robust concept.

Replacement of mooring lines could be performed in accordance with the principles shown and described in ref. /9/ and /13/.

## 9.5 Access facilities

Access facilities are described in the OceanTech document ref. /10/. Tugboats and anchor handling vessels should be used. ROV robots must also be taken into use during the replacement.

# 10 Access strategy

This chapter outlines the access strategy for execution of O&M activities on the bridge. This includes access for personnel, equipment and materials.

Access facilities shall ensure, technical and economic optimal, performance of inspection, maintenance and rehabilitation of elements and systems. It shall be possible to perform these activities with minimal disturbance to road traffic, as well as maritime traffic. In addition, it shall be possible to comply with all occupational health and safety requirements as specified by the Norwegian legislation.

In case of an accident, permanent access facilities shall facilitate a safe evacuation route and safe access for rescue personnel.

The following design phases shall detail, how access facilities facilitate optimal O&M (e.g. based on material choice and dimensions). The project Design Basis shall detail robust requirements for access facilities that balances technical (incl. safety for personnel) and economic consequences.

Permanent access facilities comprise:

- Shared use path (SUP) which also shall provide access for an Under-Bridge Inspection Unit

- Roadway incl. shoulder

- Service roads, i.e. roads other than the above that also provide access to, or close to, the bridge

Non-moveable equipment comprises:

- Catwalk in bridge interior from abutment to abutment (passage by foot or using electrical vehicles. The latter require that turnaround areas are established at certain locations).

- Interior and exterior stairs, platforms, doors and hatches. Exterior doors and hatches shall be equipped with a locking system. Doors and hatches shall be watertight. Passage from roadway level to the bottom of the pontoons shall be possible. Passage from roadway level to tower top and bottom and between tower legs beneath the roadway girder. Passage 'from A to B' includes transport of personnel, materials and equipment. Verification shall be performed as part of the design. At certain locations, e.g. in piers, a shaft for hoisting of materials and equipment will be beneficial. This also needs to be verified as part of the design. In addition, it shall be possible to inspect, maintain and replace bearings from permanent access facilities. As a secondary access and evacuation route passage from pier interior to pontoon exterior shall be possible. This allow for entering or exiting the bridge by boat.

- Interior and exterior railings
- Anchor points for rope access (tower, piers and pontoons)
- Anchor points for a Sky Climber (tower)
- Bollards on pontoons (for boats)

Permanent moveable equipment comprises:

- Elevator in tower leg (from the bottom to the top with the possibility to stop and exit in between, incl. stop and exit at crossbeam and at roadway level
- Self-propelled inspection gantry beneath the bridge girder (preferably one that travels on both types of bridge girders – concrete and steel)

Portable access equipment comprises:

- Bucket truck
- Underbridge inspection unit (travel along the shared use path in one side of the bridge girder and along the shoulder / slow lane on the other side of the bridge)
- Sky Climber for tower*
- Moveable ladders/scaffolding, e.g. in the bridge girder interior*
- Electrical vehicles for the bridge girder interior*
- Possibly small vehicles for travel on the shared use path
- Boat or barge
- Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicle (AUV)
- Divers equipment
- Rescue equipment (moveable tripod with hoist, etc.)

*Should be delivered as part of the bridge. Remaining objects shall be standard equipment, which is readily available on the market, and accommodated for during design of the bridge.

# 11 Risk-based inspection and maintenance

## 11.1 Introduction

The purpose of risk-based[1] inspection (RBI) and reliability centred maintenance (RCM) planning is to ensure that inspections and scheduled replacements are performed before compromising safety as well as minimising life cycle costs. The latter has been a goal for O&M planning during the past decades, where sampling/theme-wise inspections are common.

Deterioration and failure of elements and systems are associated with a large degree of uncertainty. Risk- and reliability-based methods are excellent methods when dealing with uncertain processes.

When infrastructure managers introduce RBI, they often seek to optimise current practise (e.g. SVV in Norway and Rijkswaterstaat in the Netherlands) and often targeted towards major infrastructure assets, like a major bride or a major tunnel that is staffed daily. Similar considerations have been applied during inspection planning for other major bridges, incl. Queen Elisabeth II in UK, the future Messina bridge in Italy etc.

In many countries (as in Norway) handbooks specify rules for inspection and maintenance which are robust, when dealing with a portfolio of structures of different age, geometry, material etc. Often these structures undergo principal inspection every 5-6 years. Handbook-based inspection and maintenance rules may not be economic optimal when considering major bridges with many similar details, difficult access and with an almost daily staffing. RBI and RCM methods can be used for economic optimisation of inspection and maintenance with due consideration of reliability, safety and any other constraints.

RBI has been applied in the oil and gas industry (incl. offshore) during the latest decades.

## 11.2 RBI

RBI comprise elements and systems for which the failure pattern is predictable and for which the remaining, acceptable deterioration can be determined based on the result of a condition evaluation. One example is corrosion of a steel girder as failure mode, where coating constitutes the protection system. RBI shall contain a description of inspection type, location and interval. The inspection program shall be optimised according to a vulnerability criterion (vulnerability, see Appendix A) for every element/system.

[1] In some projects the evaluation of consequences is omitted. Then the expression 'reliability-based inspection' is used.

## 11.3 RCM

RCM comprise elements and systems for which the failure pattern is predictable but for which the remaining, acceptable deterioration cannot be determined based on the result of a condition evaluation. Such elements and systems are often mechanical, hydraulic and/or electrical. RCM shall contain inspection interval (if possible), mitigation measures, maintenance interval and needed spare parts in order to maintain a acceptable level of safety.

## 11.4 Method

The use of RBI and RCM methods shall ensure that:

- Correct individual inspection and maintenance strategy is proposed for every element and system with special attention towards critical and/or vulnerable elements and systems.
- Inspection plans are evaluated and optimised during the operational phase based on inspection results in order to prolong service life, optimize inspection frequency and prevent escalation of damages.
- The bridge elements and systems operate as intended and according to specified reliability levels.
- Identified risks are managed through inspection and maintenance according to acceptance criteria related to fatalities, environmental damage, economy and availability.
- Operation and maintenance costs are at optimum.

During RBI and RCM planning each element and system is analysed and the optimal individual strategy is established. These individual strategies are then combined and adjusted in order to establish an optimal inspection plan for the entire bridge (the results of this report shall contribute to an increased and systematic detailing of O&M during the next phases of the project).

# 12 Structural Health Monitoring System (SHMS)

## 12.1 Introduction

The purpose of a Structural Health Monitoring System (SHMS) is to provide data for:

- verification of design
- basis for maintenance decision-making (e.g. estimation of remaining service life)
- basis for operational decision-making (e.g. traffic restrictions related to incidents)

SVV wants a lean SHMS that collects, processes and presents 'need to know' and not 'nice to know' data. The reasons are listed below:

- a SHMS comprise elements and systems with a short service life / become obsolete quite fast, i.e. O&M related costs are significant
- collection and interpretation of data (calculations etc.) may come with a significant cost

It should therefore be carefully considered which monitoring systems should be permanent (monitoring of mooring prestress) and which can be removed after design verification of structural response and which can be launched as campaigns subsequently (fatigue in orthotropic steel girder). That is, an SHMS should be designed as consisting of sub-modules that can be established, used, and shut down as needed.

A Structural Health Monitoring System is needed, see e.g. /12/, comprising a monitoring part (sensor system and data acquisition) and a data evaluation part.

The data evaluation module may, if needed, comprise the following modules:

- interpretation of data (detection of abnormal response that exceeds specific thresholds)
- estimation of remaining service life
- notification of extreme events
- notification of alerts and warnings (e.g. notification of the bridge operator in case of ship impact)

The data evaluation module for elements and systems above and below water is described in the following section.

## 12.2 SHMS for elements and systems above and below water

As part of the data interpretation module and related response activities, the following shall be included:

- Comparison of anemometer readings (weather data, e.g. wind speed) with relevant design values
  - To assess wind load response of the structure in case of extreme wind loads
  - To warn users in case of reduced comfort due to high wind speeds
- Correlation of GPS and tilt-meter readings with results obtained from the finite element analyses used to design the bridges
  - To assess the combined load effects of wind, wave, tidal currents and traffic loads in order to update service life models
  - To warn users in case of visual deformations of bridge girder, tower and piers
- Stay cable monitoring (visual comfort and fatigue, possibly launched as a campaign)
- Weigh-In-Motion (WIM) data (traffic load assessment, possibly launched as a campaign)
- Permanent monitoring of mooring lines. Comparison of such data with exposure and structural response data (ref. above) shall be performed. As part of the SHMS design, it should be considered if draught sensors could provide need to know data.
- Cathodic protection monitoring, se section 7.1.3.

As part of the remaining service life module, the following shall be included (possibly as a campaign):

- Fatigue in welded joints of the orthotropic steel deck. To this aim, strain and external exposure data (traffic and temperature) shall be combined into appropriate fatigue accumulation models to determine the remaining fatigue life.

As part of the extreme event notification (e.g. ship impact), the following shall be included:

- Provide data that informs decision-making regarding the launch of a special inspection. In particular, following a ship impact event, acceleration data and tilt-meter data shall be analysed to characterize the intensity of the event and shall also be compared with the corresponding design data.

