Seismic assessment and retrofitting of New Zealand state highway bridges

2005 NZSEE
Conference

H.E. Chapman & M.K. Lauder
Transit New Zealand (retired)

J.H. Wood
John Wood Consulting

ABSTRACT: Over recent years Transit New Zealand (Transit), has undertaken a systematic assessment of the seismic security of the approximately 2500 state highway bridges for which it is responsible. This paper outlines current progress on the assessment and retrofitting of the bridges, and discusses the results of the detailed assessment of 24 of the bridges and subsequent peer review. Inter-span linkages have been upgraded on Priority 1 routes and detailed assessments of 50 bridges have been undertaken to identify other structural vulnerabilities and risks of damage. However, the bulk of the physical retrofit of these vulnerabilities has yet to begin and much else remains to be done. The detailed assessments have shown that the many variables that influence the results of a structural analysis require input of a significant amount of judgement, both in deciding the input parameters for the analysis and in interpreting the results. The two peer reviewers found, however, that in most cases it was possible to reach a consensus on the appropriate degree of retrofit and priority ranking for the structures involved. The interaction that was possible as a result of using two peer reviewers working together was also found to be valuable in weighing the assessments and making recommendations.

1 INTRODUCTION

In addition to extensive retrofitting of the Wellington Thorndon Overbridge and the Auckland Harbour Bridge (completed some years ago) Transit has been undertaking a systematic assessment of the seismic security of the approximately 2500 other state highway bridges for which it is responsible. The project began with a screening of all its bridges (Chapman *et al* 2002). The screening project showed that subsequent actions should be taken in two fields:

- Improving or installing inadequate or non-existent linkages between spans on 188 (later adjusted to 170) bridges, and
- Detailed seismic assessment of 335 bridges, which were identified as having a "high" or "significant" level of risk of major traffic disruption or failure.

The bridges were ranked in groups for subsequent actions. This paper outlines current progress and discusses the results and conclusions drawn from the first 24 detailed seismic assessments.

2 SCOPE OF THE PROJECT

For the purposes of this project the state highways routes were categorised into three priority classes:

- Priority 1 routes: Motorways and expressways, and state highways carrying more than 4000 vehicles per day that provide essential links to large centres of population or carry significant numbers of commercial vehicles;

- Priority 2 routes: State highways carrying generally between 1000 and 4000 vehicles per day, or where the routes provide alternative access to large centres of population, and
- Priority 3 routes: The remaining low volume highways in the network that are largely intra-regional in character.

Of the 170 bridges found to require improvement to their inter-span linkages 89 are on Priority 1, 45 on Priority 2 and 36 are on Priority 3 routes. Completion of most of the retrofitting of linkages on the 89 bridges on Priority 1 routes is expected by the end of 2005 at a cost of approximately $5 million.

Of the 335 bridges requiring detailed assessment 192 are on Priority 1, 72 on Priority 2 and 71 are on Priority 3 routes. Completion of detailed assessment of the highest ranked 50 on Priority 1 will be completed by the end of June 2005 at a cost of $1.9 million. Physical retrofitting works on these bridges and detailed analysis of further structures has yet to be programmed. However, Transit feels that there is little point in completing further detailed analysis of lower priority bridges until substantive progress is made on the implementation of the remedial works on the highest priority group.

By May 2004, 24 of the detailed assessment reports had been completed and Transit initiated a peer review to confirm consistency of approach and methodology in determining the reported deficiencies, solutions and economics. The peer reviewers were also required to comment on the structural deficiencies identified and on the appropriateness of the proposed retrofit solutions, to present alternative opinions and solutions if they differed from those in the reports, and to recommend a priority order for retrofit of the bridges. Following is a summary of the outcome of the peer review.

3 FACTORS THAT INFLUENCE SEISMIC ASSESSMENT

Assessment and ranking of bridges for seismic vulnerability, risk and retrofit is a complex process. It is necessarily subjective because of the many influential and variable factors that must be considered.

