DESIGN, RETROFIT AND INSPECTION OF RAILWAY BRIDGES IN NEW ZEALAND

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ABSTRACT

This paper presents a brief overview of bridging in New Zealand. Two aspects of significance in bridge design in New Zealand are seismic and scour resistance. Both earthquakes and floods have the potential to significantly damage infrastructure and affect operations. Discussed are some of the insitu retrofits that have been designed to improve the network’s resistance to events of this nature without the replacement of the existing structures. In addition the paper outlines the inspection processes utilised for the maintaining of a safe bridging asset.

KEY WORDS: New Zealand, Bridges, Earthquakes, Scour, Design, Inspection

INTRODUCTION

New Zealand is a country located on the Pacific Ring of Fire that is very young by geological standards and surrounded by vast areas of ocean. These factors combine to result in a land mass subject to earthquakes, volcanic activity, land movement, and high rainfall resulting in flooding and scour.
Through this land operates a network of around 4000km (2500 miles) of narrow gauge 1067mm (3’6”) track. This network is illustrated in Figure 1. The railroad is primarily engaged in the hauling of freight, although commuter operations are operated in Auckland and Wellington and some inter-city passenger trains operate. The operation includes over 400 route km (249 miles) of 25kV AC traction overhead between Palmerston North and Hamilton and 100 route km (62 miles) of 1500V DC commuter operation in Wellington.

In addition the Company operates three inter-island ferries between Wellington and Picton. Two are conventional ships carrying rail, road and passenger traffic and the third is a high speed catamaran carrying road and passenger traffic only.

The network has approximately 2% of its length on bridges and another 2% in tunnels. This amounts to some 1660 rail bridges, 149 tunnels and nearly 13,000 culverts. Bridging stock is quite varied and diverse, ranging from timber spans of beams and trusses, (Figure 2), to complex pre-stressed concrete viaducts, (Figure 3). This diversity requires a number of different inspection techniques.

This paper discusses some of the aspects of design and inspection used in New Zealand to deal with these environmental challenges.

**THE BRIDGING STOCK**

Varied styles of bridging have been in vogue at various times over the railroads history. From the earliest private railways of various gauges timber was the dominant construction material. Some early abutments and bridges were constructed in masonry, concrete or cut stone. During the early half of the 20th Century the use of iron and steel spans on timber piers was predominant with concrete piers becoming typical in the 1920’s onwards. Concrete ballast decks and spans began appearing in the late 1920’s. After a period of
concrete span construction in the 60’s and 70’s designs reverted back to steel on concrete piers. This was primarily driven by the release of good quality steel spans from service through the construction of the concrete bridges to replace structures with timber piers at risk from scour. These spans were refurbished and reinstalled in track.

Numbers of each style of bridging remain in service today. Figure 4 illustrates the age profile of the bridging stock.

**DESIGN OF BRIDGES**

Design of bridges in New Zealand is undertaken using a combination of the AREMA Manuals, Tranz Rail amendments to those for the New Zealand environment, and New Zealand standards. New Zealand standards used include the Loadings Code ([1](#)), and the Concrete Code ([2](#)). AREMA is used for steel design and Australian and New Zealand standards for timber. Amendments to the AREMA recommendations include adjustment of the height of application of loads such as wind and centrifugal to take into account size and gauge factors.

Applied loading is typically Coopers E40, with an alternate loading of 4 23.4 tonne axles at 1.6m centres, (25.8 short tons at 5.25 feet), which has the effect of E50 loading on short spans and floor systems. This provides for the maximum axle loads of 18 tonnes, (19.8 short tons), currently typical in the system.