# 13 References

/1/ Bjørnafjorden, VegRAMS: Mandat og føring for arbeidet 2020-17-04

/2/ Preferred solution, K12 – Appendix O, Material technology and steel in marine environment, Ferry free E39 – Fjord crossings Bjørnafjorden: 2020-04-17

/3/ Design Basis Bjørnafjorden, Side- and anchored floating bridge, rev. C, 2014-03-07

/4/ Bjørnafjorden Suspension Bridge, K1 & K2 Life Cycle Cost Study, doc. no. SBJ-20-C3-AAS-40-RE-001 Rev 0, 02.06.2017

/5/ Bjørnafjorden Suspension Bridge, K1 & K2 Management, Operation and Maintenance, doc. no. SBJ-20-C3-AAS-40-RE-002 Rev 0, 02.06.2017

/6/ Concept development, Floating bridge E39 Bjørnafjorden, Preferred solution, K12 – main report, doc. no. SBJ-33-C5-AMC-90-RE-100, Rev. 0, 15.08.2019

/7/ Concept evaluation Appendix A, Floating bridge E39 Bjørnafjorden, Drawings binder, doc. no. SBJ-32-C5-AMC-90-RE-101 Rev 1, 31.08.2019

/8/ Material selection, surface treatment and corrosion protection for floating bridge Bjørnafjorden, SINTEF Report no. 2020:00852, Rev 0.2 2020-09-07

/9/ Cost Estimate – Cofferdam on Pontoons, OceanTech dok. no. 20008-Z-RA-002, Rev 01, 2020-09-10

/10/ Methodology for dry access to pontoons of floating bridge Bjørnafjorden, OceanTech dok. no. 19008-Z-RA-001, Rev 03, 2019-07-19.

/11/ Inspection philosophy and scope estimates for the marine componnets, Bjørnafjorden, ferry free E39, Statens Vegvesen.

/12/ Preferred solution, K12 – Appendix M, Mooring System, Ferry free E39 – Fjord crossings Bjørnafjorden: 2019-08-15

/13/ Preferred solution, K12 – Appendix N, Construction and marine operations, Ferry free E39 – Fjord crossings Bjørnafjorden: 2019-08-15

/14/ Design Basis, E39 Bjørnafjorden – Rev A, 2020-10-08

/15/ K12 - Design of mooring and anchoring, Rev. 0, 2019-10-15

/16/ K12 – RAM-analysis Rev 1.0, 2020-11-13

# Bilag A Risk Based Inspection, Maintenance and Rehabilitation (Methodology)

# 1 Concept for Reliability-based Inspection, Maintenance and Rehabilitation

## 1.1 Basic terms

Component:

A component can either be an element (e.g. stay cable, bolt) or a system (e.g. dehumidification system, structural health moniroting system). A system may also comprise one or more elements.

Criticality:

An components criticality class is a measure related to the risk of failure of the component developed in the operation period of the bridge.

The risk is in principle a summation of all risks related to all (identified) possible failures that may occur for the component in the operation period. A risk is defined as the product of the likelihood of the failure to occur and the consequences of the failure.

Vulnerability:

An components vulnerability class is a measure of the time period that is expected for the failure to develop after the failure has been observed to initiate. The vulnerability class is determined by considering all failures as identified for the component.

For each component is determined the values for:

1 Criticality Class

2 Vulnerability Class

by considering all (identified) possible failures of the component.

It is important that an adequate component hierarchy is used with proper relation to as well design properties and inspection, maintenance and rehabilitation methodology.

## 1.2 Introduction to RBI and RCM

Risk based Inspection, Maintenance and Rehabilitation (I, M and R) planning may be performed using the concepts of Reliability Based Inspection (RBI) and Reliability Centered Maintenance (RCM).

RBI and RCM methods ensure that:

- Correct maintenance strategy is proposed for all elements and systems with adequate attention towards critical and/or vulnerable elements and systems.

- Inspection plans are optimised, evaluated and updated during the operational phase based on inspection results in order to prolong service life, optimise inspection frequency and prevent escalation of damages, i.e. also decreasing maintenance costs.

- The bridge elements and systems operate at specified availability and reliability levels.

- Identified risks are either eliminated through design, or otherwise managed through I, M and R and reduced to levels where fatalities, environmental damage, and operational risks meet the predefined acceptance criteria.

- Operation and maintenance costs are at optimum and benchmarked against the life cycle cost analysis.

The method consists of two main parts:

- Reliability Based Inspections (RBI):
  Inspections to be carried out on components for which the failure pattern is known and for which the remaining, acceptable deterioration can be determined based on the result of a condition evaluation (which may include an estimate of remaining structural capacity).
  Meaning: components that are maintained <u>condition based.</u>
  Example: concrete or steel pylon leg

- Reliability Centered Maintenance (RCM)
  Maintenance to be carried out on components for which the failure pattern is known but for which the remaining, acceptable deterioration cannot be foreseen based on the result of a condition evaluation.
  Meaning: components that are maintained/replaced either:
  - when a failure has occurred (non-critical components)
    Example: bulb in lighting
  - in due time before a failure is expected to occur (critical components).

Expected time for failure is estimated according to empirical model
Example: racon (a type of radar transponder commonly used to mark maritime navigational hazards)

The method has been used in its full extent, as far as bridges are concerned, in Detailed Design of the Messina Strait Bridge in Italy as well as several existing bridges such as Queen Elisabeth II crossing in UK. Ref. /1/ describe a semi-quantitative use of the method.

The method is especially valid for unique structures, as the Bjørnafjord cable-stayed bridge, for which the complexity and the number of components of certain types call for theme-wise I, M and R plans. Further, it is for such project appropriate to benchmark design towards Operation and Maintenance and thereby ensure that O&M concerns are integrated in the design.

# 2 Risk Based I, M and R methods for Bjørnafjorden cable-stayed bridge

The risk-based methods are used in the three main O&M related tasks in the current stage of the VegRAMS process:

- assessing of criticality and vulnerability for elements and systems
- highlighting O&M aspects before next design phase
- establishment of an initial Inspection, Maintenance and Replacement Program (I, M and R Program)

Above items are treated separately in the following sections.

## 2.1 Assessing Criticality and Vulnerability for elements and systems

The initial conceptual design for a component, which may be determined rather generic, is reviewed regarding its criticality and its vulnerability, all according to the actual exposure zone and according to the other impacts (wear and tear, static and dynamic loading etc).

The analysis will for each component define if the component is related to RBI or to RCM.

The criticality and vulnerability assessment comprise three steps:

1. Each type of component of the bridge is rated with a criticality based on general experience with the performance of this type of component. The criticality is rated inconsiderable, low, medium, high or very high. The criticality is derived from a criticality matrix as shown in Table 2.2.

   E.g. a component type is rated highly critical, if failure by experience is likely, and if consequences of its failure at the same time also is known to be severe.

2. Each type of component of the bridge is rated with a vulnerability based on an estimate of the criticality in relation to the expected time period ("time to failure") in which a failure development can be observed. The vulnerability is rated very robust, robust, semi-robust, vulnerable or very vulnerable. The vulnerability is derived from a vulnerability matrix as shown in Table 2.3.

   E.g. a component type is rated very vulnerable, if criticality is very high and by experience time for failure development is short - days or hours.

3. The design is carried out (not part of the current stage of the VegRAMS process). The designs of all RCM components rated high or very high are

adjusted until their criticalities can be reduced to either low or medium. The designs of all RBI components rated vulnerable or very vulnerable are adjusted until their vulnerabilities can be reduced to either robust or semi-robust.

**Consequence of failure**

To apply this approach, rating of the consequences and probabilities are needed for each component. Table 2.1 shows a semi-quantitative allocation of consequence which serve as basis for the criticality analysis. A factor of 4 has been applied between the different consequence classes, 1-4, so a proper differentiation between functional failure consequences can be made. The considered ratings of consequences comprise four types of consequences:

- Unavailability
- Costs
- Fatalities (risk to humans)
- Environmental damage

Definition of the four consequences and the interrelation between the different consequence categories are described in the following.

*Unavailability* is a measure that reflects the expected amount of time during which partial or total bridge closure for road users would be required, if a functional failure was to occur. Unavailability relates to the societal impact and the cost of operation interruption, and is measured and categorised as shown in Table 2.1. It is assumed that users in mean will have a 25 km detour if BSB will be completely closed. The detour takes approximately 17 minutes extra (90 km/hour assumed). According to ref. /3/ the annual daily traffic between Stavanger n. and Hordaland gr. is between 3400 and 9000 vehicles/day, i.e. 6200 vehicles/day in mean. According to SVV at meeting 19.04.2016 an annual daily traffic of 12.000 vehicles/day in 2045 may be used as reference. 10% heavy vehicles have been assumed. According to ref. /4/ costs associated with time delay may be taken as 211 NOK/hour for light vehicles (taken as a mean value of business, commuter and leisure travel) and 676 NOK/hour for heavy vehicles (trucks). According to ref. /4/ costs associated with the actual travel (detour) may be taken as 1.74 NOK/km for light vehicles and 5.05 NOK/km for heavy vehicles (trucks). Level of detailing of assessment of costs is considered sufficient at the present stage of the project. User cost due to traffic disturbance has been estimates as (2016 values used directly)

12000 x [ 0.9 x (1.74 x 25 + 211 x 17/60) + 0.1 x (5.05 x 25 + 676 x 17/60) ] = 1.5 million NOK per day (approximately 0.14 million EUR per day).

Furthermore, it is foreseen that closure of one lane or one side of the bridge will cause minimal congestion if nothing at all, i.e. cost of possible congestion will not be considered. Because of this, the relation between costs and unavailability measured in closure of a single lane is a guestimate.

*Cost* (Economic consequence) is a measure that reflects the additional expected costs, if a functional failure was to occur. Costs are related to the additional maintenance cost that would be required to bring the system back to a state, where it can meet expected life targets, including spare parts, inspection, and repair. In addition, if additional maintenance and repair was not carried out, the cost category includes any costs associated with reduction in life span, due to loss of reliability or structural integrity.

*Fatalities* is a measure that reflects the expected impact on health measured in injuries or fatalities, if a functional failure was to occur. Fatalities (Risk to humans) is estimated based on recent studies for another European major bridge, ref. 1, where the cost of 1 fatality is approximately 3 million Euro and serious injuries are 1/10 of a fatality – 0.3 million Euro. These numbers are used for the present assessment also.

*Environmental damage*, is a measure that reflects the expected impact on the environment and the extent to which government environmental regulations or standards have been breached, if a functional failure mode was to occur, is treated in a more qualitative way, hence, there is no strict relationship to cost.