There are recognised analytical procedures for estimating the effects of ground motions on a structure but it is still necessary to decide appropriate values and parameters that must be adopted before the analysis can be performed. Some that have a significant influence on the results are:

- The physical stiffness, strength and ductile properties of the structure’s components;
- The likelihood, intensity and duration of shaking that must be considered for the bridge;
- The amount of energy that would be absorbed within the structure and within its connection to the ground during shaking of varying intensity. Observation of flexural structures that have been exposed to strong shaking often shows that they perform better than theory might predict. Factors that are not sufficiently taken into account in an analysis apparently have a significant influence, even though material strength values used in the analysis represent “probable” rather than “minimum specified” values. Where the shear capacity of a structure is the limiting factor, this additional performance factor is apparently not so available;
- The nature of the ground at the bridge site and its likely response and reliability during shaking – in particular whether it is likely to liquefy and if so, how seriously this may affect the bridge, and
- The overall likely response of the structure to ground shaking, and also the secondary effects on critical components, which are not necessarily captured by the structural analysis, and which might cause structural failure.

Each of these items, and hence the results, are imprecise when a structural analysis is performed.

Outside the structural field there are other matters that have a significant influence on the assessment and ranking of whether valuable resources should be spent on retrofitting a bridge. These include:

- The amount of traffic carried by the bridge and whether the bridge is the key vulnerability of the route;

- The availability of alternative detour routes, should the bridge be out of service. In this case there is uncertainty of whether the alternative route would be available, depending on its proximity and vulnerability, and on the area affected by the damaging earthquake;
- The probability of loss of use of the bridge due to significant damage or collapse;
- The ease with which a temporary replacement crossing can be provided;
- The consequential effects that loss of use of the bridge would have on access for emergency relief vehicles, on the delivery of fuel and food and on loss of production;
- The likelihood of injury and loss of life arising from possible collapse of a bridge, and
- Determination of the best trade-off between acceptable risk and the cost of its mitigation.

Again, the uncertainties in some of these items are considerable.

It is evident that determination of which, and to what degree, bridges should be retrofitted is very subjective. The peer review process demonstrated, however, that by reviewing a number of detailed assessments together it is possible to develop a consensus of where and to what degree retrofitting is justifiable, and relative ranking of the structures. It is still likely, however, that a range of opinions will be held by different assessors, relating to the prevailing level of risk and the appropriate level of retrofit that should be applied.

4 METHOD USED FOR THE DETAILED ASSESSMENTS UNDERTAKEN

The three Consultants who carried out the assessment work followed a similar methodology. This methodology was outlined in the scope of work document prepared by Transit.

4.1 Earthquake Risk

In several of the early assessments site specific hazard studies were carried out to determine the earthquake risk at the bridge site. However, for most of the assessments the loading spectrum used was based on the AS/NZS 1170.4 draft code, and appropriate site classifications, zone factors and return period factors were chosen by reference to this code.

4.2 Strength Assessments

Material strengths were based on construction test results or design information where this was available but for most of the older bridges it was necessary to use typical characteristic values given in the Transit Bridge Manual. Characteristic strengths (specified 28 day concrete and minimum steel yield strength values) were increased by factors recommended by Priestley, Seible and Calvi (1996) to allow for ageing effects of concrete and typical conservative practices in batching concrete and in the manufacture of steel reinforcement.

Section strengths were generally based on the recommendations made by Priestley, Seible and Calvi (1996). These recommendations result in shear strengths of most critical sections being significantly higher than derived from the Concrete Structures Code (NZS 3101).

4.3 Ductility and Structural Performance Factors

Most of the bridges assessed were designed before the development of ductility-based design and capacity design concepts. Although many have moderate strengths under lateral loading they do not have details that enable them to survive strong shaking without serious damage or, even, collapse.

