Seismic security of state highway bridges: screening and retrofit – progress summary

NZSEE 2002 Conference

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ABSTRACT: Transit New Zealand is undertaking a project to retrofit state highway bridges so as to ensure that seismic performance of the network will be to an acceptable standard. Preliminary screening of all 3800 bridges and culverts has been completed, and structures that require further analysis have been identified. The paper describes the background to the project, the methodology used and the results of the screening. It also discusses the basis of ranking the structures for further analysis, the issues involved in allocating a justifiable level of funding that will provide the required security of the network and the options for procuring the design and construction services necessary for implementing the programme.

1 INTRODUCTION

Since 1999, Transit New Zealand has screened all state highway bridges to identify those that justify retrofitting for earthquake resistance, and their order of priority.

An earlier paper (Chapman *et al*, 2000) outlined the screening procedure adopted for seismic screening of New Zealand's state highway bridges. This paper presents a brief summary of New Zealand's bridging stock and earthquake risk, (and thus the justification for the project), the policy that has prevailed to date on seismic retrofitting of bridges, the outcome from Transit New Zealand's seismic screening project, and proposals for future policy to carry forward the seismic retrofitting of bridges.

2 BACKGROUND

There are approximately 3800 bridges and culverts on the state highway network, of which 65% were built before 1970. The total length of bridging is some 125 kilometres and comprises a large proportion of short single span structures and some multispan bridges up to 1.75 kilometres in length. The most recent valuation of bridges estimates a $2.7 billion replacement cost, which represents 20% of the total asset value of the network.

Current highway bridge design in New Zealand is based on an earthquake return period of 450 years for structures on minor routes, increasing to 950 years for structures on major routes and for structures crossing motorways or railway lines. Bridges are designed for a nominal 100-year life and from this, it is estimated that there is a 10% probability that the design earthquake will be experienced within the life of bridges on major routes.

Bridge design methods for earthquake resistance have advanced considerably in New Zealand since the early 1970s, when design codes were significantly upgraded by recognition of the need to provide for inelastic structural response and the introduction of capacity design principles. Consequently, there are a large number of older bridges on the network, constructed prior to this time, that have been designed to a lesser standard.

In 1993, Transit commissioned a pilot project to develop a seismic screening procedure. Its purpose was to determine a list of state highway bridges and their order of priority for detailed assessment of the risk of their sustaining serious seismic damage. This work was focussed on events that would disrupt the state highway network. It arose largely out of experiences during the significant earthquake events in Japan and the United States in recent years, and recognition that the seismicity of the most active parts of New Zealand is similar to that of California.

As road agencies in the United States, Japan and Taiwan have recently found, the integrity of bridges is vital in the event of major disasters. Road structures should not present excessive risks to the public and systems must be in place to ensure that those damaged are returned to service as quickly as possible after emergencies. While the cost of upgrading all bridges to practically eliminate the risk of seismic damage would be prohibitive, the risk of disruption of the network through failure of the bridges needs to be acceptably low. The objective of the project, beyond the screening stage, is to determine which bridges should be retrofitted and the degree of retrofit that should be applied in each case.

The 1993 project culminated in the publication of Transit Research Report Nº 58, entitled Seismic Assessment of New Zealand Highway Bridges: Development and Testing of Preliminary Screening Procedures (Transit, 1996). This was followed by the publication of the Manual for Seismic Screening of Bridges (Transit, 1998), which included additional economic and risk assessment procedures. The manual sets out the detailed processes for screening bridges with the objective of producing a priority listing of the structures that justify detailed assessment. It also requires the identification and separate ranking of bridges that possess inadequate linkages between spans.

3 PAST POLICY ON SEISMIC RETROFITTING

To date, while there has generally been awareness in New Zealand that unacceptable seismic risk should be remedied, high risk of span collapses had generally been alleviated by the policy, from as early as 1933, of designing spans to be monolithic or interlinked. Thus, funding has been allocated primarily to raising the service standards of bridging rather than to seismic retrofitting. In cases where improved seismic performance could be achieved at small cost by combining retrofitting with improvements for service purposes, this was done.

Early in the 1990s, eight bridges in the seismic zone then thought to be the most active were retrofitted for linkage deficiencies that were identified during a pilot study that was undertaken as part of the early development work of this project. In recognition of the significance of the Thorndon Overbridge in Wellington and the Auckland Harbour Bridge in the roading network, major retrofit work has also been undertaken recently on these bridges to minimise the potential disruption from earthquakes to the strategic routes on which they lie.

