SUSTAINABLE BRIDGES

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Introduction

One of the hottest topics discussed in the international engineering community at present is global warming and climate change. Global warming and climate change would result in frequent extreme events such as high intensity rain fall, severe storms, floods and droughts and sea level rise causing coastal line moving inland, reducing valuable land area and adversity affecting people's living conditions.

In most of the countries, some infrastructures such as bridges, highways, buildings, dams and other structures are approaching their end of design life. Also, the current infrastructure management practices are not geared to increase the sustainability of such infrastructure to an acceptable standards or to meet the demands of future sustainable infrastructure development.

Therefore, strategies need to be developed for keeping existing infrastructure sustainable and building new sustainable infrastructures with minimum consumption of energy, reduction of carbon dioxide emissions and minimum impact on the environment. This can only be achieved through developing a life-cycle management plan that addresses sustainability issues at feasibility, planning and design, construction, operation, maintenance and decommission and/or removal stages.

Sustainable Infrastructure

Sustainability is generally defined as follows:

- Sustainable development meets the needs of present without compromising the ability of future generations to meet their own needs.
- Sustainable development is about achieving economic growth while protecting the environment and ensuring that economic and environmental benefits are available to all of society now and in the future.

By these definitions sustainable infrastructure can be achieved through a life-cycle management plan that addresses environment sustainability, social responsibility and economic growth at present and into the future.

This sustainable infrastructure should possess the following characteristics:

- Durability and longevity
- Preservation of natural environment
- Minimum impact on cultural heritage
- Minimum life-cycle cost
- Safety over whole life
- High performance
- Use of renewable energy

The paper will examine sustainability taking bridges as examples. When studying the sustainability of bridges, it is important to understand why bridges are important to community.

The road network is a critical component of a country's economic infrastructure and it binds communities together and bridges are a vital part of that network. Good roads are a country's measure of civilisation its state of economy and ensure its social cohesiveness and facilitate commerce. This has been true from ancient times and is just as important today and in the future.

The contribution of the transport sector to a country's economy is, and will continue to be significant as it moves into world market. In industrial nations, the use of large vehicles with higher axle loads is being promoted by the transport industry as a means of providing significant cost savings, resulting in increase of national productivity and greater economic benefits to people. This is the situation in Australia, as its transport cost accounts for approximately 20% of average household expenditure. This puts enormous pressure on road authorities in Australia to allow larger vehicles with higher axle loads on its road network.

In Australia, the mass limit review of 1996 recommended that gross mass of six axle articulated vehicles (commonly used heavy vehicles) be increased from 42.5 tonnes to 45.5 tonnes. The review also identified that bridges emerged as the greatest impediment to improve transport efficiency through mass limit increases.

There are over 60,000 bridges in the Australian road network of nearly 900,000km. In the state of New South Wales (NSW) there are 5093 bridges with a replacement value of $13.4 billion under the justification of the Roads and Traffic Authority of the NSW (RTA). These bridges were built with different materials at different times to different standards and loads in varying environments.

Some of these bridges were identified as limiting factors to allow further increases in axle loads necessary to increase Australia's national productivity.

In order to overcome this constraint, the RTA developed a method for load capacity assessment of bridges including load testing to determine the actual load carrying capacities of bridges identified as being under capacity to carry increased loads. By conducting this load assessment process, the RTA minimised the number of bridges to be strengthened or replaced saving millions of dollars to the community, yet keeping the road network open for increased loads.

Life–Cycle Management of Sustainable Bridges

The life-cycle management plan for sustainable bridges, as for any other infrastructure, contains the stages of feasibility study, planning and design, construction, operation, maintenance and demolition or reuse.

Feasibility Study

This stage is where high level decisions are made to meet government strategic objectives and anticipated economic growth. The project needs to be scoped in keeping with these objectives and different options developed and evaluated to minimise the following:

- Energy use
- Carbon dioxide emissions
- Life-cycle costs
- Resource use
- Design and construction cost
- Environment impact
- Community impact
- Heritage impact

Planning

During planning stage different routes are evaluated and a suitable one is selected after extensive value management and risk management studies are carried out by engaging all stakeholders.

Design

Design is a multi-disciplinary process that generally involves bridge engineers, environmentalist, geologist, geotechnical engineers and architects to address the following issues:

- Traffic at present and expected future growth
- Waterway requirements
- Climate change impact
- Mining subsidence
- Geotechnical impact
- Site constraints
- Durability
- Material selection
- Construction operation and maintenance
- Community impact

Having considered the above issues a bridge type is selected that is durable and long lasting with a minimum life-cycle cost, minimum impact on environment, heritage, energy consumption and community.

Construction

Construction industry has a large and direct impact on the economy, society and environment and therefore has a major role in delivering sustainable bridges. During this phase, the energy saving, carbon dioxide emission reduction and environment protection can be achieved by adopting the following measures;

- Minimise amounts of excavated materials, balance cut and fill in earth works
- Reuse building materials and construction waste
- Increase durability and minimise maintenance cost by enforcing strict quality controls
- Use energy efficient and high performing construction equipment
- Promote use of construction automation technologies
- Protect environment by preventing industrial discharge to environment

The sustainability indicators for construction measure the success of construction in achieving sustainability and they are:

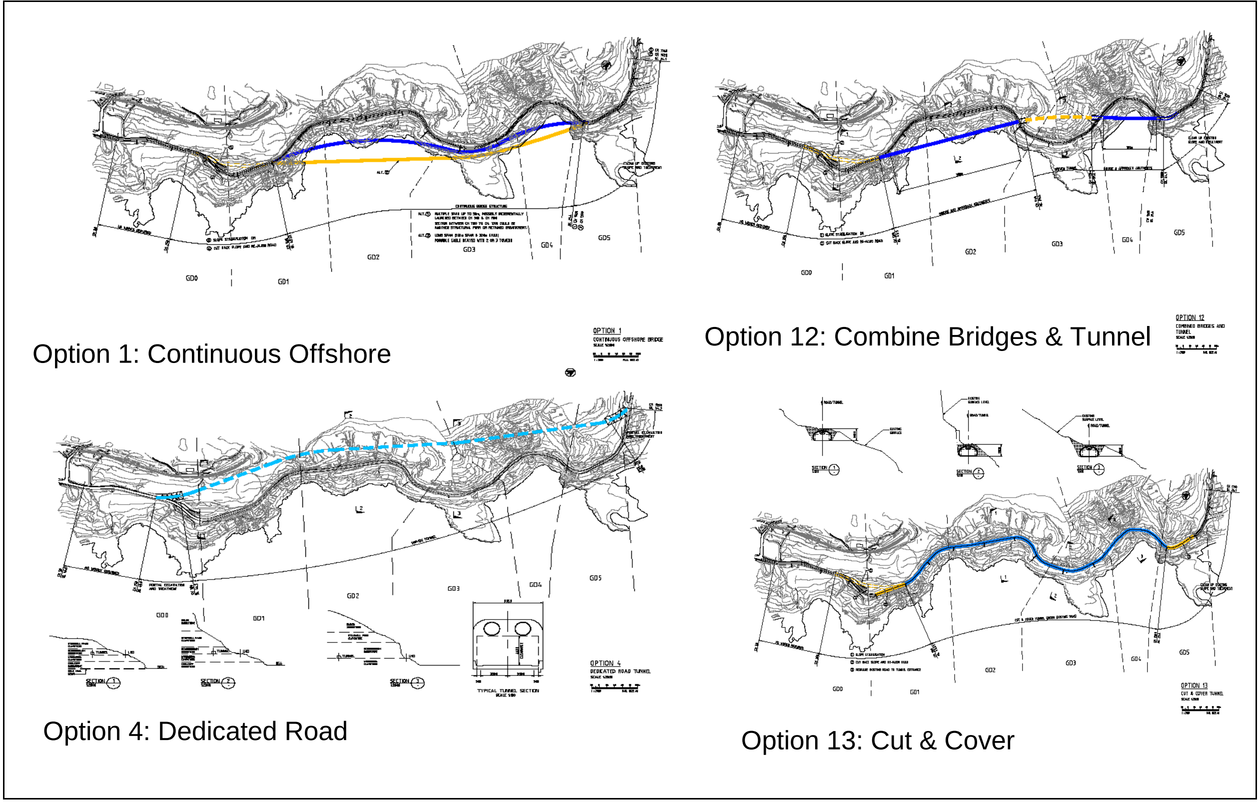
- Environmental protection
- Impact and benefits to society
- Economic benefits

Environment protection is measured by how construction impacts on climate change, land, ecology and water use and how construction is carried out by minimising energy use and carbon dioxide emissions. Also processes need to be developed and implemented to minimise dust, noise and traffic delays during construction as these result inconvenience and health hazards to public.