As with most systems today the Engineer is required to provide the cheapest solution that satisfies the risk profile that the company operates with. The replacement of assets is a last resort. Therefore innovative ways of building and repairing structures are sought. Below we discuss some aspects of design requirements and retrofit solutions that have been adopted to meet the challenge of low cost and low risk.
**Seismic Design**

New Zealand is a seismically active country that experiences a number of earthquakes each year. Over the years a number of innovative designs have been used to provide structures with the required seismic resistance. In the depression era the concrete ballast deck bridges were continuous over 4 spans and the designers allowed for seismic movement by providing split pier tops at the span discontinuities. These initial designs eventually were superceded by bridges designed with anchor piers, stepping piers, (Figure 3), and floating abutments.

The design codes (3) used by Tranz Rail require that bridges be designed for seismic loading using the loading combination: Dead + Earth Pressure + Bouyancy + Normal River Flow + Earthquake. The seismic loading is determined through the use of the New Zealand Loadings Code (1). This determines loading through various parameters such as seismic zone, soil conditions, the structures period and its ductility.

Typical new construction at present is usually to provide concrete caissons constructed outside the loading gauge with reinforced concrete caps. This type of construction is illustrated in Figure 5. The design of these reinforced concrete piers requires that the formation of plastic hinges due to seismic loading occurs in the top of the pile below the cap rather than in the cap itself. This is the opposite to the requirements for building frames where the plastic hinges are required in the beams. This is achieved by heavily reinforcing the cap-column joint with shear steel to attract the plastic hinge zone to the top of the pile.

Typically pile casings are left on the structures where these are either buried or in locations where they are not generally in the publics eye. Research sponsored by the railroad into the effects of the pile casing on seismic loadings (4) found that the practice of leaving the casing on the piles provided substantial increases in strength. The traditional design practice is to ignore the contribution of the casing and to design the piles as spirally reinforced columns. This provides a conservative approach to the seismic design of piers.
Seismic Retrofit

The wide spread use of concrete for bridge piers commenced in the 1920’s. Early concrete bridge piers were typically constructed as mass concrete units with little or no reinforcement. These piers had inherent weaknesses when subject to seismic loading that was likely to be exacerbated by the quality of the concrete, its placement and the presence of construction joints. Although these piers presented no concerns from normal loading of the bridge the seismic load was likely to cause significant damage when the piers went into tension.

The solution to this problem was to ensure that the piers could not develop significant tension loads under seismic loading. This was achieved by stressing the piers vertically and sometimes horizontally with externally applied prestressing cables. A cap is cast at the top and bottom of the existing mass concrete pier and this is stressed onto the old concrete pier. Steel ducts are run up the sides of the pier between these caps to place the prestressing strands inside. The top and bottom caps are then stressed together forcing the mass concrete into high compression loading hereby reducing the likelihood of tension development. An example of this technique is shown in Figure 6.

Scour Design

Scour has been a significant problem for bridge foundations over the years in New Zealand. This primarily due to the nature of the rivers, the steepness and instability of the country and the climate.

As stated previously, the predominant construction method for piers in the earlier part of the century was end bearing driven timber piles. Rivers throughout the country south of Napier tend to have gravel beds. These beds are difficult to drive piles into, whether they be timber, steel or precast concrete. The nature of this construction meant the majority of bridge replacements in the 1940’s through to the 1970’s were driven by the susceptibility to scouring in flood caused by insufficient initial embedment of the piles.
The problem was so significant that the railroad developed its formulae for designing foundations to
prevent scour based on the history of scour failures (5). Using these formulae design for scour is based on
the combination of two effects, the general bed scour and the local scour at a pier, (Refer to Figure 7). The
depth of scour calculated is then added to the free length of pile above ground for the pier design so that all
scourable material is ignored in any contribution to pier stability. In addition to checking the railroad’s
formulae the scour depth is also calculated using the Lacey formula. The worst scenario is used for design.

Typically the construction of new piers in these gravel river beds is with steel caissons filled with
reinforced concrete. Where driving piles into this material is required the pile must be driven through a
cylinder that has been excavated to the design scour depth to ensure embedment is achieved. Generally,
driven piles are avoided in scourable situations and caissons are used.