Table 2.1 provides ratings for each type of consequence with four levels of ratings. For the failure of a given type of component, it will be the most severe consequence rating, which determines the overall rating.

*Table 2.1 Consequence ratings for failure of a given type of component. *'Disastrous' consequences are handled as a part of ULS verification. (1 EUR is approximately 10.5 NOK)*

| **Consequence Class** | **Unavailability (days/year)** | **Costs (Euro)** | **Fatalities (Risk to humans)** | **Environmental damage** |
|---|---|---|---|---|
| Insignificant | None | <0.04 million | None | None |
| Marginal | 1 Roadway lane, 15 hours | 0.04 million | Psychological | None or temporary minor damage |
| Serious | 1 Roadway lane, 5 days | 0.18 million | 2 First Aid Injuries | Temporary severe damage |
| Severe | Complete disruption of the bridge, 5 days | 0.71 million | 2-3 Serious Injuries | Long-term effects |
| Very severe | Complete disruption of the bridge more than 5 days | > 0.71 million | More than 3 Serious Injuries | Permanent minor damage |
| Disastrous* | > 1½ year | > 75 million | > 23 fatalities | Permanent severe damage |

**Likelihood of occurrence**

Probability of failure, which may cover a large range of events, may in the conceptual design phase be rated qualitatively into five levels. The probabilities are defined based on the likelihood of failure to occur during the service life for the population of each type of component:

- Very unlikely
- Unlikely
- Occasional
- Likely
- Very likely

**Criticality**

Based on the range of consequences and probabilities for a failure, Table 2.2 provides the criticality rating of a given component. The table shows the criticality matrix with a rating into very high, high, medium, low and inconsiderable. A colour coding of red, yellow and green has been applied to indicate the criticality rating. Moreover is for convenience below the matrix inserted a value for the criticality classes.

The matrix shall be used qualitatively in the current stage of the VegRAMS process. Later in the design stage a quantitative approach can be used for some components.

If a failure risk (likelihood times consequence) is unacceptable (too high), it must be lowered, for instance by either:

- strengthening the design and / or
- add protection measures and / or
- remove/reduce impacts

*Table 2.2 Criticality matrix. *System or element failures that could result in 'disastrous' consequences are handled as a part of the ULS design.*

| Likelihood of occurrence | Consequence of failure | | | | | |
|---|---|---|---|---|---|---|
| | Insignificant | Marginal | Serious | Severe | Very severe | Disastrous* |
| Very unlikely | Inconsiderable | Inconsiderable | Inconsiderable | Low | Low | High |
| Unlikely | Inconsiderable | Inconsiderable | Low | Medium | Medium | High |
| Occasional | Inconsiderable | Low | Medium | Medium | High | Very High |
| Likely | Inconsiderable | Low | Medium | High | Very High | Very High |
| Very likely | Inconsiderable | Medium | High | Very High | Very High | Very High |

Criticality classes, C0: Inconsiderable, C1: Low, C2: Medium, C3: High, C4: Very High

The criticality is subsequently used as input to the vulnerability evaluation, see next section, and directly as input for assessment of the maintenance strategy for components where degradations cannot effectively be measured before failure (RCM-components).

### Vulnerability

The time to failure for a certain degradation mechanism is the time over which the progress of failure can be observed by inspection, monitoring or by other means based on normal best practice. For example, an overload failure of a lamella in an expansion joint will happen immediately (classified as hours), whereas a failure of topcoat on towers will happen over several years. The same holds for gradual deformation versus a brittle failure mode.

Table 2.3 shows a set of vulnerability rates, depending on criticality class and time to failure:

- Very Robust (R0)
- Robust (R1)
- Semi Robust (R2)
- Vulnerable (R3)
- Very Vulnerable (R4)

*Table 2.3 Vulnerability matrix.*

| Criticality | Time for failure development | | | | | |
|---|---|---|---|---|---|---|
| | Years | Quarters | Months | Weeks | Days | Hours |
| Inconsiderable | Very Robust | Very Robust | Very Robust | Very Robust | Very Robust | Very Robust |
| Low | Very Robust | Robust | Robust | Semi-Robust | Semi-Robust | Semi-Robust |
| Medium | Robust | Semi-Robust | Semi-Robust | Semi-Robust | Vulnerable | Vulnerable |
| High | Robust | Semi-Robust | Semi-Robust | Vulnerable | Vulnerable | Very vulnerable |
| Very High | Semi-Robust | Semi-Robust | Vulnerable | Vulnerable | Very vulnerable | Very vulnerable |

Vulnerability classes, R0: Very Robust, R1: Robust, R2: Semi-Robust, R3: Vulnerable, R4: Very Vulnerable

The rated vulnerability is used to define the required inspection and maintenance program for RBI components. If any type of component is considered very vulnerable, the design and the I, M and R program shall be adjusted until the vulnerability of the designed component is reduced to robust or semi-robust. The vulnerability may be decreased by selection of other materials, increase of inspection regime or by installation of adequate sensors connected to a Structural Health Monitoring System.

## 2.2 Highlighting O&M aspects before next design phase

A relatively small group of components consume 80 to 90 percent of the total LCC costs. Coating of steel structures, roadway wearing course, mechanical and electrical installations are normally among these components in an ordinary cable-supported bridge.

For each of these components the relevant alternative designs may be analysed in future stages of the project. The set of solutions giving minimum LCC for the total assemblage shall be selected.

The analysis includes implementation/incorporation of access facilities and access equipment in the design.

## 2.3 Establishment of an Initial Inspection and Maintenance Analysis (IMAA)

Some basic parameters for the specific element/system have to be assessed before an initial I, M and R program can be generated. The parameters are:

- Time for failure development, $\Delta T_f$ , is an estimation of the period of time it takes the failure mode to evolve from "detected for the first time" to a predefined failure limit.

- Time for damage tolerance, $\Delta T_d$ , is an estimation of the period of time a predefined failure of the element/system can be tolerated.

The appropriate methodology, RCM or RBI, will be determined by comparing the time for failure development with the selected inspection interval. If time for failure development is higher than selected inspection frequency, then the element/system is a RBI element/system, i.e. failure will not happen before next inspection. Otherwise the element/system is a RCM element/system, i.e. failure may happen before next inspection.

It should be noted that time for damage tolerance has not been accounted for in the above framework for categorisation into RBI or RCM elements/systems.

An initial inspection and maintenance strategy is formulated based on criticality ratings for RCM elements and systems and on vulnerability ratings for RBI elements and systems.

A default inspection interval for RCM elements/systems is proposed automatically using the criticality analysis result, see Table 2.4.

*Table 2.4 Assessment of default inspection interval based on criticality.*

| **Criticality** | **Criticality class** | **Default principal inspection interval** |
|---|---|---|
| Inconsiderable | C0 | 5 years or more |
| Low | C1 | 5 years |
| Medium | C2 | 2 years |
| High | C3 | 1 year |
| Very High | C4 | 6 months or less |

For some RCM systems and elements with continuous monitoring there is no need for inspections at all, because it is known at all time, whether the system or element is working or not and may not need maintenance. However, for many systems there is a need for service inspections in order to have the system running at all times (and in order to ensure an optimal maintenance plan), and in those cases the default inspection interval is nice to know.

A default inspection interval for RBI elements/systems is proposed automatically using the vulnerability analysis result, see Table 2.5.

*Table 2.5 Assessment of default inspection interval based on vulnerability.*

| **Vulnerability** | **Vulnerability class** | **Default principal inspection interval** |
|---|---|---|
| Very Robust | R0 | 5 years or more |
| Robust | R1 | 5 years |
| Semi-Robust | R2 | 2 years |
| Vulnerable | R3 | 1 years |
| Very Vulnerable | R4 | 6 months or less |

The proposed default inspection interval may be optimized during further RBI analyses.

In addition to the recommended/default principal inspection interval the initial I&M-plan will recommend a maintenance strategy. If time for failure development is less than the selected inspection frequency, the proposed maintenance strategy will be "Immediately plan or perform corrective/periodic preventive maintenance". In other words, you need to have spare parts in stock/on-site when performing inspections. If the component is "failed" it is named "corrective maintenance" and if the component is not failed it is named "periodic preventative maintenance". For RCM elements and systems, the inspection interval may be interpreted as a maintenance interval. On the other hand, if time for failure development is larger than the selected inspection frequency, the proposed maintenance strategy will be "Periodic corrective/preventive maintenance". In other words, if not cost optimal (could be other objectives also) you do not need to correct a possible failure during the inspection where failure is first identified. Instead, it is to be evaluated if "preventive maintenance" is cost optimal (could be other objectives also) or you can simply wait until failure happens "corrective maintenance". For RCM elements and systems, the maintenance interval is probably between 1 or 2 times the inspection interval preferably set by an Mean Time Between Failure (MTBF) estimate.

Circuitization is an analysis that determines bridge elements and systems that are exposed to the same deterioration mechanism/rate, which are then grouped as circuit.

When selecting reference areas within an component it is important to include vulnerable areas, or areas where the degradation rate is highest, which in bridges terminology may include:

- Areas where the protective system is applied during construction phase.
- Areas where design changes during construction phase have been made.
- Most difficult areas from a workmanship point of view.
- Prone areas identified during warranty inspection (e.g. concrete repairs).
- Areas subjected to mechanical wear from e.g. inspection gantries.
- Those areas that are most vulnerable towards deterioration, weather, fatigue, vibration etc.

If it is identified that the above areas degrade differently, they may be treated separately in the I&M-plan, if it is beneficial from an economical point of view.

Inspection and maintenance planning utilises the results of the initial Inspection and Maintenance Activity Analysis (IMAA) and has the objective of creating an overall optimal inspection and maintenance programme. This is achieved by performing similar works at the same time. The main relations to be considered are:

- Type of activity
- Activity intervals
- Needed competences
- Cost

- Geographic location
- Use of traffic regulation
- Access facilities
- Consumption of man-hours
- Consumption of spare parts
- Robustness/redundancy
- Failure impact on other elements/systems
- Acceptance criteria

Using a Bridge Management System (BMS), where inspection and maintenance results together with economy is gathered, and the I&M Manual, and the IMAA framework and the LCC framework as reference, an overall optimal inspection plan may be established and maintained/updated.