A significant difficulty that arises in assessment work on older structures is that many have not been detailed in accordance with modern design principles. This results in uncertainty about post-elastic behaviour of the load resisting members and the level of ductility and energy dissipation available. As in the usual design procedure, the assessment procedure estimated ductility and damping by choosing ductility and structural performance factors to reduce and modify the elastic load spectrum. For most of the bridges assessed these factors were selected by expert judgement. Although testing information is available about the performance of a number of older structures most of this is specific to a particular structure or detail and was of limited use for the present assessment work. The choice of these factors can have significant effects on the results of the analysis.

On many of the bridges the peer reviewers felt that the Consultants had been too pessimistic about the post-elastic performance. In some cases structural performance factors of 1.0 and ductility factors of 1.5 or less were adopted when high damping from soil-structure interaction or flexural failures dominated the response, indicating that higher values would be appropriate. There was a tendency to base the assessment on the worst likely performance rather than the best estimate of performance. In determining the overall risk of serious damage and collapse, the need for retrofit and to rank the retrofit work the peer reviewers used a less conservative best estimate approach.

4.4 **Structural Analysis Methods**

Most of the bridges were analysed by a static inelastic plastic collapse mechanism frame analysis ("pushover" analysis). In this method the lateral load is incremented with the member stiffnesses modified as various members reach their yield levels. The degree of damage is assessed by the rotations at the plastic hinges and the collapse load is determined from the load corresponding to the development of a collapse mechanism. By calculating or estimating the structural periods of vibration the damage or collapse level loads can be used in conjunction with the loading spectra to give return periods for the onset of damage and/or collapse. The loading spectra are derived for a range of earthquake event return periods and are suitably modified by ductility or structural performance factors. This allows the estimated probability of damage or collapse within an estimated remaining life period (usually 50 years) to be determined.

Some of the larger bridges were modelled as three-dimensional space frames and analysed using modal response spectrum methods. Generally only elastic analyses were undertaken using this approach but the member stiffnesses were adjusted progressively to reflect member yielding and failure. As was the case for the simpler structures, return periods for damage and collapse were estimated using the analysis results in conjunction with modified and scaled elastic loading spectra.

Generally the degree of structural modelling sophistication and analysis complexity was similar to that currently used for design.

4.5 **Economic Analysis**

An economic analysis for each of the bridges was carried out in accordance with the Transit Project Evaluation Manual to give benefit/cost ratios (BCRs) for each of a number of retrofit options. Damage and traffic disruption costs were investigated for a number of earthquake levels as defined by event return periods (or probability of exceedance). Only eight of the bridges had retrofit BCR's greater than 1.0. However, this factor was regarded as being an unreliable indicator of the need for retrofit and was not found to be useful for setting retrofit priorities (see Section 5).

5 **VULNERABILITIES AND RETROFIT OPTIONS**

5.1 **Summary of Results**

Details of the bridges assessed and some of the parameters used in the assessment of the need and priority for retrofit are shown in Table 1 together with a list of the main structural vulnerabilities identified for each bridge and a summary of the retrofit works recommended. The bridges are arranged in priority order with the highest priority labelled 1 and the lowest 4.

All bridges were on Priority 1 routes and fourteen of the bridges were on State Highways 1 and 2. All but seven of the bridges were less than 50 years old and most of these were expected to have remaining lives of at least 50 years.