**Scour Retrofit**

Risk due to scour today is monitored on an individual pier basis. Prevention of scour through the provision
of protection works such as weirs or rock groynes is the preferred method to protect bridges as these are the
least expensive and easiest works to undertake. However, this is not always possible or acceptable to local
authorities and more direct intervention with the existing structure is required. These remedial works are
carried out on only the pier affected by scour and not the entire bridge and are known as underpinning.
Repairs are generally made by entirely replacing timber piers with a concrete pier constructed with caissons
filled with reinforced concrete of similar design to those shown in Figure 5. Where a concrete pier has
scoured the remedial action taken is to install new caissons alongside the existing pier. These are taken
down to a founding depth well below the scour depth where a concrete plug is driven to provide end
bearing capacity. The existing pier is sometimes utilised by casting a new pier cap around the pier base
above any existing piling and attaching it to new caissons placed at the ends of the piers. In some cases the
existing pier is not utilised at all as it may be constructed with caissons or have insufficient stability due to
the scouring. In these situations the new cap is cast around the top of the pier and the new caissons extend
to this height. An example of this later type is shown in Figure 8.
STRUCTURES INSPECTION

Inspection Process

Currently in New Zealand railroads are self-regulated – in other words there are no FRA guidelines to work to. An operating licence must be gained from the Land Transport Safety Authority, a Government agency, by the presentation of documentation for approval such as codes and standards, rules and regulations and Working Timetables to operate. Part of these codes and standards include the specification for structures inspection processes.

To manage both the civil asset and the associated inspection programmes, Tranz Rail operates both a track database and a structures database. The structures database logs all information relating to a structure enabling easy access to a large range of information from any office. The generic record fields contained in database for bridges are listed in Table 1 and as can be seen are quite extensive.

Structure type, competencies and authorities define the inspection process. The structure type determines the frequency at which inspections must be carried out. These frequencies are shown in Table 2. In addition to the detailed inspections required, the Track Inspectors note any visible deterioration and report this on a frequent basis as part of their normal inspection duties. These duties involve the inspection of all lines either once or twice per week depending on traffic and tonnage. Special Inspections can also be generated for a number of reasons. These may be directed at the entire bridge or specific components at the discretion of the Inspector or the Engineer and are usually the result of floods, earthquakes or impact damage.

The detailed requirements for inspections of various types of structures are defined in the Structures Inspection Manual (6). The manual acts as both a field guide and a training manual for the inspectors. The inspection report is designed in such a manner that there is enough information for the engineer to analyse or re-rate a structure without the need for a site visit. An example of part of an inspection report for a
timber bridge is shown in Figure 9. Information such as span length, beam centres and pile centres along caps is all provided in millimetres for the engineer. Other information provided includes the types of decay with magnitude and location, surface defects, material type and age.

To assist inspectors in the field it is normal practice to permanently mark some components. All timber is marked with the last 2 digits of the year it was installed in the bridge and additionally with SH if it was second hand when installed. These dates can be seen recorded on the inspection report. This has just recently caused some minor problems as there are a few timbers that are over 100 years old still in service. In addition, all piles are also marked with the depth to founding in roman numerals. On steel piles these are welded on the pile, on concrete they are cast in and timber is marked with a router.

The inspection process begins with the generation of an order to perform an inspection. This generates a written report that is created by overwriting in hand the previous inspection report stored in the bridge database. This report is submitted with recommendations to the Bridge Maintenance Engineer who reviews the report and its recommendations. Following review the Engineer may either issue any maintenance work order required, carry out an engineering inspection, re-rate the bridge or file into the system. The process is outlined in Figure 10. As can be seen from this figure it is also the Inspectors role to check all work completed on a structure has been done to the correct standards and is complete before any work order is signed off. Where the work cannot be programmed or completed for some reason it becomes the inspectors duty to check the unsatisfactory components for deterioration to ensure a safe condition is maintained at all times.

Inspection records are kept on both the individual bridge files as original paper copies and the last current report is also kept in the structures database. On these reports all notations, (whether in the computer or on paper), by the inspector or the engineer are identifiable.