At the present stage such an optimized plan has not been elaborated as:

- Design needs to mature.
- Details on the actual O&M organisation are being developed.
- Actual supplier information is an important input and needed.
- Important changes during the construction phase are important input and needed.
- Specificatins of the SHMS system is not completed

In the operation phase, I, M and R tasks will be executed as outlined in previous phases, and feedback will be provided to adjust the risk based I, M and R program based on inspection and maintenance results. It is expected that a Bridge Management System (BMS) will serve as a proper platform for this work.

Updating of risk based I, M and R programme includes establishment, review and/or adjustment of the following items:

- Acceptance criteria’s
- Condition thresholds (RBI elements and systems)
- Failure probability percentiles (RCM and RBI elements and systems)
- Time for failure development which lead to an adjusted vulnerability level

- Time for damage tolerance
- Failure detection method
- Mitigation measures
- Inspection interval
- Maintenance type
- Maintenance interval
- Repair time
- Spare part requirements in order to minimize repair time if critical
- Spare part stock
- Key parameters to monitor
- Inspection result
- Degree of uncertainty related to the degradation process (RBI elements and systems) or probability of failure density function (RCM elements and systems)
- Verification that the inspected areas/items are good representatives.

# 3 References

/1/ Messina Bridge – Reliability Based Inspection and Reliability Centered Maintenance – The Challenge, Poul Linneberg et al., IABMAS 2012

/2/ Statens Vegvesen: Håndbok R411, Bruforvaltning, 2018

/3/ Statens Vegvesen: Ferjefri E39, Hovedrapport, 2012
http://www.vegvesen.no/_attachment/415285/binary/711216

/4/ Statens Vegvesen: Håndbok V712, Konsekvensanalyser, 2018

# Bilag B Risk Based Inspection and Maintenance analysis

# Risk based Inspection and Maintenance

E39 Bjørnafjorden Bridge - Operation and Maintenance



## How to fill in the Risk based Inspection and Maintenance sheets

**1) Define the system/elements**

**2) Failure mode: Identify for each element the set of functional failures**

**3) Criticality Matrix: Fill in for each functional failure**

3a) Assess the consequences for the bridge regarding unavailability, cost, fatalities and environmental damage given a function failure

3b) Assess qualitatively the probability of the worst consequence happening, given the functional failure has occurred

| Likelihood | Consequence of failure | | | | | |
|---|---|---|---|---|---|---|
| | Insignificant | Marginal | Serious | Severe | Very Severe | Disastrous* |
| Very unlikely | 0 | 0 | 0 | 1 | 1 | 3 |
| Unlikely | 0 | 0 | 1 | 2 | 2 | 3 |
| Occasional | 0 | 1 | 2 | 2 | 3 | 4 |
| Likely | 0 | 1 | 2 | 3 | 4 | 4 |
| Very likely | 0 | 2 | 3 | 4 | 4 | 4 |

| Criticality | | Default principal inspection interval (years) |
|---|---|---|
| Class | Criticality | |
| C 0 | Inconsiderable | (5 or more) |
| C 1 | Low | (5) |
| C 2 | Medium | (2) |
| C 3 | High | (1) |
| C 4 | Very High | (0.5) |

**4) Vulnerability Matrix: Fill in for each functional failure**

4a) Assess the Time for failure development. How long time does it take for the failure to evolve from "first time detected" to a predefined failure threshold limit (Hours, days, weeks, months, quarters, years)?

| Criticallity | Time for Failure Development | | | | | |
|---|---|---|---|---|---|---|
| | Years | Quarters | Months | Weeks | Days | Hours |
| Inconsiderable | 0 | 0 | 0 | 0 | 0 | 0 |
| Low | 0 | 1 | 1 | 2 | 2 | 2 |
| Medium | 1 | 2 | 2 | 2 | 3 | 3 |
| High | 1 | 2 | 2 | 3 | 3 | 4 |
| Very High | 2 | 2 | 3 | 3 | 4 | 4 |

| Vulnerability | | Default principal inspection interval (years) |
|---|---|---|
| Class | Vulnerability | |
| R 0 | Very robust | (5 or more) |
| R 1 | Robust | (5) |
| R 2 | Semi-Robust | (2) |
| R 3 | Vulnerable | (1) |
| R 4 | Very vulnerable | (0.5) |

**5) Fill out failure and detection analysis**

**6) Initial Inspection and Maintenance Activity Analysis (IMAA)**

6a) Assess the time for damage tolerance. How long time can a predefined failure of the element/system be tolerated?

6b) Assess initial inspection interval based on proposed default inspection interval or experience

6c) Asess the Mean Time Between Failure (if RCM element).

6d) Assess spare parts and key parameters to monitor.

**Remarks:**

All default parameters should be verified by supplier information or other relevant reference

This is an initial IMAA analysis and results should be benchmarked against LCC and further I&M studies related to eg. supplier information

# Risk based Inspection and Maintenance

E39 Bjørnafjorden Bridge - Operation and Maintenance



| Element no. | Element no. according to SVV handbook V441 | Element Name | Functional Failure | Concequence of failure: Unavalibality | Cost | Fatalities | Environment | max(consequence) | Consequence comment | Likelihood | Criticality | Time for failure development (Hours, Days, Quarters, Years) | | Vulnerability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.00 | D3 | Concrete Girder | | | | | | | | | | | | |
| 1.01 | | Concrete girder - Reinforced Concrete | Degradation of concrete and reinforcement | 5 | 3 | 5 | 0 | 5 | Consequences of fatalities are severe, however considered very unlikely. | 1 | | 10 | Years | |
| 1.02 | | Prestressing tendons | Degradation of tendons elements | 5 | 4 | 5 | 0 | 5 | Consequences of fatalities are severe and 1:1 replacement not possible, however considered unlikely. | 2 | | 10 | Years | |
| 2.00 | D3 | Steel Girder | | | | | | | | | | | | |
| 2.01 | | Steel girder - Structural Steel, internal surfaces | Corrosion, internal: Bridge girders are subject to internal corrosion. | 5 | 5 | 5 | 3 | 5 | Consequences of steel failure caused by corrosion could be disastrous, however considered very unlikely. | 1 | | 10 | Years | |
| 2.02 | | Steel girder - Dehumidification System | System malfunction | 2 | 2 | 2 | 0 | 2 | Malfunction of dehumidification system happens before degration of steel. No consequences if system is reastablised within a few month. | 1 | | 1 | Months | |
| 2.03 | | Steel girder - Structural steel, external surfaces | Corrosion, external: Bridge girders are subject to external corrosion from weather variations. | 5 | 5 | 5 | 3 | 5 | Consequences of steel failure caused by corrosion could be disastrous, however considered very unlikely. | 1 | | 10 | Years | |
| 2.04 | | Steel girder - Weldings | Cracks in weldings caused by fatigue: Bridge girders are subject to fatigue from traffic, wind, etc.. | 5 | 5 | 5 | 3 | 5 | Consequences of weld failure caused by fatigue could be disastrous, and could happen occasionally. | 3 | | 2 | Years | |
| 2.05 | | Steel girder - Coating System | Degradation of coating, due to weather conditions and material durability | 0 | 4 | 1 | 0 | 4 | Economical consequences of failing coating system could be severe in terms of extra costs to sandblasting and preparing of surface. | 1 | | 10 | Years | |
| 2.06 | | Steel girder - Top coating | Degradation of material, due to weather conditions and material durability | 0 | 4 | 1 | 0 | 4 | Economical consequences of failing coating system could be severe in terms of loss of ability to renew topcoat -> full coating system is necessary. | 2 | | 10 | Years | |
| 3.00 | C2 | Concrete column | | | | | | | | | | | | |
| 3.01 | | Reinforced Concrete | Degradation of concrete and reinforcement | 5 | 3 | 5 | 0 | 5 | Consequences of fatalities are severe, however considered very unlikely. | 1 | | 10 | Years | |
| 4.00 | C3 | Steel column | | | | | | | | | | | | |
| 4.01 | | Steel columns - interior surfaces | Corrosion, internal: Columns are subject to corrosion in indoor environment | 5 | 5 | 5 | 3 | 5 | Consequences of steel failure caused by corrosion could be disastrous, however considered very unlikely. | 1 | | 10 | Years | |
| 4.02 | | Steel columns - Dehumidification System | System malfunction | 2 | 2 | 2 | 0 | 2 | Malfunction of dehumidification system happens before degration of steel. No consequences if system is reastablised within a few month. | 1 | | 1 | Quarters | |
| 4.03 | | Steel columns - exterior surfaces | Corrosion, external: Columns are subject to corrocion due to weather variations. | 5 | 5 | 5 | 3 | 5 | Consequences of steel failure caused by corrosion could be disastrous, however considered very unlikely. | 1 | | 10 | Years | |
| 4.04 | | Steel columns - Weldings | Fatigue in welds: Columns are subject to fatigue from traffic, wind, etc.. | 5 | 5 | 5 | 3 | 5 | Consequences of weld failure caused by fatigue could be disastrous, and could happen occasionally. | 3 | | 2 | Years | |
| 4.05 | | Steel columns - Coating system | Degradation of coating due to weather conditions and material durability | 0 | 4 | 1 | 0 | 4 | Economical consequences of failing coating system could be severe in terms of extra costs to sandblasting and preparing of surface. | 1 | | 10 | Years | |
| 4.06 | | Steel columns - Top coat | Degradation of top cating due to weather conditions and material durability | 0 | 4 | 1 | 0 | 4 | Economical consequences of failing coating system could be severe in terms of loss of ability to renew topcoat -> full coating system is necessary. | 2 | | 10 | Years | |
| 5.00 | C3 | Concrete Towers | | | | | | | | | | | | |
| 5.01 | | Concrete towers - Reinforced Concrete | Degradation of concrete and reinforcement | 5 | 3 | 5 | 0 | 5 | Consequences of fatalities are severe, however considered very unlikely. | 1 | | 10 | Years | |