In addition good construction practice needs to be implemented to construct durable and sustainable bridges. Some of the measures for good construction practices are:

- Enforce adequate construction quality assurance or quality control
- Implement high-performance construction specifications
- Use suitable materials for concrete
- Proper concrete placement
- Proper concrete curing and formwork removal
- Suitable surface protection system for steel elements

The Sea Cliff Bridge in NSW is presented as an example of design and construction of a sustainable bridge in an aggressive marine environment. Figure 1 shows four options out of the 14 considered, where as Figures 2 and 3 show different stages of construction and the completed bridge respectively.


Option 1: Continuous Offshore

Option 12: Combine Bridges & Tunnel

Option 4: Dedicated Road

Option 13: Cut & Cover

Figure 1 – Some Options Considered

A suitable option was selected based on the following criteria:

- Direct design and construction cost.
- Restore two lane road.
- Road user - risk
- Time for project delivery
- Minimal closures for geotechnical events
- Whole of life cost.

The bridge types considered were:

- Cable stay
- Suspension
- Combined Balanced Cantilever and Twin-Tee incrementally launched bridge.

Having considered the above, Balanced Cantilever and Twin-Tee Incrementally launched bridge was selected.

This bridge option was selected based on:

- Geography
- Ground Condition
- Access for pier constructability
- Geometry of the route
- Aesthetics

Durability

Launching of Deck

Substructure Construction

Pier Construction

Figure 2 – Different Stages of Construction

Figure 3 – Completed Sea Cliff Bridge

Operation and Maintenance

All bridges after construction pass to the phase of operation and maintenance and this phase lasts until the end of its services life.

Sustainability during this phase can be achieved by implementing a well planned asset management cycle. This will extend the service life of bridges and eliminate the need for their replacement, extensive rehabilitation or strengthening.

Asset Management cycle for Sustainable Bridges

Earlier in the paper it was stated that the bridge infrastructure in Australia is subjected to significant increase in mass, volume and frequency of heavy vehicles. This has resulted in a accelerated deterioration of the bridge stock, particularly ones constructed before 1948.

The RTA has developed an Asset Management cycle to minimise deterioration of its bridge stock and keep them sustainable whilst allowing them to carry higher loads without compromising their safety and performance.

The Asset Management cycle has 3 phases. They are:
Phase 1 – Routine Activities
Phase 2 – Investigation and Assessment
Phase 3 – Decision Making and Action

The three phases are detailed in Figures 4, 5 and 6.