In 1999, contracts with Transit's regional bridge consultants were initiated to undertake seismic screening of all state highway bridges on a regional basis. That work has now been completed.

4 THE SCREENING PROCEDURE

The screening procedure is described in a paper by Chapman *et al*, (Chapman *et al*, 2000). The screening methodology includes data gathering, site visits in some cases, risk assessment and derivation of economic indicators for the purposes of prioritisation for more detailed analysis. It is essentially a sieving process with increasing degrees of refinement so as to minimise the number of structures to which the more complex screening steps are applied. This was important, given that there are a large number of bridges and culverts on the network.

An important part of the screening procedure is the identification of deficiencies in linkages between spans. Although the policy since 1933 has been to make spans monolithic or interlinked, 188 bridges were judged to have inadequate linkages, a few having no linkages at some supports.

The screening procedure includes early elimination of culverts from more detailed stages and, subject to a review of their details, smaller bridges and bridges designed after 1972. A total of 2842 bridges were eliminated on these bases. For the remaining 971 bridges the following steps were applied:

- The Seismic Attribute Grade (SAG) was calculated. The SAG is the product of the following three indices:
  - Hazard index - derived from the seismicity at the bridge site and geological factors that affect the bridge structure;
  - Importance index - which takes into account the annual average daily traffic count (AADT), the strategic importance of the route, and any utilities carried by the bridge; and
  - Vulnerability index - the capability of the bridge itself, determined from the bridge's age, length and structural form;
- A risk assessment, using a qualitative risk assessment procedure in accordance with AS/NZS 4360:1995. Risk events (vulnerabilities) were identified for each bridge, with up to five events being noted in some cases. Only those identified with a "High" or "Significant" level of risk (generally corresponding with possible failure of the bridge or a component, or a high level of traffic disruption) were considered further;
- For each risk event rated "High" or "Significant", an Economic Ranking Indicator (ERI) was derived. This gives a measure of the comparative consequence and probability of loss of use of the bridge. The ERI is, however, of low precision because of the nature of the screening process, which is aimed at providing an initial ranking of structures.

The procedure adopted for final ranking of the structures on a national basis was ultimately varied from that set out in the Manual for Seismic Screening for Bridges, and has been based on the following four criteria, considered in order:

- The priority assigned to the route on which the bridge is located;
- Whether the bridge was likely to collapse onto facilities putting lives at risk;
- The ERI of the risk event of highest ERI associated with the bridge;
- The number and significance of the risk events associated with the bridge.

Route priorities were defined as follows:

- Priority 1 Routes: State highways carrying high traffic volumes (generally above 4000 vehicles per day) that provide essential links to large centres of population or that are significant carriers of commercial vehicles. They include all motorways and expressways. The large centres of population are urban areas (of which there are approximately 20 with populations above 20,000 people) or regions;
- Priority 2 Routes: State highways carrying medium traffic volumes (generally between 1000 and 4000 vehicles per day) or where the routes provide alternative access to large centres of population;
- Priority 3 Routes: The balance of the state highway network.

In general, avoided traffic disruption is the dominant benefit derived from seismic retrofitting and was the basis for the original ERIs calculated. However, for structures likely to collapse, the associated damage cost could also be significant. As a consequence, the ERIs for risk events likely to result in collapse of a bridge or span were modified from that initially calculated solely based on traffic disruption, to also take the damage cost into account.

The ERIs, are not comprehensively calculated benefit/cost ratios, but because they use similar input factors they could be confidently used, along with the other criteria listed above, as the best available indicators for initially ranking the most critical bridges for the detailed assessments required prior to physical retrofit works. However, it must be recognised that judgement was relied on heavily in the screening process, and as a result economic ranking indicators were only used as a guide to the final ranking of the structures. Thus it is appropriate that judgement be applied in the final steps of ranking the bridges for assessment, and was, or will need to be, applied through the steps of considering:

- Where the overlap should occur between high ERI bridges on routes of lower priority with bridges of low ERI on routes of higher priority;
- The influence of the number and significance of risk events associated with a bridge in adjusting a bridge's final ranking from that determined based on ERI values.

5 RESULTS OF THE SCREENING

Table 1 sets out a summary of the number of bridges passing through each stage of the screening process.