Table 1. Predicted earthquake performance, recommended retrofit and priority

TNZ Region and State Highway	Bridge Name	Age (yrs)	Length M	Estimated Replacement Cost - $'000 See Note 3	Ratio: Retrofit to Estimated Replacement Cost	AADT Vehicles per day	Shortest Detour Route		Probability of Closure (Collapse) in 50 yrs from EQ's %	Main Structural Vulnerabilities in Earthquakes	Recommendations for Retrofit		
							Description	**Extra Dist. (km)**			**Description**	**Cost $'000**	**Priority**
2 SH 16	Lincoln Bridge No 1	46	52	1,100	0.31	19,550	Local	Small	0 (<40)	Shear failures Abutment A footing and Abutment B pile cap.	Strengthen Abutments A & B + tie abutment walls	345	1
9 SH 2	Pakuratahi River Bridge	33	66	1,200	0.33	4,800	Manawatu Gorge	100–200	15 (10-15)	Transverse passive failures at abutments damaging friction slabs Pier piles fail in flexure.	Strengthen abutments and deck linkage	400	1
9 SH 1	Waikanae River Bridge	40	80	1,550	0.32	23,000	Manawatu Gorge or Akatarawa Rd	90 30	15 (10–15)	Failures in abutment piles and beams. Flexure/shear **failure** in pier columns.	Cylinders at abutments and strengthen abutment beams. Jacket pier columns.	495	1[1]
10 SH 1	Dashwood Rail Overbridge	72	24	400	0.44	3,500	East of existing route	26	90 (55)	Abutment footings slide, and damage to abutment walls. Pier columns fail in shear.	Rock anchor abutments + jacket piers if deck diaphragm action inadequate.	175	1
10 SH 1	Wairau River Bridge	65	293	5,000	0.16	6,170	Local	9	≤65 (<40)	Failures in abutment pile caps, beam/pier connections and pier piles.	Strengthen abutments with piles or consider replacement.	800?	1
9 SH 1	Southern Rail Overbridge	39	139	6,800	0.04	85,600	Hutt Rd	0	5 (5)	Failure of keys and dowels in connections between walls and deck or floor. Risk of liquefaction at site.	Strengthen joints with steel angles.	295	2
10 SH 1	Spring Creek Bridge	65	43	750	0.53	6,200	Local	9	20 (15-20)	Failure of abutment walls and pier piles.	Strengthen abutments with piles.	400?	2
11 SH 1	Clarence River Bridge	32	305	7,600	0.04	2,080	SH's 7, 65, 6 & 63	108	64 (5)	Failure of mid-span joint shock absorbers and hangers. Failures in pier piles and pilecaps.	Replace mid-span hinge linkages.	300	2
11 SH 74	Horotane Valley Overpass No 1	41	40	550	0.35	4,800	Local	0	15-92 (18)	Damage to pier diaphragms holding down and linkage bolts. Flexural shear failure of pier footings. Risk of liquefaction at site.	Construct new diaphragms & install new linkages at the piers but consider replacement.	195	2
11 SH 74	Horotane Valley Overpass No 2	41	40	700	0.28	4,800	Local	0	15-92 (18)	As for Horotane Valley Overpass No 1.	Construct new diaphragms & install new linkages at the piers but consider replacement.	195	2
11 SH 74	Port Hills Road Overpass No 1	41	72	1,200	0.22	4,200	Local	0	28-64 (8-22)	Failure holding down bolts and linkage rods. Flexural failure of some pier columns and footings. Risk of liquefaction at site.	Upgrade pier linkages & add shear keys. Construct Column F annulus	265	2
11 SH 74	Port Hills Road Overpass No 2	41	69	700	0.28	2,000	Local	0	30-64 (5-10)	As for Port Hills Overpass No 1.	Upgrade pier linkages & add shear keys. Construct Column B annulus.	195	2
2 SH 1	Main Highway Underpass	43	71	2,150	0.10	14,200	Local streets	1	10 (4)	Failure of holding down and wall tie-backs at Abutment A. Flexural hinging in Abutment D columns and superstructure joint.	Ground anchors increase transverse restraint at Abut. A. Steel jackets to Abutment D columns and piers.	215	3

Table 1 Continued on next page……..