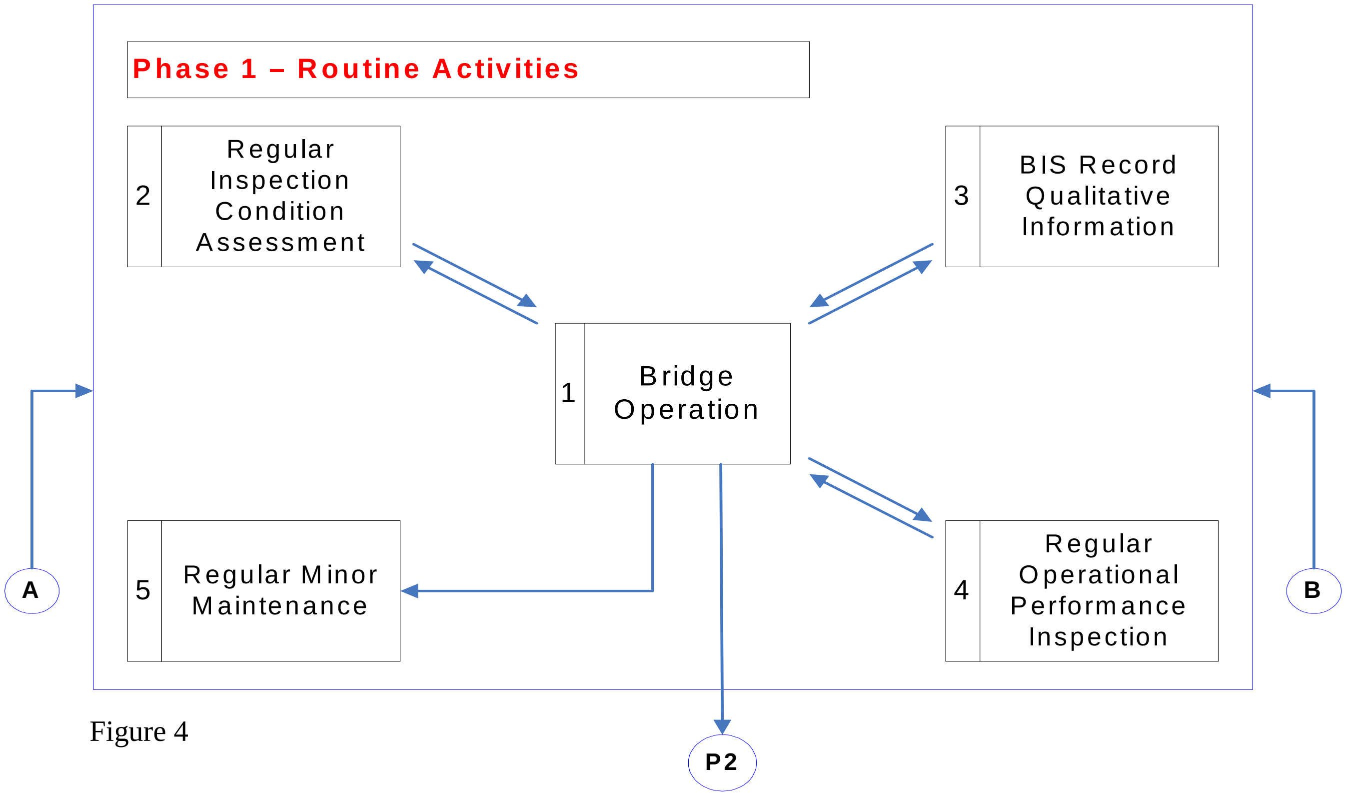


Figure 4

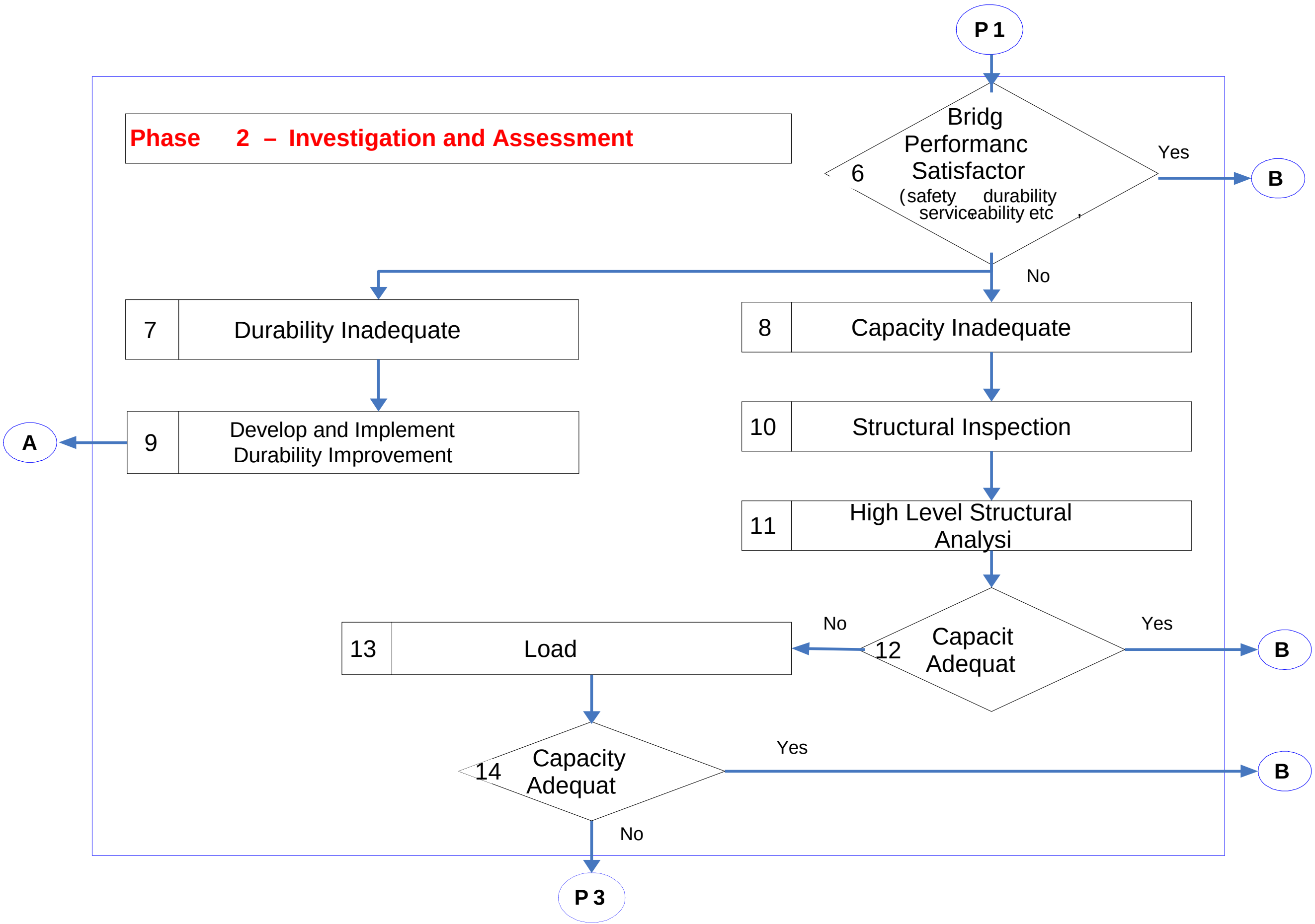


Figure 5

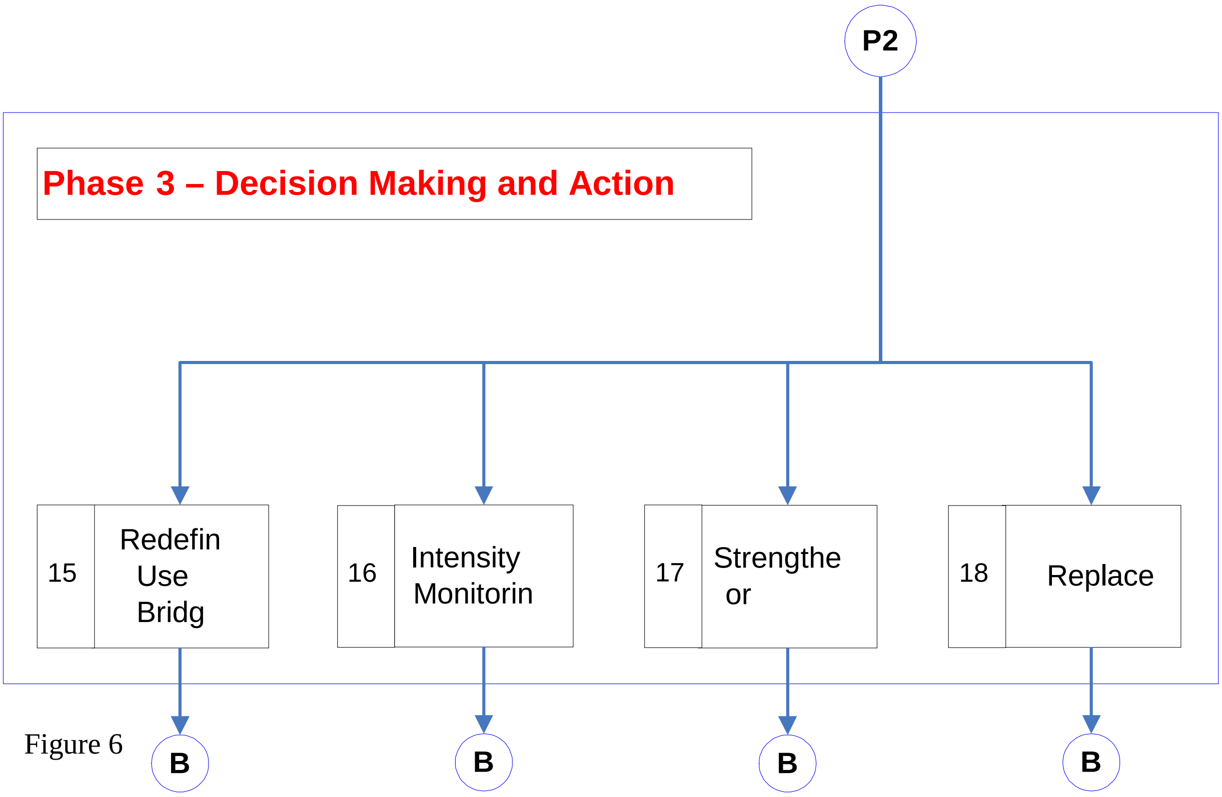


Figure 6

The Phase 1 covers routine activities such as regular inspection and regular minor maintenance work. The Phase 2 has two streams, one is the durability assessment and the other is the structural capacity assessment. The Phase 3 is where decisions are made to redefine the use of bridge, monitor its performance, strengthen or repair or replace the bridge.

Bridge Information System (BIS)

It is through a properly developed BIS that a good asset management cycle can be implemented. BIS provides a database to store, update and access the necessary information for effective management of bridges. The information in BIS should cover information on design, construction, inspection, load capacity, maintenance, strengthening and attached utility services.

Bridge Inspection

Inspection is the process by which information on physical and structural conditions are collected and updated to effectively manage bridges. Inspection should commence at the handover of a new bridge and continue through its service life at predetermined regular intervals dependant on type of bridge. The RTA has a four (4) level inspection process.

Level 1 inspection applies to all bridges and it is the basic drive-by inspection carried out on a regular basis.
Level 2 inspection is a more detailed visual assessment of element conditions carried out at two yearly intervals by trained bridge inspectors.
Level 3 inspection is a detailed structural inspection carried out by a practicing bridge engineer. It is based on a reported or suspected deterioration or damaged critical elements generally arising out of level 2 inspection.
Level 4 inspection is conducted before carrying out a load capacity assessment of a bridge to determine the extent of deterioration or section losses of its critical elements, so that these information (‘As is’ condition of a bridge) can be fed into the model for assessment.

Durability of concrete Bridges

Concrete deterioration due to the corrosion of reinforcement commonly referred to as ‘concrete cancer’ presents a significant risk to the integrity of the RTA’s concrete bridges along the coast. The costs to rehabilitate such affected structures are very high and increases exponentially as the condition of the bridge worsens.

As a more pro-active approach the RTA, has undertaken a global review of the durability condition of its coastal concrete bridge stock which is located within the aggressive marine environments that present the greatest corrosion risk to its bridge stock.

Some of the findings from the review are:

- Long term remedial solutions need to be implemented to prevent structural performance of these bridges being compromised by reinforcement corrosion.
- If long term remedial solutions cannot be implemented within 5 years due to lack of funding or resources, remedial options need to be put in place in the next one to two years to halt or at least inhibit the on set of further concrete deteriorate.
- The RTA is presently investigating the financial and technical viability of the Sacrificial Cathodic Protection (CP) system as a potential interim measure.
- The RTA’s in-house trial data suggests that such systems offer corrosion control and thus offer a cost effective short to medium ‘holding’ solution until long-term solutions can be implemented.