A feature of timber bridges in New Zealand is that the majority are constructed with Australian hardwoods, usually New South Wales Ironbark. These timbers, although very strong, have the characteristic of rotting
from the inside out. This requires the inspectors to bore the timber on the neutral axis and to determine through feel and the shavings what cavities are present and whether they contain any rot that is either active or inactive. Some of the fungi that can be found can cause rapid deterioration so the detection of the state of activity is very important. In addition the timber piles in the ground are subject to surface rots, particularly Jelly Rot, in the highly oxygenated layers of soil near the ground surface. This phenomenon requires all piles to be excavated during detailed inspections and any rot found to be traced to its full extent. When this type of rot is discovered an order to clean or remove the rotted section, (stumping), will be created.

A number of new electronic inspection tools developed through the electricity industry for the inspection of timber power poles have been appearing on the market. These operate utilising technology such as ultrasound or similar to create a view of the timbers cross section. They have not proven to be any worth to rail as these devices detect the presence of cavities but not the type of fungal activity which is occurring if any.

**Competencies**

Traditionally Structures Inspectors who have risen through the ranks from the bridge gangs have undertaken inspections. This gives them an extensive background on how structures work and the problems associated with various types of structures. Typically the Inspector would be a trade qualified carpenter who has received both classroom and on the job training to work in the role. Inspectors are expected to be able to climb the structures, assess material condition and performance, evaluate paint and fastener condition, undertake non-destructive testing and recommend repairs.

A Registered Professional Engineer, (equivalent to a PE in the US), undertakes analysis of the reporting by the Inspectors. It is the Engineer’s role to ensure that the structure remains safe for the required use, repairs are carried out, any re-rating is completed and records are amended. The Engineer is also expected to be
able to conduct full engineering inspections of the structures as an Inspector would excepting the boring of timber.

CONCLUSION

The challenge of the New Zealand environment is different to many other areas of the world. The rugged nature of the country with the presence of seismic, thermal and high rainfall activity have led to a number of challenges is maintaining the railroad asset. The concept of retrofitting bridges has been used very successfully in the scenarios described within this paper and with other scenarios both to maintain serviceability but also to reduce capital and maintenance costs.

REFERENCES

3. Code Supplements – Bridges and Structures, Tranz Rail Ltd.
LIST OF FIGURES

Figure 1: Tranz Rail Network
Figure 2: Timber truss bridge
Figure 3: Modern prestressed concrete viaduct
Figure 4: Age of bridging stock
Figure 5: Typical new construction
Figure 6: Seismic retrofit
Figure 7: Scour Depths
Figure 8: Underpinned pier
Figure 9: Example inspection report
Figure 10: Inspection Process

LIST OF TABLES

Table 1: Bridge Database Record Fields
Table 2: Inspection Frequencies for Structures
FIGURE 1: Tranz Rail Network
FIGURE 2: Timber Truss bridge
Figure 3: Modern prestressed concrete viaduct
FIGURE 4: Age of Bridging Stock

Age of Active Bridge Stock*
*based on construction date

Number

Decade

FIGURE 4: Age of Bridging Stock
Figure 5: Typical new construction
FIGURE 6: Seismic Retrofit
Total Scour depth = $D_{S1} + D_{S2}$ (metres)

Figure 7: Scour depths
Figure 8: Underpinned pier
FIGURE 9: Example Inspection Report

<table>
<thead>
<tr>
<th>Description</th>
<th>Estimated Life</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge on a straight. Consists of 5 No. spans of 4 No. Hardwood beams on 6 No. piers of 3 No. plumb driven Hardwood piles.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PIER 1
Piles out of ground = 500

**PILE 1** 300 dia. Ironbark (No date)
- Bores sound.
- Weather splits - shakes all faces full length up to 5 wide x 15 deep.