Table 1. Numbers of Bridges in Stages of the Screening Procedure

Total number of bridges, including culverts, on the state highway network	3813
Bridges eliminated early in the process from any screening (includes culverts, bridges being replaced within 5 years, and structures not managed by Transit)	1491
Bridges eliminated later in the screening process (where designed after 1972, or where their seismic performance is assessed to be good based on a number of criteria)	1351
Bridges remaining, for which the SAG was calculated and which were subjected to risk assessment	971
Bridges identified with "high" and "significant" risk levels (another 53 bridges of unknown construction details may need to be added after further assessment)	381
Bridges separately identified with linkage deficiencies	188

Notable differences in the results of the screening were found to exist between the regions during the process of the screening. These arose due to:

- Regional seismicity;
- Regional topography, and hence the predominant types or sizes of bridges;
- The years during which the region's roading was primarily developed and the prevalent types of bridge used in the region at the time;
- The extent to which the region's roading infrastructure has undergone upgrading and realignment over time.

The screening procedure relies heavily on the judgement of the consultants undertaking the work, particularly in identifying details that could be vulnerable, in judging the severity of damage that may ensue and the strength of shaking required to induce that damage. Consequently some inconsistency of results was apparent between regions, as different consultants considering similar bridges and conditions of site and seismicity could arrive at somewhat different conclusions. This posed a problem particularly when merging the screening results from the different consultants together into a combined national ranking list.

Where routes would be effectively severed as a consequence of collapse or severe damage to a bridge, an ERI value cannot be calculated. In general, bridges for which an ERI value cannot be calculated are located on priority 3 routes. Severance of the route would tend to imply a high priority for assessment and retrofit of a bridge within its route priority group of bridges, but where the community isolated is very small, some judgement may need to be exercised in ranking the bridge. To date the prioritisation of bridges for detailed assessment has focused on identifying the top 50 bridges, with the cut-off falling within the route priority 1 group of bridges.

6 COST OF SCREENING

Given that there are a large number of bridges and culverts on the network, screening has been essential as a means of identifying the number of bridges with significant deficiencies for earthquake resistance and of ranking those bridges for more detailed assessment and justification for retrofitting. The cost of screening, including the collection of information on the structures, was approximately \$850 per bridge, which is a small fraction of the cost of a detailed assessment and benefit /cost ratio calculations.

A secondary benefit that has been obtained from the project is the gathering and updating of information on the bridge stock. Although records of the structures are kept, the project has led to a review of the records and improvement in the accessibility of some of the data.

7 BRIDGES WITH LINKAGE DEFICIENCIES IN SUPERSTRUCTURE ELEMENTS

International practice in seismic retrofitting of bridges generally recognises that the provision of linkages should be the first priority of a seismic retrofit programme. The risk of span collapse in moderate earthquakes, taking the structure out of service, can be relatively high.

The screening work looked specifically at structures with spans that were neither interlinked nor otherwise restrained against significant movement, or were restrained only by holding down bolts with inadequate strengths.

Through the use of linkages between spans, holding-down bolts, shear keys, web cleats and tie-bars into piers, a significant increase in security can be achieved against collapse at relatively modest cost. For many bridges, the retrofitting measures also offer the added benefit of alleviating the seriousness of other seismic deficiencies. The assessed costs for linkage retrofit on the 188 bridges identified range from \$5,000 to \$375,000, with an average cost of approximately \$36,000.

A simplified approach was taken to assessing the benefit/cost ratios for retrofitting the bridges with linkage deficiencies because the retrofit solutions are relatively simple and similar on many of the structures. Furthermore, the cost of detailed analysis would have exceeded the cost of physical works in many cases. Detailed assessments were therefore completed for five "typical" bridges and the benefit/cost ratios for the remaining bridges were derived by comparison with those five by making appropriate adjustments for the following factors:

- Traffic volume;
- Seismic zone (hazard) factor for the site; and
- Length of detour necessary should the bridge become unserviceable.

The variable structural characteristics and site conditions associated with the bridges were such that it was unusual for exact likeness to exist between any particular bridge and bridges of the sample analysed. Consequently, the benefit/cost ratios were assessed to lie within one of three bands, namely: less than 2, between 2 and 4, and exceeding 4. Using this approach, the benefit/cost ratios for the 188 structures were estimated at a cost of less than $1000 per bridge – again, much less than the cost of detailed analyses.