# Risk based Inspection and Maintenance

E39 Bjørnafjorden Bridge - Operation and Maintenance

| Element no. | Element no. according to SVV handbook V441 | Element Name | Functional Failure | Concequence of failure | | | | max(consequence) | Consequence comment | Likelihood | Criticality | Time for failure development (Hours, Days, Quarters, Years) | | Vulnerability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Unavalibality | Cost | Fatalities | Environment | | | | | | | |
| 5.02 | | Posttensioning elements | Degradation of tensioning elements | 5 | 4 | 5 | 0 | 5 | Consequences of fatalities are severe and replacement not possible, however considered unlikely. | 2 | | 10 | Years | |
| 5.03 | | Steel anchor box - internal surfaces | Corrosion, internal:<br>Anchor boxes are subject to corrosion in indoor environment | 0 | 1 | 1 | 0 | 1 | Consequences of steel failure caused by corrosion could be disastrous, however considered unlikely. | 2 | | 10 | Years | |
| 5.04 | | Steel anchor box - Dehumidification System | System malfunction | 1 | 1 | 1 | 0 | 1 | Malfunction of dehumidification system happens before degration of steel. No consequences if system is re-established within a few month. | 2 | | 1 | Quarters | |
| 5.05 | | Steel anchor box - Coating system | Degradation of coating due to indoor environment | 0 | 2 | 1 | 0 | 2 | Economical consequences of failing coating system could be severe in terms of extra costs to sandblasting and preparing of surface. | 1 | | 10 | Years | |
| 6.00 | C31 | Tower foundation | | | | | | | | | | | | |
| 6.01 | | Reinforced Concrete | Degradation of concrete and reinforcement | 5 | 5 | 5 | 3 | 5 | Consequences of fatalities are severe, however considered very unlikely. | 1 | | 10 | Years | |
| 7.00 | C8 | Abutment | | | | | | | | | | | | |
| 7.01 | | Reinforced Concrete | Degradation of concrete and reinforcement | 5 | 3 | 5 | 0 | 5 | Consequences of fatalities are severe, however considered very unlikely. | 1 | | 10 | Years | |
| 8.00 | G4 | Cable system | | | | | | | | | | | | |
| 8.01 | | Stay cables | Material loss in wires | 5 | 5 | 5 | 3 | 5 | Loss of stay cable is disastrous, however considered very unlikely. Failure development period, assuming there is no prot. systems available, (from corrosion starts to critical) is assumed to be more than 10 years. | 1 | | 10 | Years | |
| 8.02 | | Galvanisation of wires in cable | Degradation of galvanisation. | 0 | 3 | 0 | 0 | 3 | Loss of galv. happens before corrosion and therefore only relates to extra costs due to extra analyses and inspections. If primary prot. system function 100% correct galv. will not degrade. | 2 | | 10 | Years | |
| 8.03 | | Grease (fedt) | Loss of material | 0 | 3 | 0 | 0 | 3 | Loss of grease happens before corrosion and not subject to replacement if lost completely. If primary prot. system function 100% correct grease will not degrade. | 2 | | 10 | Years | |
| 8.04 | | PE sheet | Degradation of PE sheet | 2 | 4 | 1 | 0 | 4 | Secondary corrosion protection of wires. Consequences of fatalities are severe, however considered unlikely. | 2 | | 10 | Years | |
| 8.05 | | HDPE | Degradation of material. Caused by weather impact | 0 | 1 | 1 | 1 | 1 | Economical consequences could be serious in terms of extra analyses and inspections. | 2 | | 10 | Years | |
| 8.06 | | Stay cabel anchors | Corrosion anchouage: Anchorages in deck and tower are subjected to corrision from weather variations | 5 | 4 | 4 | 3 | 5 | Consequences of anchorage failure caused by corrosion could be disastrous, however considered unlikely. | 2 | | 10 | Years | |
| 8.07 | | Stay cable damping system | Wear and tear:<br>Damping systems are subject to wear and tear. | 0 | 4 | 1 | 0 | 4 | Economical consequences could be serious in terms of extra analyses, inspections or replacement. | 3 | | 5 | Years | |
| 9.00 | C7 | Steel pontoons | | | | | | | | | | | | |
| 9.01 | | Steel pontoons - interior surfaces | Corrosion, internal:<br>Pontoons are subject to corrosion in indoor environment | 5 | 5 | 5 | 3 | 5 | Consequences of steel failure caused by corrosion could be disastrous, however considered very unlikely. | 1 | | 5 | Years | |
| 9.02 | | Steel pontoons - Dehumidification System | System malfunction | 1 | 1 | 1 | 0 | 1 | Malfunction of dehumidification system happens before degration of steel. No consequences if system is reastablised within a few month. | 1 | | 1 | Quarters | |

# Risk based Inspection and Maintenance

E39 Bjørnafjorden Bridge - Operation and Maintenance

| Element no. | Element no. according to SVV handbook V441 | Element Name | Functional Failure | Concequence of failure: Unavalibality | Cost | Fatalities | Environment | max(consequence) | Consequence comment | Likelihood | Criticality | Time for failure development (Hours, Days, Quarters, Years) | | Vulnerability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9.03 | | Steel pontoons - exterior surfaces | Corrosion, external:<br>Pontoons are subject to corrocion due to weather variations. | 5 | 5 | 5 | 3 | 5 | Consequences of steel failure caused by corrosion could be disastrous, however considered very unlikely due to the use of SDSS in splash zone. | 1 | | 10 | Years | |
| 9.04 | | Steel pontoons - Weldings | Fatigue in welds:<br>Pontoons are subject to fatigue from traffic, waves, etc. | 5 | 5 | 5 | 3 | 5 | Consequences of weld failure caused by fatigue could be disastrous, and could happen occasionally. | 3 | | 2 | Years | |
| 9.05 | | Steel pontoons - Coating system | Degradation of coating due to weather conditions and material durability | 3 | 4 | 4 | 3 | 4 | Economical consequences of failing coating system could be severe in terms of extra costs to sandblasting and preparing of surface. | 3 | | 5 | Years | |
| 9.06 | | Steel pontoons - Top coat | Degradation of top cating due to weather conditions and material durability | 3 | 4 | 4 | 3 | 4 | Economical consequences of failing coating system could be severe in terms of loss of ability to renew topcoat -> full coating system is necessary. | 3 | | 5 | Years | |
| 9.07 | | Steel pontoons - interior cathodic protection (if any) | Degradation of cathotic protection if they detach or bad connection with steel | 0 | 2 | 0 | 0 | 2 | Cathodic protection are designed to be detoriated. However premature failure/quicker detoriation or bad connection with steel can result in quicker degradation of coating and steel. | 1 | | 10 | Years | |
| 9.08 | | Steel pontoons - extorior cathodic protection | Degradation of cathotic protection if they detach or bad connection with steel | 0 | 3 | 0 | 0 | 3 | Cathodic protection are designed to be detoriated. However premature failure/quicker detoriation or bad connection with steel can result in quicker degradation of coating and steel. | 2 | | 10 | Years | |
| 9.09 | | Steel pontoons - Watertight openings | Failure of seal in inspection hatches and manholes. | 0 | 2 | 0 | 0 | 2 | Seals must be changed due to detoriations of materials. | 2 | | 5 | Years | |
| 9.10 | | Steel pontoons - Water detection system | System malfunction | 0 | 2 | 0 | 0 | 2 | A failure of the water detection system is not serious as the interior surfaces are coated. | 3 | | 1 | Years | |
| 10.00 | C43 | B7 Mooring | | | | | | | | | | | | |
| 10.01 | | Pontoon conection, chain stopper/fairlead | Degradation of material. Caused by weather impact and marine growth. | 3 | 3 | 1 | 1 | 3 | Consequences of chain stopper failure is severe, however considered unlikely. | 2 | | 5 | Years | |
| 10.02 | | Pontoon conection, chain stopper/fairlead | Fatigue in conections | 4 | 4 | 1 | 1 | 4 | Consequences of chain stopper failure is severe, however considered unlikely. | 2 | | 5 | Years | |
| 10.03 | | Top chain | Degradation of material. Caused by weather impact and marine growth. | 3 | 3 | 1 | 1 | 3 | Consequences of chain failure could be severe, however considered unlikely. | 2 | | 5 | Years | |
| 10.04 | | Top chain | Damage from ship impact | 4 | 4 | 1 | 1 | 4 | Consequences of chain failure could be severe, however considered very unlikely. | 1 | | 5 | Years | |
| 10.05 | | Mooring wire | Material loss in wires. | 4 | 4 | 1 | 1 | 4 | Consequences of chain failure could be severe, however considered unlikely. | 2 | | 5 | Years | |
| 10.06 | | Mooring wire | Damage from ship impact | 4 | 4 | 1 | 1 | 4 | Consequences of chain failure could be severe, however considered very very unlikely. | 1 | | 5 | Years | |
| 10.07 | | Bottom chain | Degradation of material. | 4 | 4 | 1 | 1 | 4 | Consequences of anchorage failure could be severe, however considered unlikely. | 2 | | 5 | Years | |
| 10.08 | | Suction anchor | Degradation of material. | 4 | 4 | 1 | 1 | 4 | Consequences of anchorage failure could be severe, however considered very unlikely. | 1 | | 10 | Years | |
| 10.09 | | Cathodic proction (if any) | Degradation of cathotic protection if they detach or bad connection with steel | 0 | 3 | 0 | 0 | 3 | Cathodic protection are designed to be detoriated. However premature failure/quicker detoriation or bad connection with steel can result in quicker degradation of coating and steel. | 2 | | 10 | Years | |
| 11.00 | E | Surfacing | | | | | | | | | | | | |
| 11.01 | | Roadway - Surfacing | Loss of integrity (friction) | 1 | 1 | 4 | 0 | 4 | Consequences of fatalities are severe and loss of integrity are likely to occur. Failure development caused by i.e. freeze-thaw could be within 1 day. | 4 | | 1 | Days | |