Table 1. Predicted earthquake performance, recommended retrofit and priority

TNZ Region and State Highway	Bridge Name	Age (yrs)	Length M	Estimated Replacement Cost - $'000 See Note 3	Ratio: Retrofit to Estimated Replacement Cost	AADT Vehicles per day	Shortest Detour Route		Probability of Closure (Collapse) in 50 yrs from EQ's %	Main Structural Vulnerabilities in Earthquakes	Recommendations for Retrofit		
							Description	Extra Dist. (km)			Description	Cost $'000	Priority
9 SH 1	Otaki River Bridge	49	208	4,050	0.09	17,900	Manawatu Gorge	100	10 (3)	Instability of abutment slopes. Flexural failures in pier piles.	Secure abutment slopes, strengthen abutment structure.	350?	3
9 SH 1	Pukerua Bay Overbridge	67	41	800	0.39	22,000	Paekakariki Hill Road	6	12 (5-15)	Failure of abutment slopes. Plastic hinging in abutment piles.	Stiffen deck diaphragm action; soil nail abutment slopes.	315	3[2]
10 SH 6	Pelorus River Bridge	53	52	1,050	0.19	2,500	SH6, SH63, Kerr Hill Rd, SH6	130	- (5)	Rocking and stepping of pier unseating trusses. Damage to truss bearing angles, wind bracing bolts and bottom chord angles.	Install vertical anchor bars at piers and strengthen trusses or consider base isolating trusses.	200?	3
10 SH 6	Racecourse Creek Bridge	38	19	300	0.09	2,500	SH6, SH63, Kerr Hill Rd, SH6	130	50 (4)	Failure of abutment holding down bolts. Flexural yielding in pier crosshead beam.	Install additional holding down bolts at abutments; enhance deck diaphragm action	28	3
11 SH 74	Heathcote Valley Overpass	41	9	400	0.20	8,400 over 1,000 under	Local	0	15-40 (12–35)	Shear failure in nib walls at top of abutment s and flexural failure at mid-height of abutment walls.	Secure deck to abutments with steel corbels.	78	3
11 SH 78	Port of Timaru Access Bridge	32	187	6,150	0.25	2,550	Local streets	2	60 (15-25)	Failure of Abutment F holding down bolts and Abutment A tendon anchorages. Failure of foundations in several piers.	Install seat extenders at Abut. F and ground Anchors at Abut. A. Install additional piles at piers, steel jacket pier columns & add linkage bolts to in-span hinges.	1,560	3
2 SH 1	Beach Rd Underpass	40	48	1,200	0.25	13,800	Local streets	7	10 (2)	Flexural hinging at bottom of pier columns, shear failure in pier capping beams. Risk of liquefaction at site.	Strengthen pier capping beams and joints. Steel jacket pier columns.	295	4
10 SH 1	Waima River Bridge	32	150	2,550	0.24	2,130	SH 70, 7, 65, 6, 63	117- 480	5-8 (6)	Plastic hinging in abutment and pier columns.	Steel jacket pier columns.	600	4
11 SH 7	Glenallen Stream Bridge	51	27	500	0.30	2,150	Various	300 max	33 (5-10)	Flexural damage in arch side walls.	Cross-tie walls with rods.	150	4
2 SH 1	Drury Rail Overbridge	84	11	300	0	16,800	Local streets	0	10 (3)	Failure of connections at top of abutment walls and flexural hinging at mid-height of abutment walls.	Not necessary	-	-
10 SH 1	Woodside Creek Bridge	48	37	650	0	3,000	Not an issue	N/A	19 (Not Expected)	Deck/Pier and Deck/Abutment joint damage. Shear failure in abutment piles.	Not necessary	-	-

1. On the basis that the Kapiti Western Link Road is not committed for construction by the end of 2006 – otherwise Priority 2.
2. On the basis that the Pukerua Bay bypass will not be opened before 2012 – otherwise no action is necessary.
3. The estimated replacement cost is based on a parameter cost rate per square metre times the anticipated area of the replacement bridge deck. The rate includes for investigation, design, construction and supervision but does not include for contingencies or for the cost of approach works, nor for the cost of demolition of a collapsed bridge or the provision of a temporary crossing structure.