**PILE 2** 275 dia. Ironbark (No date)  Sound.
- Stumped at 1500 under cap in 1990.
- Stump Sound.
- Splice Steel cylinder.

**PILE 3** XVI 275 dia. Ironbark (No date) 3 [Supplementary report 1999 Increase.]
- 140 x 130 pipe and Decay at 80 under cap
- 80 x 100 pipe and Decay at 400 3 yrs rebore.
- 50 x 50 pipe and Decay at 700
- Sound at 1.000
- No sign of white rot; dried out.
- Vertical splits through pile head up to 10 wide x 600 long.
- Pile head getting bored out.

**CAP** 350 x 300 x 4000 (Second Hand 1940)
Pile centres = 440/1570/1510/480
Beam centres = 1160/560/550/560/1150
- 50 x 50 Pipe & Heart Decay at 550 End 1 over Pile No. 1.
- Bores sound at 900.
- Remainder bores sound.
- Top face at outside of beams.
- Weather shakes up to 10 x 20 deep.
- No. 2 face No. 1 end horizontal split from end of End 1 1.0m long x 10 wide x 100 deep.
- Pipe and knot End 1.
- Pipe 700 deep.

**SPAN 1**
Span seating centres = 5420

**BEAM 1** 400 x 300 x 5650 Ironbark (Second Hand 41)
- Bores sound.
- Weather shakes Left Hand face 3 No. over 1750 at Centre line 8 wide x 50 deep x 600 long.

**BEAM 2** 400 x 300 x 5650 Ironbark (1978)
- Bores sound.

**BEAM 3** 400 x 300 x 5650 Ironbark (Second Hand 1941)
- 90 x 50 Trace White Spot and Decay at 300 End 2
- 80 x 50 Heart decay at 900.
- Bores sound at 1500. Remainder bores sound.
Figure 10: Inspection Process
**TABLE 1: Bridge Database Record Fields**

<table>
<thead>
<tr>
<th>Database sections</th>
<th>Specific data held</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic</td>
<td>Metrage, Line, Name, Owner, Pier type, Span type, Number of spans, Overall length, Deck type, Number of tracks, Curve radius, Gradient, Date Constructed,</td>
</tr>
<tr>
<td>Structural</td>
<td>Span lengths, Plan numbers, Superstructure components, Sub-structure Components, Foundation components</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Footwalk data, Bridge appendage data (wing walls, ballast guards, cables, traction poles, impact beams, etc), Catchment data (area, slope, design flow, max recorded flow, max flood level), Painting data (area, paint type, date painted)</td>
</tr>
<tr>
<td>Rating</td>
<td>Normal &amp; Maximum rating, weakest point</td>
</tr>
<tr>
<td>Detailed Inspection</td>
<td>Current detailed inspection report</td>
</tr>
<tr>
<td>Supplementary Inspection</td>
<td>Any supplementary inspection records ordered from the detailed inspection.</td>
</tr>
<tr>
<td>General Inspection</td>
<td>Current annual general inspection records</td>
</tr>
<tr>
<td>Engineering Inspection</td>
<td>Any data relating to an Engineer's inspection of the asset.</td>
</tr>
</tbody>
</table>
### TABLE 2: Inspection Frequencies for Structures

<table>
<thead>
<tr>
<th>Structure Type</th>
<th>General Inspection Frequency</th>
<th>Detailed Inspection Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridges</td>
<td>Annually</td>
<td>8 yearly</td>
</tr>
<tr>
<td>Tunnels</td>
<td>None¹</td>
<td>8 yearly</td>
</tr>
<tr>
<td>Culverts</td>
<td>None²</td>
<td>8 yearly</td>
</tr>
<tr>
<td>Miscellaneous structures</td>
<td>None</td>
<td>8 yearly</td>
</tr>
</tbody>
</table>

1. Miscellaneous structures are defined as: Floodlight towers, turntables, retaining walls, timber radio masts, signal gantries, traction poles, etc.

2. Track inspectors also monitor as part of their duties