8 FUTURE POLICY AND PROPOSED INITIAL PROGRAMME OF WORK

8.1 *Detailed Assessment and General Retrofit*

The retrofitting of the Thorndon Overbridge and the Auckland Harbour Bridge was funded and completed on the basis of the "lifelines" importance of those structures. They are clearly key strategic links in the nation's road network and were assessed as posing very high risks without the retrofitting work proceeding. The works were thus accorded a high priority for retrofitting and the work was progressed with some urgency even though, in the case of the Thorndon Overbridge, the benefit/cost ratio was very low.

In the analysis of the potential collapse of the above two structures, consideration was given to the following issues:

- Safety of the public both on and under the bridges;
- Consequential effects on business and leisure activities;
- Effects on emergency services; and
- General effects of delays on the community.

While the scale of these issues for the remaining state highway bridges considered in this screening project may not be as large as for those two bridges, they are nevertheless important for the communities they serve. Those effects have been represented in the screening process along with the vulnerability of the bridges involved. Further detailed analysis is now required to more accurately quantify the benefits and costs involved as a basis for resolving the extent of physical retrofitting work to be carried out.

Transit New Zealand has resolved to proceed with detailed assessment of the top 50 of the 381 ranked structures over the next 3 years, for which funding will now be sought from Transfund New Zealand. The cost of that work will be of the order of $1.5M to $2.0M. While it is currently unclear how many of the 381 bridges should ultimately be subject to detailed assessment, the results of the 50 detailed analyses to be commissioned will eventually assist with that decision.

Not to proceed with that work would leave the network exposed to the risk of major disruption in the event of significant earthquakes in some areas. Like the Auckland Harbour Bridge, the Thorndon Overbridge and, to a lesser degree, the Shell Gully Bridge on the Wellington Urban Motorway the benefit/cost ratios in many cases are expected to be below the current funding cut-off level because of the high cost of the retrofitting work.

8.2 *Retrofit of Linkage Deficiencies*

Detailed design and retrofit of linkage deficiencies has been given high priority for funding and implementation, with work to start this year and to be completed over the next four years. $6.9 million will be sought for a programme of seismic retrofitting of bridges with linkage deficiencies, spread over the next five years, with those on the highest priority routes and high assessed benefit/cost ratio being remedied first.

9 IMPLEMENTATION

At the time of writing this paper, decisions have not yet been made on how best to implement the programme of detailed assessment and physical retrofit works. Should this work be centrally coordinated or managed in regional groupings as all other Transit work is implemented? An important consideration is the available pool of suitably experienced resources to undertake the detailed assessment work, which is likely to constrain the timeframe over which the work can be undertaken.

For retrofit of linkage deficiencies it is likely that significant similarity will exist in the retrofit required for bridges of similar type. This suggests that benefit may be derived from developing standardised solutions and bundling some of the detailed assessment and design work together over regional boundaries.

For physical works contracts, little in the way of synergies are likely to be developed from bundling work, though efficiencies in contract management may be derived from bundling together a number of the smaller linkage retrofit works.

Beyond the immediately planned programme of work, a decision remains to be made as to how many bridges will ultimately be subjected to detailed assessment. This will require consideration of the relative priorities of the highly ranked route priority 2 bridges versus the lowly ranked route priority 1 bridges and possibly even similarly of the highly ranked route priority 3 versus the lowly ranked route priority 2 bridges. These decisions will necessarily be judgemental.

10 CONCLUSION

A major project of assessing the seismic security of all state highway bridges has been completed. The process has been conducted in two parts, concluding in recommendations to progressively retrofit 188 bridges that have linkage deficiencies, and in a programme of detailed assessment of 50 structures where more substantial and costly retrofitting may be appropriate.

A range of factors were taken into account in the screening, with the key ones being route importance, site seismicity and bridge capability.

A question frequently asked in overseas countries subject to a high seismic event probability is: "Can I afford <u>not</u> to undertake a prudent programme of seismic retrofitting?" The critical decision is how much funding a prudent asset manager would put into this activity compared to other competing demands for funding.

As a prudent asset manager, it is vital for Transit to undertake an appropriate programme of seismic retrofitting of its bridging stock. The quantum of work currently proposed is seen as reasonable, justifiable and achievable. The extent of future work will be decided on the basis of the experience gained from implementation of the current proposals.

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