| Element no. | Element no. according to SVV handbook V441 | Element Name | Functional Failure | Concequence of failure: Unavalibality | Cost | Fatalities | Environment | max(consequence) | Consequence comment | Likelihood | Criticality | Time for failure development (Hours, Days, Quarters, Years) | | Vulnerability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.02 | | Roadway - Surfacing | Loss of protection to steel or concrete structures. Permeability of surfacing causing corrosion of steel box girder or degradation of concrete box girder. | 5 | 5 | 5 | 3 | 5 | Consequences of steel failure caused by corrosion could be disastrous, however considered very unlikely. | 1 | | 10 | Years | |
| 12.00 | H2 | Road sign | | | | | | | | | | | | |
| 12.01 | | Road signs - analog | Rodent bites, Wear and tear. | 1 | 1 | 1 | 1 | 1 | Defects have effect on road safety | 3 | | 1 | Days | |
| 12.02 | | Road signs - LED display | Malfunction, rodent bites, Wear and tear. | 1 | 2 | 1 | 1 | 2 | Defects have effect on road safety | 3 | | 1 | Days | |
| 13.00 | H2 | B9.2 Electrical systems - Critical | | | | | | | | | | | | |
| 13.01 | | Eg. trafic light, navigation ligthing for ships and flights , essential monitoring systems | Malfunction, rodent bites, Wear and tear. | 5 | 5 | 5 | 3 | 5 | Failure may impose a severe risk for ships, flights and other vehicles. Impact may leed to serious damage to the bridge | 2 | | 1 | Hours | |
| 14.00 | H2 | B9.2 Electrical system - Non-critical | | | | | | | | | | | | |
| 14.01 | | Eg. internal navigation lighting in box girder, non-essential monitoring systems | Malfunction, rodent bites, Wear and tear. | 1 | 1 | 3 | 1 | 3 | Failure may impose a risk to O&M personel | 2 | | 1 | Hours | |
| 15.00 | H15 | Railings (Crash barriers and other railing) | | | | | | | | | | | | |
| 15.01 | | Railings - Structural Steel | Material loss due to corrosion:<br>Railings are subject to external corrosion from weather variations. | 2 | 1 | 4 | 0 | 4 | Consequences of fatalities are severe, however considered very unlikely. | 1 | | 10 | Years | |
| 15.02 | | Railings - Galvanisation | Degradation of galvanisation. | 1 | 2 | 1 | 0 | 2 | There are no speakable consequences given that galvanisation is reestablished within few years. Costs of renewal would slightly increase. | 2 | | 10 | Years | |
| 16.00 | H11 | Bearings | | | | | | | | | | | | |
| 16.01 | | Bearings | Wear and tear:<br>Bearings are subject to wear and tear. | 1 | 4 | 0 | 0 | 4 | Lack of maintenance of sliding parts could have costful results. This is however considered unlikely. | 2 | | 4 | Years | |
| 17.00 | H16 | Drainage System | | | | | | | | | | | | |
| 17.01 | | Drainage System | Malfunction. Constipation due to insufficient cleaning | 1 | 1 | 4 | 1 | 4 | A failure of the drainage system could have fatal consequences. This could happen occasionally. | 3 | | 12 | Hours | |
| 18.00 | H51 | SHMS (Structural Health Monitoring System) | | | | | | | | | | | | |
| 18.01 | | SHMS | Malfunction & Wear and tear & Rodent bites | 3 | 2 | 1 | 0 | 3 | On a long term failure may impose a risk for the structure | 2 | | 1 | Hours | |
| 19.00 | H3 | Permanent access facilities (foreseen) | | | | | | | | | | | | |
| 19.01 | | Permanent access facilities - Structural Steel | Material loss due to corrosion | 1 | 2 | 3 | 0 | 3 | Access facilities could occasionally fail, however this has very little consequence. Galvanisation has to fail before this will happen. | 2 | | 6 | Years | |
| 19.02 | | Permanent access facilities - Galvanisation | Degradation of galvanisation. | 1 | 1 | 1 | 0 | 1 | There are no speakable consequences given that galvanisation is reestablished within few years. Costs of renewal would slightly increase. | 2 | | 10 | Years | |
| 19.03 | | Permanent access facilities - Escalator | Malfunction, rodent bites, Wear and tear. | 1 | 1 | 1 | 0 | 1 | - | 2 | | 10 | Years | |

# Risk based Inspection and Maintenance

E39 Bjørnafjorden Bridge - Operation and Maintenance

| Element no. | Element Name | Functional Failure | Criticality | Vulnerability | Failure and detection analysis: Failure detection Yes/No | Detection method | Mitigation measures other than maintenance | Recommendations - Can failure be eliminated or managed in ways other than maintenance? | Inspection and Maintenance Activity Analysis (IMAA): Time for Damage Tolerance [$\Delta t_d$] (Years) | Initial selected pricipal inspection interval [$\Delta t_i$] (Years) | RCM or RBI | Default principal inspection interval, based on criticality (RCM) or vulnerability (RBI) [Years] | Mean time between failure, MTBF [Years] | Recommended principal inspection strategy | Recommended Maintenance stategy | Comments to Inspection/maintenance strategy | Spare part requirement in order to minimize repair time (if critical) | Key parameter to monitor (Usual signs of degredation related to concrete and steel is not listed) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.00 | Concrete Girder | | | | | | | | | | | | | | | | | |
| 1.01 | Concrete girder - Reinforced Concrete | Degradation of concrete and reinforcement | | | Yes | Inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | - | - | - |
| 1.02 | Prestressing tendons | Degradation of tendons elements | | | Yes | Inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Corrosion is a consequence of a failing protection system. Time for damage tolerance is therefore set to 5 years, which is the same as the protection system. | | |
| 2.00 | Steel Girder | | | | | | | | | | | | | | | | | |
| 2.01 | Steel girder - Structural Steel, internal surfaces | Corrosion, internal: Bridge girders are subject to internal corrosion. | | | Yes | Inspection | - Dehumidification system | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Corrosion is a consequence of a failing protection system. Time for damage tolerance is therefore set to 5 years, which is the same as the protection system. | None | Relative humidity inside girder. |
| 2.02 | Steel girder - Dehumidification System | System malfunction | | | Yes | Inspection | None | Installation of two smaller dehumidification units rather than one large in each dehumidified bridge girder section. | 2 | 2 | RCM | (5 or more) | - | Periodic Inspection every 2 years | Periodic corrective/preventive maintenance (PIBM) | Inspection interval should be provided by the supplier of the system | Filters | Continuos monitoring of humidity and air flow inside the Steel Box Girder should give a warning if the system is failing |
| 2.03 | Steel girder - Structural steel, external surfaces | Corrosion, external: Bridge girders are subject to external corrosion from weather variations. | | | Yes | Inspection | -Coating system | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Corrosion is a consequence of a failing protection system. Time for damage tolerance is therefore set to 5 years, which is the same as the protection system. | None | Visual inspection and assessment of Coating Condition Indicator, CC. |
| 2.04 | Steel girder - Weldings | Cracks in weldings caused by fatigue: Bridge girders are subject to fatigue from traffic, wind, etc.. | | | Yes | Inspection | - SHMS, measuring loads on bridge (fatigue levels and cycles) | | 5 | 2 | RBI | (2) | - | Periodic Inspection every 2 years | Periodic corrective/preventive maintenance (PIBM) | Monitoring should be installed, however this can only be carried out at selected spots. | None | Hot spots (i.e. areas under wheel) identified during design. Cracklength. |

# Risk based Inspection and Maintenance

E39 Bjørnafjorden Bridge - Operation and Maintenance

| Element no. | Element Name | Functional Failure | Criticality | Vulnerability | Failure and detection analysis: Failure detection Yes/No | Detection method | Mitigation measures other than maintenance | Recommendations - Can failure be eliminated or managed in ways other than maintenance? | Inspection and Maintenance Activity Analysis (IMAA): Time for Damage Tolerance [$\Delta t_d$] (Years) | Initial selected pricipal inspection interval [$\Delta t_i$] (Years) | RCM or RBI | Default principal inspection interval, based on criticality (RCM) or vulnerability (RBI) [Years] | Mean time between failure, MTBF [Years] | Recommended principal inspection strategy | Recommended Maintenance stategy | Comments to Inspection/maintenance strategy | Spare part requirement in order to minimize repair time (if critical) | Key parameter to monitor (Usual signs of degredation related to concrete and steel is not listed) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.05 | Steel girder - Coating System | Degradation of coating, due to weather conditions and material durability | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | X amount of Coating system for spot repairs. | Adhesion and Cross-cut test. |
| 2.06 | Steel girder - Top coating | Degradation of material, due to weather conditions and material durability | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | X amount of Coating system for spot repairs. | Visual inspection and assessment of Coating Condition Indicator, CC. |
| 3.00 | Concrete column | | | | | | | | | | | | | | | | | |
| 3.01 | Reinforced Concrete | Degradation of concrete and reinforcement | | | Yes | Inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | |
| 4.00 | Steel column | | | | | | | | | | | | | | | | | |
| 4.01 | Steel columns - interior surfaces | Corrosion, internal:<br>Columns are subject to corrosion in indoor environment | | | Yes | Inspection | - Dehumidification system<br>- EMC System | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Corrosion is a consequence of a failing protection system. Time for damage tolerance is therefore set to 5 years, which is the same as the protection system. | None | Relative humidity inside columns. |
| 4.02 | Steel columns - Dehumidification System | System malfunction | | | Yes | Inspection | None | | 5 | 5 | RCM | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Inspection interval should be provided by the supplier of the system | Filters | Continuos monitoring of humidity and air flow inside the columns should give a warning if the system is failing |
| 4.03 | Steel columns - exterior surfaces | Corrosion, external:<br>Columns are subject to corrocion due to weather variations. | | | Yes | Inspection | -Coating system | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Corrosion is a consequence of a failing protection system. Time for damage tolerance is therefore set to 5 years, which is the same as the protection system. | None | Visual inspection and assessment of Coating Condition Indicator, CC. |
| 4.04 | Steel columns - Weldings | Fatigue in welds:<br>Columns are subject to fatigue from traffic, wind, etc.. | | | Yes | Inspection | - SHMS, measuring loads on bridge (fatigue levels and cycles) | | 5 | 2 | RBI | (2) | - | Periodic Inspection every 2 years | Periodic corrective/preventive maintenance (PIBM) | Monitoring should be installed, however this can only be carried out at selected spots. | | Hot spots identified during design. |