The management cycle for of durability of concrete bridges is shown in the flowchart in Figure 7

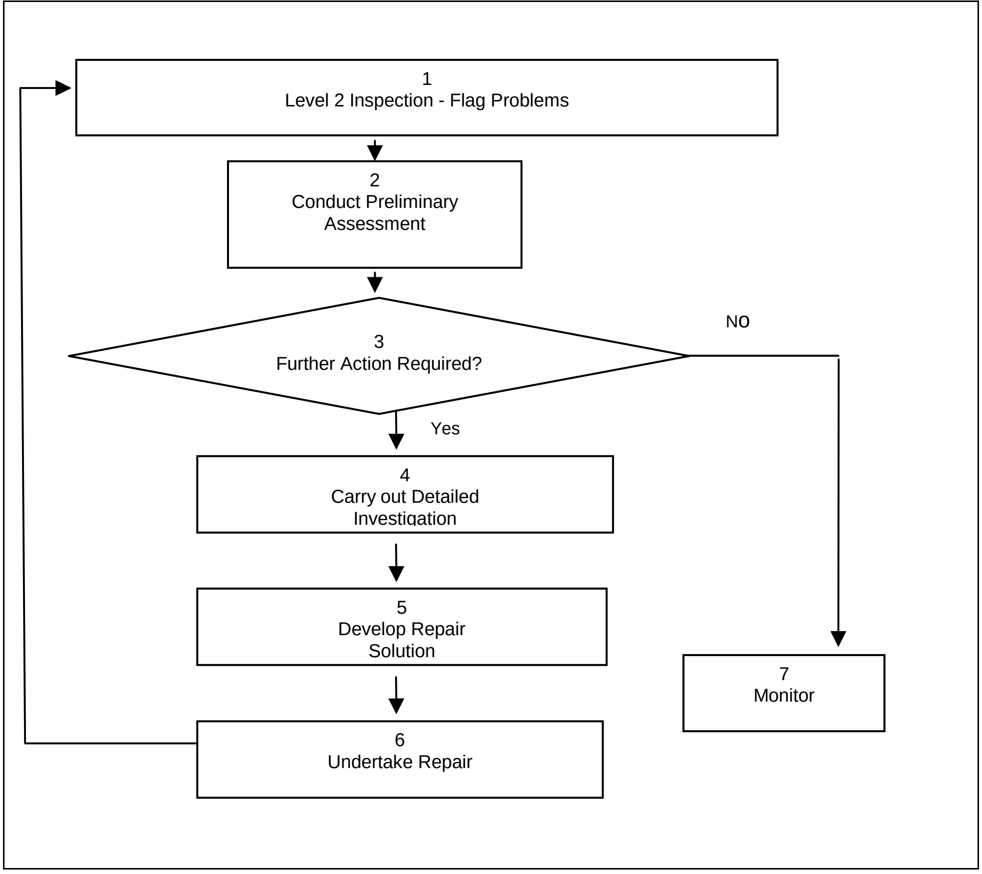


Figure 7 – Management Cycle for Durability of Concrete Bridges

Preliminary Assessment of Concrete Bridges

The steps for preliminary assessment are:
- Carry out testing of concrete
- Determine cause of deterioration
- Assess whether deterioration is widespread

Detailed Investigation for Concrete Bridges

The detailed investigation is necessary only if deterioration is widespread and the steps for detailed investigation are:
- Undertake investigation of areas with widespread deterioration.
- Confirm cause of deterioration by testing for chloride ingress, carbonation, resistivity and potential mapping.
- Determine areas of corrosion activity.
- Determine repair options including costs.

Having undertaken the above investigation a suitable repair solution is selected based on life-cycle costs analysis.

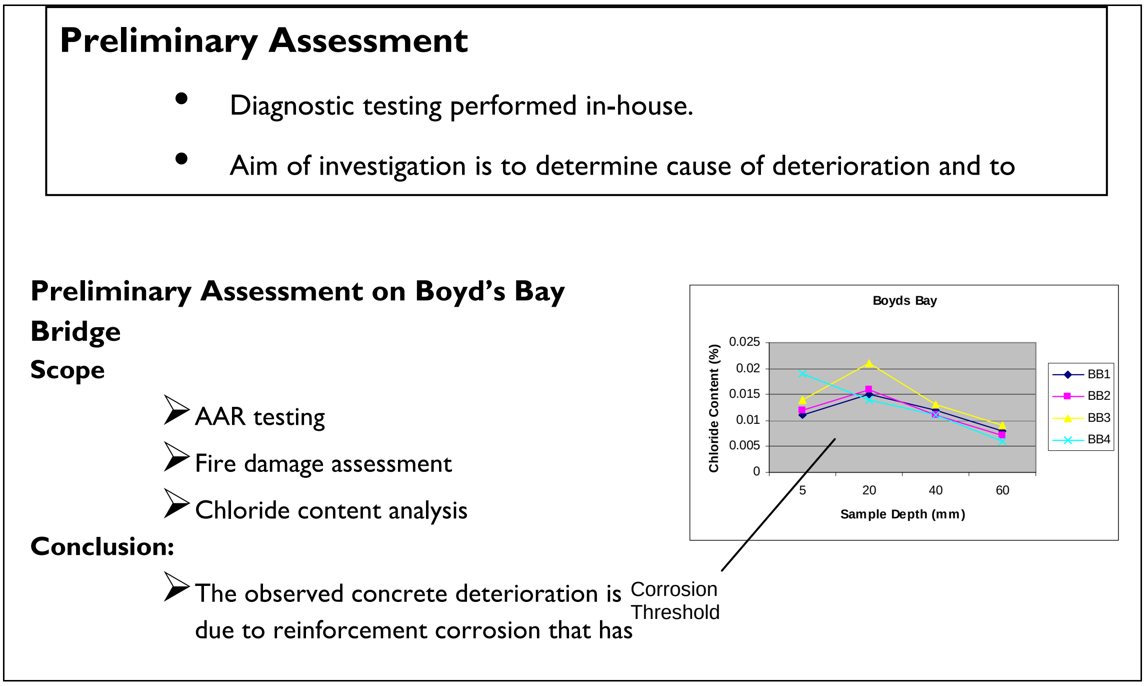
Boyd's Bay Bridge in Teed Heads, NSW is presented as an example.

Figure 8 – Boyd’s Bay Bridge. Located on the Tweed River, Tweed Heads

Problem Flagged

Level 2 (2 yearly) inspection identifies concrete damage.

Figure 9 – Damaged Concrete



Preliminary Assessment

- Diagnostic testing performed in-house.
- Aim of investigation is to determine cause of deterioration and to

Preliminary Assessment on Boyd's Bay Bridge

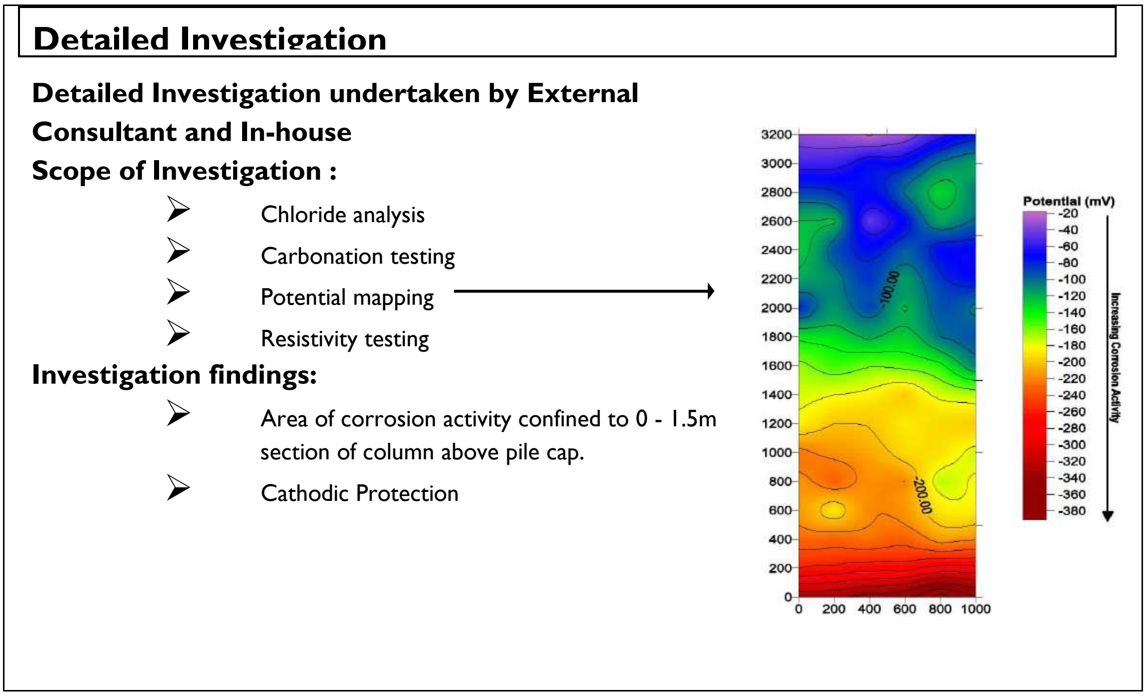
Scope

- AAR testing
- Fire damage assessment
- Chloride content analysis

Conclusion:

- The observed concrete deterioration is due to reinforcement corrosion that has

Figure 10 - Preliminary Assessment



Detailed Investigation

Detailed Investigation undertaken by External Consultant and In-house

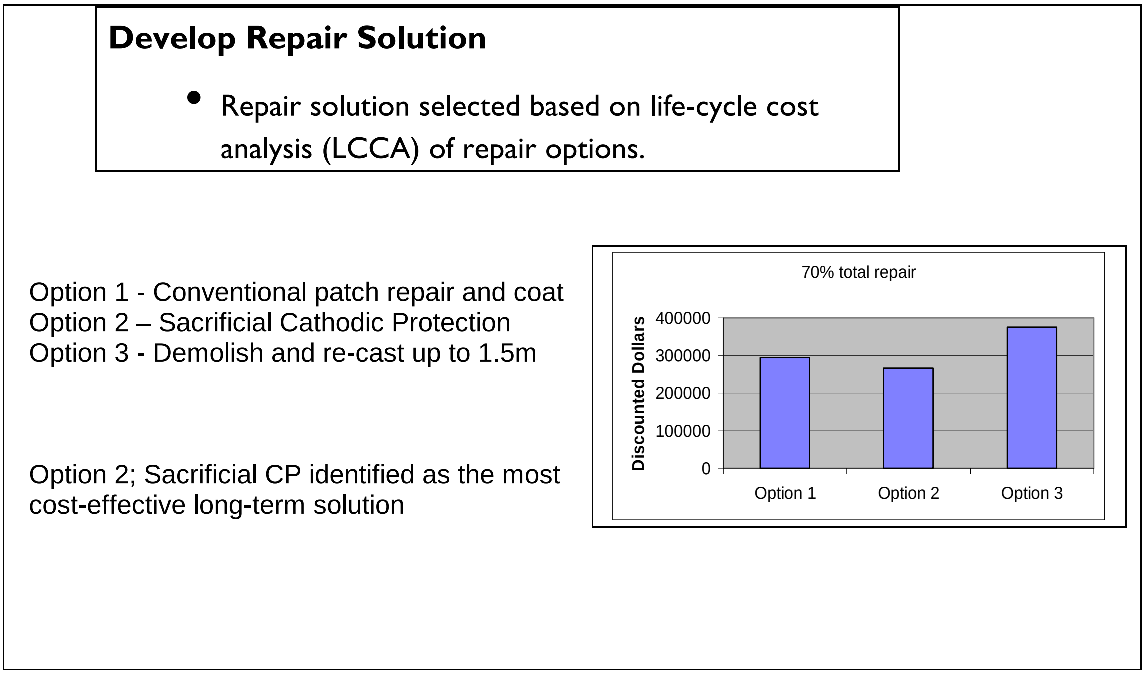
Scope of Investigation :

- Chloride analysis
- Carbonation testing
- Potential mapping
- Resistivity testing

Investigation findings:

- Area of corrosion activity confined to 0 - 1.5m section of column above pile cap.
- Cathodic Protection

Figure 11 – Detailed Investigation



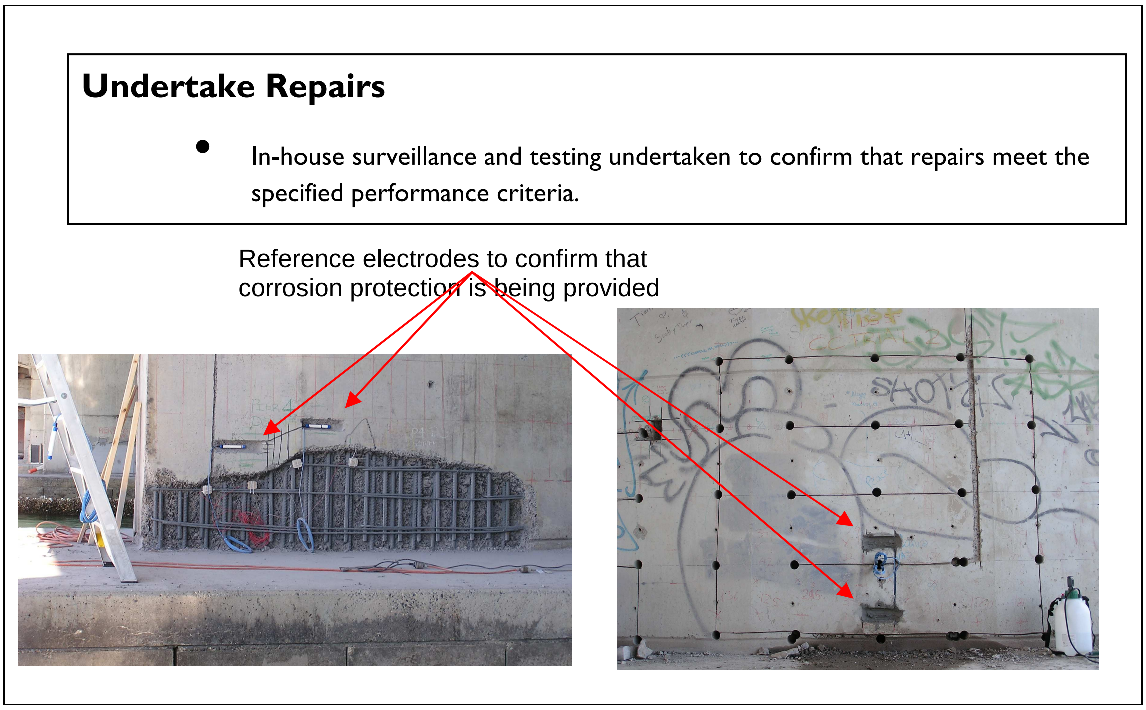
Develop Repair Solution

- Repair solution selected based on life-cycle cost analysis (LCCA) of repair options.

Option 1 - Conventional patch repair and coat
Option 2 – Sacrificial Cathodic Protection
Option 3 - Demolish and re-cast up to 1.5m

Option 2; Sacrificial CP identified as the most cost-effective long-term solution

Figure 12 – Repair Solution



Undertake Repairs

- In-house surveillance and testing undertaken to confirm that repairs meet the specified performance criteria.

Reference electrodes to confirm that corrosion protection is being provided

Figure 13 – Surveillance to Identify Performance

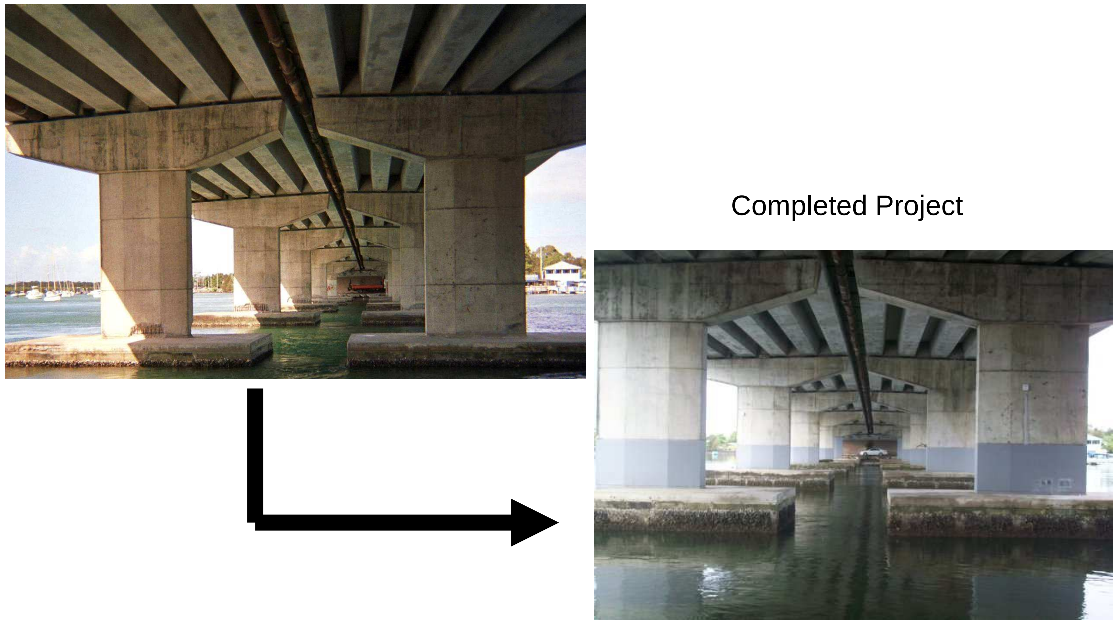


Figure 14 – Completed Bridge

Durability of Steel Bridges

The process developed by RTA for managing steel bridges is shown in Figure 15

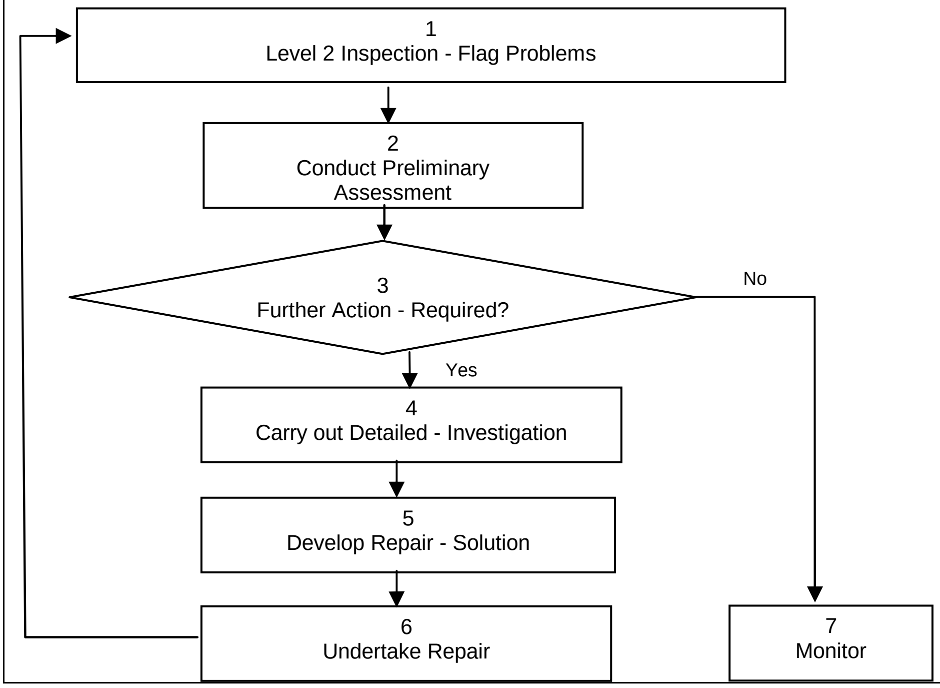


Figure 15 – Process for Management of Steel Bridges

Preliminary Assessment for Steel Bridges

The process for preliminary assessment is:

- Inspect elements for surface cleanliness.
- Establish extent, intensity and method of surface preparation required
- Carry out Level 2 inspection to determine steel condition state and paint condition state of elements.
- Conduct routine maintenance by cleaning, removal of debris and provision for drainage, if the condition of the bridge is in state 1 (as per BIS).
- Carry out further investigation if the bridge is in any other state.

Detailed Investigation for Steel Bridges

The process for this investigation is:

- Map areas of paint in condition state 2 to 4.
- Test coating samples.
- Provide a report identifying paint failures and defining required surface preparation and option for paint systems.

Having completed these investigations develops repair options identifying extent of repairs and a suitable paint system to protect the elements from the environment.

Bridge Load Capacity Assessment

Bridge load capacity assessment is a very effective tool to manage a complex bridge infrastructure, particularly in an environment of increasing live loads.

Bridge Load Capacity Assessment

Bridge load capacity assessment can be conducted at different levels depending on type and age of a bridge.

Different levels of load capacity assessment with management outcomes are shown in Figure 16.

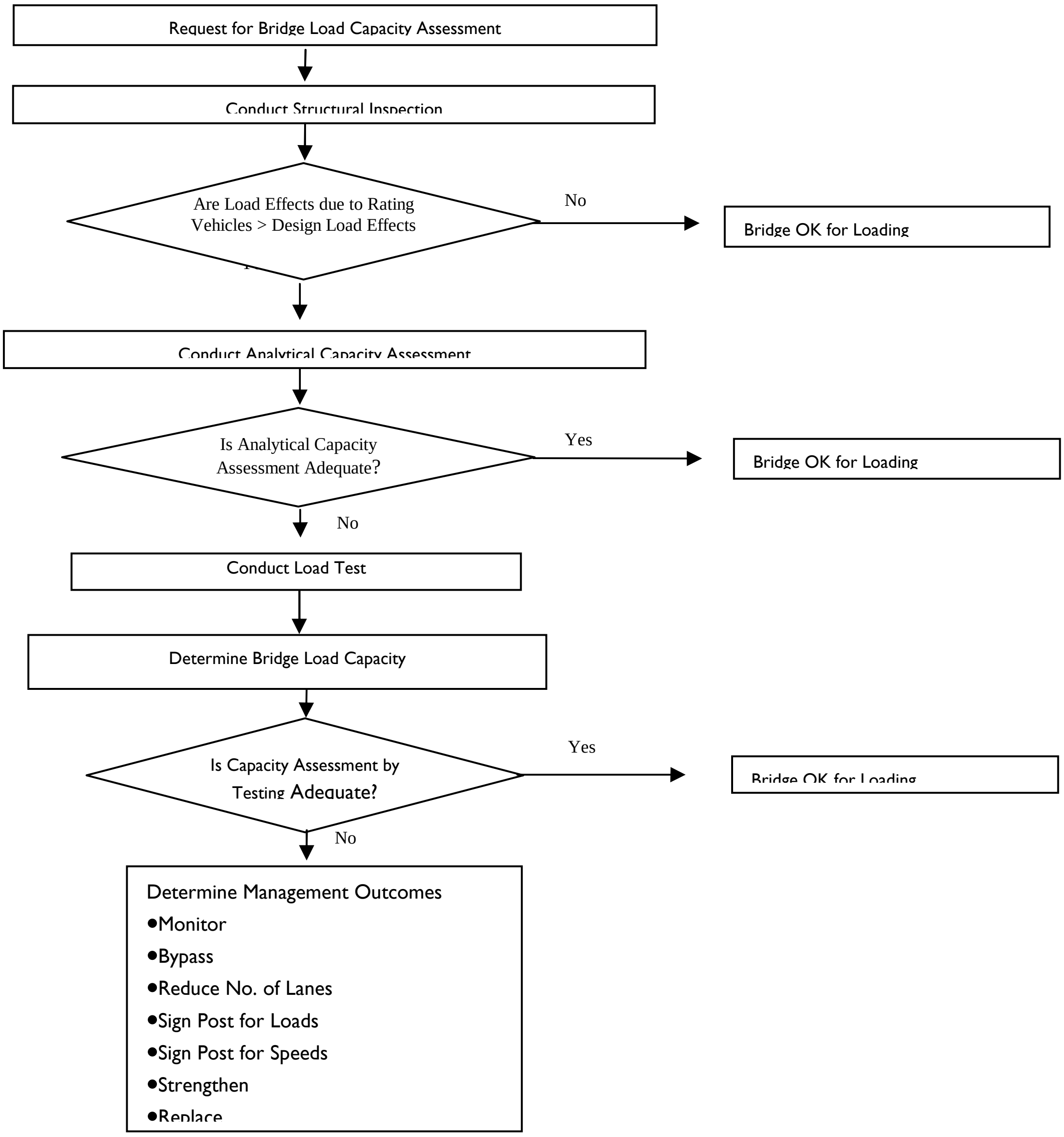


Figure 16 – Bridge Load Capacity Assessment

In 1995 the RTA developed a Bridge Proof Load Testing Facility to enable "deficient" bridges identified by analytical assessment to be evaluated at higher levels of loading, to determine their "true" load capacity without compromising their safety or performance.