# Risk based Inspection and Maintenance

E39 Bjørnafjorden Bridge - Operation and Maintenance

| Element no. | Element Name | Functional Failure | Criticality | Vulnerability | Failure and detection analysis | | | | Inspection and Maintenance Activity Analysis (IMAA) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Failure detection Yes/No | Detection method | Mitigation measures other than maintenance | Recommendations - Can failure be eliminated or managed in ways other than maintenance? | Time for Damage Tolerance [$\Delta t_d$] (Years) | Initial selected pricipal inspection interval [$\Delta t_i$] (Years) | RCM or RBI | Default principal inspection interval, based on criticality (RCM) or vulnerability (RBI) [Years] | Mean time between failure, MTBF [Years] | Recommended principal inspection strategy | Recommended Maintenance stategy | Comments to Inspection/maintenance strategy | Spare part requirement in order to minimize repair time (if critical) | Key parameter to monitor (Usual signs of degredation related to concrete and steel is not listed) |
| 4.05 | Steel columns - Coating system | Degradation of coating due to weather conditions and material durability | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | A proper amount of Coating system for spot repairs. | |
| 4.06 | Steel columns - Top coat | Degradation of top cating due to weather conditions and material durability | | | Yes | ROV Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | A proper amount of Coating system for spot repairs. | Visual inspection and assessment of Coating Condition Indicator, CC. |
| 5.00 | Concrete Towers | | | | | | | | | | | | | | | | | |
| 5.01 | Concrete towers - Reinforced Concrete | Degradation of concrete and reinforcement | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | | |
| 5.02 | Posttensioning elements | Degradation of tensioning elements | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | | Visual inspection. |
| 5.03 | Steel anchor box - internal surfaces | Corrosion, internal: Anchor boxes are subject to corrosion in indoor environment | | | Yes | Inspection | - Dehumidification system<br>- EMC System | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | X amount of Coating system for spot repairs. | Visual inspection and assessment of Coating Condition Indicator, CC. |
| 5.04 | Steel anchor box - Dehumidification System | System malfunction | | | Yes | Inspection | | | 5 | 5 | RCM | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Inspection interval should be provided by the supplier of the system | Filters | Continuos monitoring of humidity and air flow inside the anchor box should give a warning if the system is failing |
| 5.05 | Steel anchor box - Coating system | Degradation of coating due to indoor environment | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | X amount of Coating system for spot repairs. | Visual inspection and assessment of Coating Condition Indicator, CC. |
| 6.00 | Tower foundation | | | | | | | | | | | | | | | | | |
| 6.01 | Reinforced Concrete | Degradation of concrete and reinforcement | | | Yes | Inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | |

# Risk based Inspection and Maintenance

E39 Bjørnafjorden Bridge - Operation and Maintenance

| Element no. | Element Name | Functional Failure | Criticality | Vulnerability | Failure and detection analysis: Failure detection Yes/No | Detection method | Mitigation measures other than maintenance | Recommendations - Can failure be eliminated or managed in ways other than maintenance? | Inspection and Maintenance Activity Analysis (IMAA): Time for Damage Tolerance [$\Delta t_d$] (Years) | Initial selected pricipal inspection interval [$\Delta t_i$] (Years) | RCM or RBI | Default principal inspection interval, based on criticality (RCM) or vulnerability (RBI) [Years] | Mean time between failure, MTBF [Years] | Recommended principal inspection strategy | Recommended Maintenance stategy | Comments to Inspection/maintenance strategy | Spare part requirement in order to minimize repair time (if critical) | Key parameter to monitor (Usual signs of degredation related to concrete and steel is not listed) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7.00 | Abutment | | | | | | | | | | | | | | | | | |
| 7.01 | Reinforced Concrete | Degradation of concrete and reinforcement | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | | |
| 8.00 | Cable system | | | | | | | | | | | | | | | | | |
| 8.01 | Stay cables | Material loss in wires | | | Yes | Inspection | - Galv wires.<br>- PE-coating<br>- HDPE coating<br>- Structural Health Monitoring System (SHMS) | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Corrosion is a consequence of a failing protection system. Time for damage tolerance is therefore set to 5 years, which is the same as the protection system. Due to the number and nature of protection systems this interval may be increased. | None | Design anchorages in a way to make easy inspection. |
| 8.02 | Galvanisation of wires in cable | Degradation of galvanisation. | | | Yes | Special inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | | |
| 8.03 | Grease (fedt) | Loss of material | | | Yes | Special inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | | |
| 8.04 | PE sheet | Degradation of PE sheet | | | Yes | Special inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | | |
| 8.05 | HDPE | Degradation of material. Caused by weather impact | | | Yes | Inspection | None | | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | A proper amount of HDPE repair kit for spot repairs. | |
| 8.06 | Stay cabel anchors | Corrosion anchouage: Anchorages in deck and tower are subjected to corrision from weather variations | | | Yes | Inspection | None | Dehumidification of anchorages | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | A proper amount of Coating system for spot repairs. | Visual inspection |

# Risk based Inspection and Maintenance



E39 Bjørnafjorden Bridge - Operation and Maintenance

| Element no. | Element Name | Functional Failure | Criticality | Vulnerability | Failure and detection analysis: Failure detection Yes/No | Detection method | Mitigation measures other than maintenance | Recommendations - Can failure be eliminated or managed in ways other than maintenance? | Inspection and Maintenance Activity Analysis (IMAA): Time for Damage Tolerance [$\Delta t_d$] (Years) | Initial selected pricipal inspection interval [$\Delta t_i$] (Years) | RCM or RBI | Default principal inspection interval, based on criticality (RCM) or vulnerability (RBI) [Years] | Mean time between failure, MTBF [Years] | Recommended principal inspection strategy | Recommended Maintenance stategy | Comments to Inspection/maintenance strategy | Spare part requirement in order to minimize repair time (if critical) | Key parameter to monitor (Usual signs of degredation related to concrete and steel is not listed) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8.07 | Stay cable damping system | Wear and tear:<br>Damping systems are subject to wear and tear. | | | Yes | Inspection | - SHMS.<br>- EMC System | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | None | | Monitoring |
| 9.00 | Steel pontoons | | | | | | | | | | | | | | | | | |
| 9.01 | Steel pontoons - interior surfaces | Corrosion, internal:<br>Pontoons are subject to corrosion in indoor environment | | | Yes | Inspection | - Dehumidification system.<br>- Cathodic protection | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Corrosion is a consequence of a failing protection system. Time for damage tolerance is therefore set to 5 years, which is the same as the protection system. | None | Relative humidity inside pontoons. |
| 9.02 | Steel pontoons - Dehumidification System | System malfunction | | | Yes | Inspection | Monitoring | | 5 | 5 | RCM | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Inspection interval should be provided by the supplier of the system | Filters | Continuos monitoring of humidity and air flow inside the pontoons should give a warning if the system is failing |
| 9.03 | Steel pontoons - exterior surfaces | Corrosion, external:<br>Pontoons are subject to corrocion due to weather variations. | | | Yes | Inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Splash zone elements are produced in a corrosion resistant alloy SDSS | | |
| 9.04 | Steel pontoons - Weldings | Fatigue in welds:<br>Pontoons are subject to fatigue from traffic, waves, etc. | | | Yes | Inspection | None | | 5 | 2 | RBI | (2) | - | Periodic Inspection every 2 years | Periodic corrective/preventive maintenance (PIBM) | Splash zone elements are in a corrosion resistant alloy SDSS | | |
| 9.05 | Steel pontoons - Coating system | Degradation of coating due to weather conditions and material durability | | | Yes | Inspection | Cathodic protection outside splash zone | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | Aproper amount of Coating system for spot repairs. | |
| 9.06 | Steel pontoons - Top coat | Degradation of top cating due to weather conditions and material durability | | | Yes | Inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | A proper amount of Coating system for spot repairs. | Visual inspection and assessment of Coating Condition Indicator, CC. |
| 9.07 | Steel pontoons - interior cathodic protection (if any) | Degradation of cathotic protection if they detach or bad connection with steel | | | Yes | Inspection | | Evaluate to use Fresh waterdue to less corrosion | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | Extra anodes | Monitoring current flow from anode |