Before conducting Proof Load Testing or any other bridge testing discussed in the paper, it is necessary to follow the process detailed in Figure 16. The process consists of structural inspection, material testing, structural analysis and then determine the modes of failure for increase in live loads before carrying out any type of load testing.

Structural Inspection

Structural inspection is a very important part of Load Capacity Assessment and is carried out by competent practicing bridge engineers. Prior to inspection, information is collected from Work as Executed (WAE) drawings and Past Inspection Reports.

Structural Inspection consists of 2 parts, namely Inspection for Loading and Inspection for Resistance.

Inspection for Loading is a Geometric Survey to determine the self weight, superimposed dead load and identify installation of services that may or may not be shown on the WAE drawings.

Inspection for Resistance is carried out to determine all parameters needed to determine strength of the bridge. They are:

- Member sizes
- Cracks
- Corrosion
- Settlements
- Defective Materials
- Damages
- Bridge Articulation
- Section Losses

Material Testing

Material testing is carried out to determine the actual material strength of concrete, steel or timber used in bridges, as these may vary from those shown on the drawing.

Structural Analysis

Prepare structural model of bridge taking in account its ‘as is’ condition determined from inspection. Then carry out structural analysis of the ‘as is’ condition of the bridge to determine the load capacity of the bridge to carry nominated load.

Load testing of the bridge is only carried out if its load capacity by analysis is less than the capacity required to carry the nominated load.

Non-Destructive Load Testing

Load Testing is an effective means of determining the actual load carrying capacity of a bridge. It is particularly suitable for bridges that cannot be accurately modelled for analysis or whose analytical load capacity is less than the capacity required to carry legal loads or nominated loads.

Types of Load Tests:

- Proof Load
- Performance Load
- Health Monitoring
- Dynamic Frequency analysis
- Fatigue Load
- Dynamic Load

Performance Load Testing

This is a serviceability limit state test. Bridge is carefully and incrementally loaded in the field to a pre-determined live load level, marginally higher than the legal load current at the time.

This load level is determined by multiplying the pre-determined live load by the dynamic load allowance and the serviceability limit state live load factor.

Proof Load Testing

Figure 17 – 1st Proof Load Testing (1995)

In these tests, the bridge is carefully and incrementally loaded to a pre-determined target proof load or until the bridge approaches its elastic limit, which ever occurs first.

The Target Proof Load is the lower of the theoretical ultimate live load or 2 to 2.5 times the current legal load.

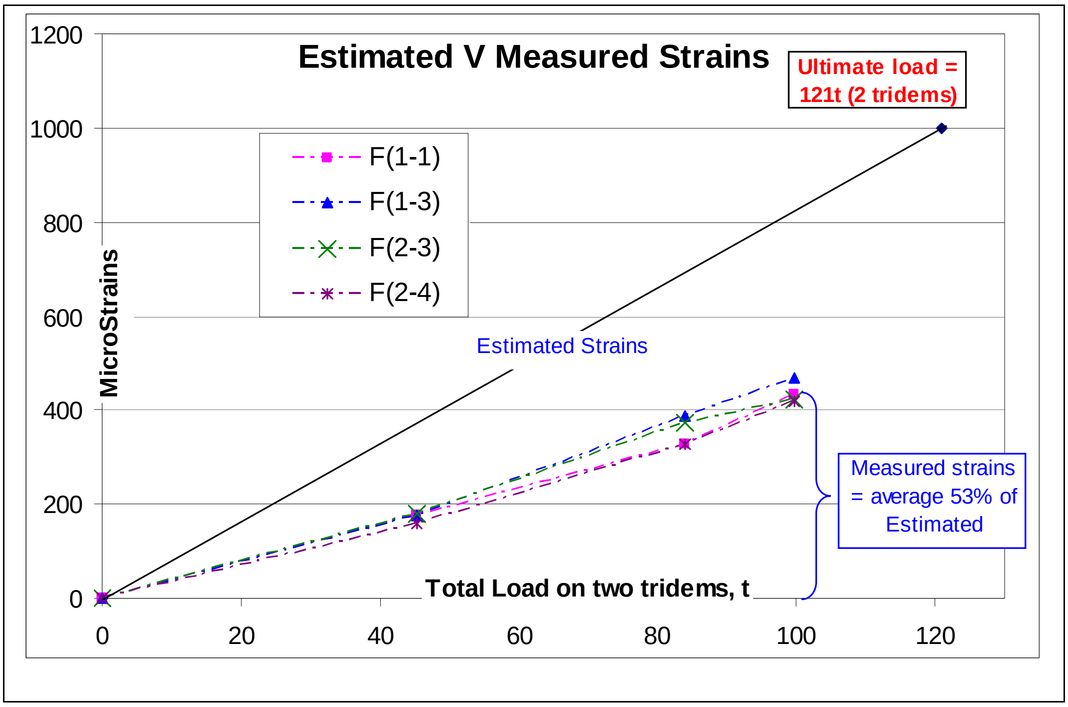


Figure 18 – Results of Proof Load Test:
Load versus strain for girders in span 1 & 2 of Red Bank Creek Bridge

Figure 18 shows the results of comparison of measured strains versus estimated strains against load for a proof load test carried out on Red Bank Creek Bridge in NSW.

Health Monitoring

Stresses strains and deflections of critical elements are measured at ambient traffic over a pre-determined period. Then same effects on these critical elements are measured for a known vehicle. From these results the maximum safe load bridge can carry is determined.

Dynamic Frequency Analysis

Bridge is excited by dropping a drop hammer on deck and dynamic frequency and stiffness of critical members are measured. Using these stiffnesses the Finite Element (FE) Model developed for the bridge is calibrated and its load capacity is determined.

Fatigue Load Test

This is a serviceability limit state test. Measure strains or deflections of critical elements for ambient traffic for a pre-determined period. For this period, determine stresses and number of cycles, and extrapolate these results for the past and into the future. From these results and using Miners rules determine the remaining fatigue life.

Dynamic Load Test

This test is carried out by running test vehicles of known axle configuration and Gross Vehicle Mass over bridge at varying known speeds, including at crawl speed. Dynamic strains, deflections and acceleration of the bridge for these speeds are measured and from these results Dynamic Load allowance (DLA) is determined.

The RTA has carried out Proof Load Testing of 56 bridges and other types of load testing for a larger number of bridges. The results from these tests have confirmed that bridges identified by analysis as being inadequate to carry current legal loads have significantly higher capacity to carry legal loads.

Results of some bridges tested are given in a table 1.

Table 1 – Comparison of Test Results

Name	**Type**	**Description Load**	**A/Rate Load**	**T/Rate Load**
Road over Rail on Pennant Hills Rd, Carlingford NSW	Jarch	17t	40t	47t
Upper Warrel Ck. On SH10 at Macksville, NSW	Sbeam	33t	40t	65t
Road over Rail on Weeroona Rd. Strathfield-West, NSW	Jarch	16t	29t	49t

Benefits – Load Capacity Assessment

Conducting structural inspection and load capacity assessment of bridges, asset managers will be able to proactively manage the aging bridge infrastructure, keep them sustainable and bring the following benefits:

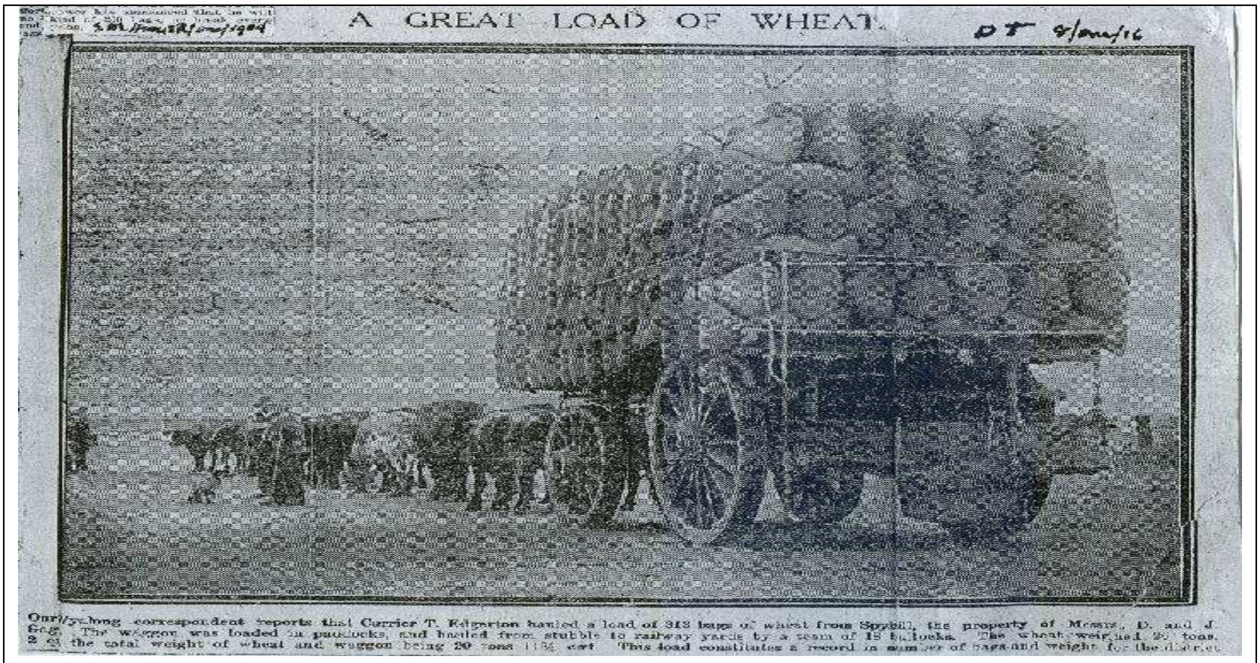
- Minimise strengthening of bridges.
- Delay replacement of bridges.
- Priorities replacement and strengthening of bridges perceived as weak links in the road network.
- Establish a basis to safely increase volume, mass and length of road freight vehicles.
- Allow more liberal movement of heavy loads across the network.
- Maximise benefits from limited funds.

In addition it also brings the following global benefits:

- Improved utilization of country’s bridge infrastructure.
- Improved national transport efficiency and productivity.
- Improve industry competiveness.
- Reduced cost of living.

Heavy Vehicles on RTA Road Network

Below are some heavy vehicles on the RTA road network.



A GREAT LOAD OF WHEAT.

DT 8/Jan/16

Our Wyalong correspondent reports that Carrier T. Edgerton hauled a load of 313 bags of wheat from Spyhill, the property of Messrs. D. and J. Gog. The waggon was loaded in paddocks, and hauled from stubble to railway yards by a team of 18 bullocks. The wheat weighed 2? tons, 2 ?, the total weight of wheat and waggon being 29 tons 11¾ cwt. This load constitutes a record in number of bags and weight for the district.

Figure 19 – In 1900, 18 bullocks, Carry 29t

Figure 20 – General Access Vehicle Semi Trailer (44.5 Tonnes)

Figure 21 – Restricted Access Vehicles

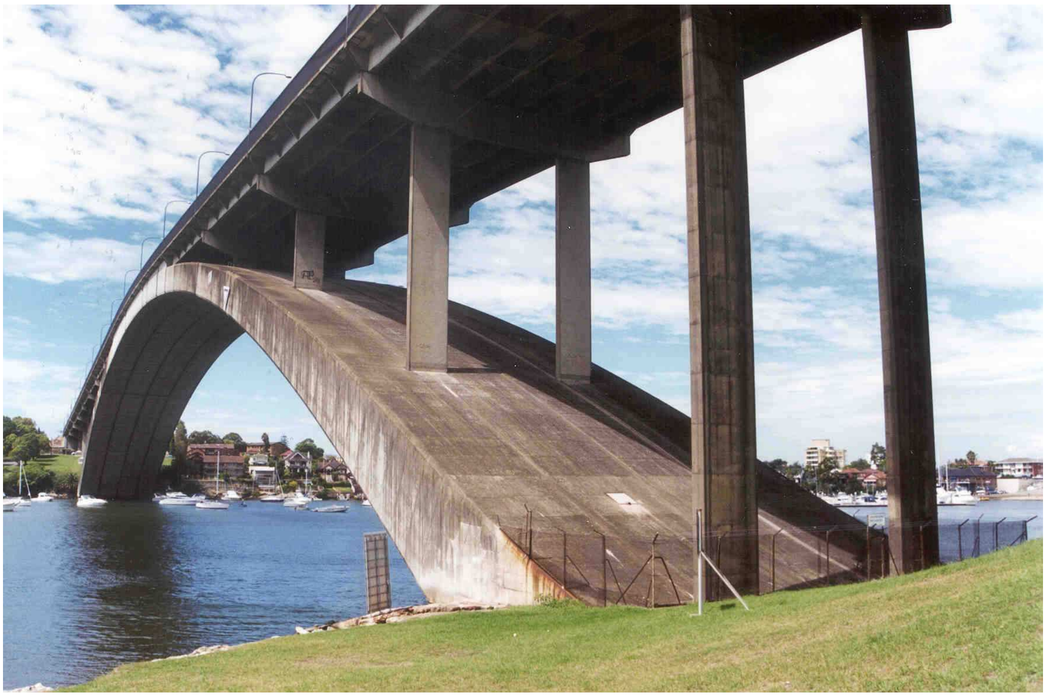
Figure 22 – Permit Vehicle, Crane

Figure 23 – Permit Vehicle

Managing Challenge

The RTA is managing effectively a very complex bridge infrastructure of different vintage bridges with different types in different aggressive environment and in a regime of significant increase of heavy loads.

The following are some examples from the RTA bridge infrastructure:



The Gladesville Bridge

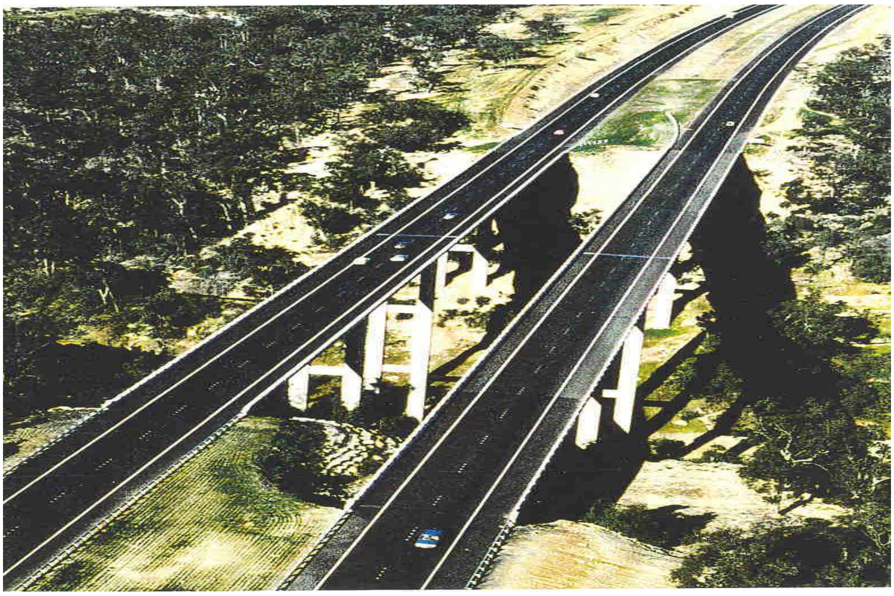
The Anzac Bridge

Woronora River Bridge

Twin Bridges over Mooney Mooney Creek

The Harbour Bridge

The Rip Bridge



Twin Bridges over the Nepean River at Douglas Park

- The 1.8km long viaduct was opened to traffic in 1986.
- The viaduct consists of prestressed concrete cast-in-place voided slab spans continuous over five and six span sections.
- There are 58 spans with span lengths from 30 to 40m.
- The piers are of reinforced concrete (RC) columns and are supported on cast-in-place RC piles founded on shale.

Viaduct between Granville & Parramatta on M4

Conclusion

Sustainability is about keeping cleaner air and water, greener earth and healthier living for the present and future generations.

All stakeholders working together innovatively thought the phases of planning, design, construction and asset management we can achieve sustainable bridges. Sustainable infrastructure bringing in benefits to the present and future generations.