| Element no. | Element Name | Functional Failure | Criticality | Vulnerability | Failure and detection analysis: Failure detection Yes/No | Detection method | Mitigation measures other than maintenance | Recommendations - Can failure be eliminated or managed in ways other than maintenance? | Inspection and Maintenance Activity Analysis (IMAA): Time for Damage Tolerance [$\Delta t_d$] (Years) | Initial selected pricipal inspection interval [$\Delta t_i$] (Years) | RCM or RBI | Default principal inspection interval, based on criticality (RCM) or vulnerability (RBI) [Years] | Mean time between failure, MTBF [Years] | Recommended principal inspection strategy | Recommended Maintenance stategy | Comments to Inspection/maintenance strategy | Spare part requirement in order to minimize repair time (if critical) | Key parameter to monitor (Usual signs of degredation related to concrete and steel is not listed) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9.08 | Steel pontoons - extorior cathodic protection | Degradation of cathotic protection if they detach or bad connection with steel | | | Yes | Inspection | | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | Extra anodes | Monitoring current flow from anode |
| 9.09 | Steel pontoons - Watertight openings | Failure of seal in inspection hatches and manholes. | | | Yes | Inspection | | | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | Extra sealing parts | |
| 9.10 | Steel pontoons - Water detection system | System malfunction | | | Yes | Inspection | | | 5 | 5 | RCM | (2) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | Extra sensors | |
| 10.00 | B7 Mooring | | | | | | | | | | | | | | | | | |
| 10.01 | Pontoon conection, chain stopper/fairlead | Degradation of material. Caused by weather impact and marine growth. | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Tension in mooring line |
| 10.02 | Pontoon conection, chain stopper/fairlead | Fatigue in conections | | | Yes | ROV Inspection | Monitoring | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Tension in mooring line |
| 10.03 | Top chain | Degradation of material. Caused by weather impact and marine growth. | | | Yes | ROV Inspection | Monitoring | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Tension in mooring line |
| 10.04 | Top chain | Damage from ship impact | | | Yes | ROV Inspection | Monitoring | | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Tension in mooring line |
| 10.05 | Mooring wire | Material loss in wires. | | | Yes | ROV Inspection | None | Use of fibre rope or polyester rope | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Tension in mooring line |
| 10.06 | Mooring wire | Damage from ship impact | | | Yes | ROV Inspection | Monitoring | | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Tension in mooring line |
| 10.07 | Bottom chain | Degradation of material. | | | Yes | ROV Inspection | Monitoring | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Tension in mooring line |

| Element no. | Element Name | Functional Failure | Criticality | Vulnerability | Failure and detection analysis: Failure detection Yes/No | Detection method | Mitigation measures other than maintenance | Recommendations - Can failure be eliminated or managed in ways other than maintenance? | Inspection and Maintenance Activity Analysis (IMAA): Time for Damage Tolerance [$\Delta t_d$] (Years) | Initial selected pricipal inspection interval [$\Delta t_i$] (Years) | RCM or RBI | Default principal inspection interval, based on criticality (RCM) or vulnerability (RBI) [Years] | Mean time between failure, MTBF [Years] | Recommended principal inspection strategy | Recommended Maintenance stategy | Comments to Inspection/maintenance strategy | Spare part requirement in order to minimize repair time (if critical) | Key parameter to monitor (Usual signs of degredation related to concrete and steel is not listed) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10.08 | Suction anchor | Degradation of material. | | | Yes | ROV Inspection | - Monitoring | Stainless steel, however this is not cost optimal. | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Tension in mooring line |
| 10.09 | Cathodic proction (if any) | Degradation of cathotic protection if they detach or bad connection with steel | | | Yes | ROV Inspection | Monitoring | Use of impressed current cathodic protection for chains. | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Monitoring current flow from anode |
| 11.00 | Surfacing | | | | | | | | | | | | | | | | | |
| 11.01 | Roadway - Surfacing | Loss of integrity (friction) | | | Yes | Inspection | To be designed easy for winter maintenance tasks. | | 0,003 | 0,003 | RBI | (0.5) | - | Periodic Inspection every 0,003 years | Periodic corrective/preventive maintenance (PIBM) | 0,003 year = 1 day (Roadpatrol daily) | | Friction |
| 11.02 | Roadway - Surfacing | Loss of protection to steel or concrete structures. Permeability of surfacing causing corrosion of steel box girder or degradation of concrete box girder. | | | Yes | Inspection | To be designed easy for winter maintenance tasks. | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Corrosion is a consequence of a failing protection system. Time for damage tolerance is therefore set to 5 years, which is the same as the protection system. | | |
| 12.00 | Road sign | | | | | | | | | | | | | | | | | |
| 12.01 | Road signs - analog | Rodent bites, Wear and tear. | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RCM | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | (Roadpatrol daily) | | |
| 12.02 | Road signs - LED display | Malfunction, rodent bites, Wear and tear. | | | Yes | Inspection | None | Stainless steel, however this is not cost optimal. | 5 | 5 | RCM | (2) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Essential electrical part should be checked daily | Spare parts should be stored at site for a quick fix | Alarm if not working correct |
| 13.00 | B9.2 Electrical systems - Critical | | | | | | | | | | | | | | | | | |
| 13.01 | Eg. trafic light, navigation ligthing for ships and flights , essential monitoring systems | Malfunction, rodent bites, Wear and tear. | | | Yes | Inspection | Back up system | | 0,001 | 2 | RCM | (1) | - | Periodic Inspection every 2 years | Immediately plan or perform corrective/periodic preventive maintenance (CBM) | Essential electrical part should be checked daily | Spare parts should be stored at site for a quick fix | Alarm if not working correct |
| 14.00 | B9.2 Electrical system - Non critical | | | | | | | | | | | | | | | | | |

| Element no. | Element Name | Functional Failure | Criticality | Vulnerability | Failure and detection analysis: Failure detection Yes/No | Detection method | Mitigation measures other than maintenance | Recommendations - Can failure be eliminated or managed in ways other than maintenance? | Inspection and Maintenance Activity Analysis (IMAA): Time for Damage Tolerance [$\Delta t_d$] (Years) | Initial selected pricipal inspection interval [$\Delta t_i$] (Years) | RCM or RBI | Default principal inspection interval, based on criticality (RCM) or vulnerability (RBI) [Years] | Mean time between failure, MTBF [Years] | Recommended principal inspection strategy | Recommended Maintenance stategy | Comments to Inspection/maintenance strategy | Spare part requirement in order to minimize repair time (if critical) | Key parameter to monitor (Usual signs of degredation related to concrete and steel is not listed) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14.01 | Eg. internal navigation lighting in box girder, non-essential monitoring systems | Malfunction, rodent bites, Wear and tear. | | | Yes | Inspection | None | | 0,02 | 2 | RCM | (2) | - | Periodic Inspection every 2 years | Immediately plan or perform corrective/periodic preventive maintenance (CBM) | non-essential electrical part should be checked weekly | | Alarm if not working correct |
| 15.00 | Railings (Crash barriers and other railing) | | | | | | | | | | | | | | | | | |
| 15.01 | Railings - Structural Steel | Material loss due to corrosion: Railings are subject to external corrosion from weather variations. | | | Yes | Inspection | | Stainless steel, however this is not cost optimal. | 0,003 | 0,003 | RBI | (5 or more) | - | Periodic Inspection every 0,003 years | Periodic corrective/preventive maintenance (PIBM) | Continuous monitoring means, in this case -> drive by every day to see if everything looks fine. 0,003 year = 1 day | - Bolts/nuts<br>- Crash barrier segments all included. | Thickness of galvanisation |
| 15.02 | Railings - Galvanisation | Degradation of galvanisation. | | | Yes | Inspection + NDT | None | | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Inspection interval is set to 5 years, which is the same as damage tolerance period. | A few nos of each type | Correct behaviour/movements. Thickness of sliding material |
| 16.00 | Bearings | | | | | | | | | | | | | | | | | |
| 16.01 | Bearings | Wear and tear: Bearings are subject to wear and tear. | | | Yes | Inspection | None | | 2 | 2 | RBI | (5) | - | Periodic Inspection every 2 years | Periodic corrective/preventive maintenance (PIBM) | Inspection interval is set to 2 years, which is the same as damage tolerance period. | A few nos of each type | Correct behaviour/movements. Thickness of sliding material |
| 17.00 | Drainage System | | | | | | | | | | | | | | | | | |
| 17.01 | Drainage System | Malfunction. Constipation due to insufficient cleaning | | | Yes | Inspection | - System check.<br>- Full scale test | | 0 | 1 | RCM | (1) | - | Periodic Inspection every 1 years | Immediately plan or perform corrective/periodic preventive maintenance (CBM) | Continuous monitoring means, in this case -> keep road clean daily/weekly and drive by whenever heavy rain appears and see if drainage system works. | | |
| 18.00 | SHMS (Structural Health Monitoring System) | | | | | | | | | | | | | | | | | |
| 18.01 | SHMS | Malfunction & Wear and tear & Rodent bites | | | Yes | Inspection | System Check | Redundancy for essential sensors should be established | 0,003 | 2 | RCM | (2) | - | Periodic Inspection every 2 years | Immediately plan or perform corrective/periodic preventive maintenance (CBM) | Failing sensors can be detected by missing output or deviating output. Periodic inspections deals with the overall health of the system | Essential spare part should be stored | Alarm if not working correct |
| 19.00 | Permanent access facilities (foreseen) | | | | | | | | | | | | | | | | | |

| | | | | | Failure and detection analysis | | | | Inspection and Maintenance Activity Analysis (IMAA) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Element no. | Element Name | Functional Failure | Criticality | Vulnerability | Failure detection Yes/No | Detection method | Mitigation measures other than maintenance | Recommendations - Can failure be eliminated or managed in ways other than maintenance? | Time for Damage Tolerance [$\Delta t_d$] (Years) | Initial selected pricipal inspection interval [$\Delta t_i$] (Years) | RCM or RBI | Default principal inspection interval, based on criticality (RCM) or vulnerability (RBI) [Years] | Mean time between failure, MTBF [Years] | Recommended principal inspection strategy | Recommended Maintenance stategy | Comments to Inspection/maintenance strategy | Spare part requirement in order to minimize repair time (if critical) | Key parameter to monitor (Usual signs of degredation related to concrete and steel is not listed) |
| 19.01 | Permanent access facilities - Structural Steel | Material loss due to corrosion | | | Yes | Inspection | None | | 5 | 5 | RBI | (5) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | |
| 19.02 | Permanent access facilities - Galvanisation | Degradation of galvanisation. | | | Yes | Inspection + NDT | None | | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | | | Thickness of galvanization |
| 19.03 | Permanent access facilities - Escalator | Malfunction, rodent bites, Wear and tear. | | | Yes | Inspection | None | | 5 | 5 | RBI | (5 or more) | - | Periodic Inspection every 5 years | Periodic corrective/preventive maintenance (PIBM) | Inspection interval should be provided by the supplier of the system | | |