The cost estimates and probability of collapse percentages in Table 1 are values adopted after comparisons and checks made by the peer reviewers of corresponding values presented by the Consultants. The probability of collapse values are generally lower than presented by the Consultants. The retrofit options presented are those preferred by the peer reviewers but in most cases were similar to those chosen by the Consultants.

5.2 **Ranking Method**

In order to select a priority order for retrofit a number of numerical assessment procedures were investigated. In particular an Economic Ranking Indicator (ERI, based on the ratio of traffic delay plus replacement cost to retrofit cost), which is in effect a simplified BCR, was found to have some merit and did identify the bridges that should be at the top and bottom of the ranking list. Overall it was found that expert opinion taking into account all the 12 factors identified in Section 3 was the best approach. It was not difficult for the two peer reviewers to reach a consensus using this subjective approach.

The limitations of using BCRs for making strengthening decisions has previously been discussed by Smith (2003). He concluded that, because the distribution of expected strong ground motion is so skewed that no central measure provides a good representation of risk, the best approach was to determine what is the unacceptable level of loss and then to engineer to the strength that will prevent that loss.

5.3 **Vulnerabilities**

The vulnerabilities identified covered quite a wide spectrum of deficiencies. In seven of the bridges piles lacked either sufficient strength or ductility to provide good performance. Six bridges had problems with the shear strength of pier footings or abutment components. Lack of ductility in pier columns was evident in only three bridges. The most frequent problem, evident in 12 bridges, was inadequate connections between the superstructure and substructure components.

5.4 **Retrofit Options**

Transit's performance target for new bridges is to prevent collapse, even as a result of earthquakes exceeding the "design" event. Many of the bridges listed in Table 1 do not possess the necessary resilience and are predicted to collapse, even without meeting the target performance design standard equivalent to a 1000 year return period event (5% in 50 years). They are therefore recommended for retrofitting, where possible to the target standard if the cost is judged to be acceptable. In other cases, where the risk of traffic disruption is high, but can be mitigated at reasonable cost, retrofit is also recommended. Viable strengthening methods were identified by the Consultants for all critical vulnerabilities and details recommended by the peer reviewers are summarised in Table 1. The estimated strengthening cost for each bridge varies between 4 and 53% of the bridge replacement cost with an average cost of about $360,000 per bridge. The total estimated cost of strengthening the 22 bridges recommended for retrofit is about $7,850,000.

6 **FUTURE ACTION**

Transit has a clear focus on providing the maximum availability of the state highway network at all times. Where seismic performance of structures risks this availability it is committed to reducing that risk. Its approach to date to securing the state highway bridges against disruption due to seismic damage has been a step-by-step process, starting with an overall screening process to identify those bridges that justify further action. It is generally recognised internationally that the provision of linkages between spans should be the first priority of a seismic retrofit programme and this has been actioned on bridges on Priority 1 routes. Detailed seismic assessments of 50 of the 192 bridges on

Priority 1 routes have also been completed. A total of $6.5 million has so far been spent on the linkages and assessments.

It is estimated that the cost of completing the entire seismic retrofitting programme for the state highway bridges is of the order of $140 million, although this may change significantly as more detailed seismic assessments are completed. Clearly the project must be spread over a number of years to take account of available funding, available resources and the mitigation of other hazards such as scour damage. A proposal for completion of the retrofit programme for all linkages and for detailed assessment and retrofits of bridges on Priority 1 routes estimates a cost of $45 million. However, the issue of how the detailed assessments will be handled is still to be resolved. The dilemma is to decide how quickly the work should be completed. The average cost per bridge means that it is not a programme to be embarked on lightly, and overall risk management of these structures is still to be decided. Little work has been done on scour risk of key bridges on the state highway network, for example, and the relative merits of lesser priority seismic retrofits against these other risks needs to be assessed. Nevertheless it is likely that Transit will continue to pursue a programme of retrofitting, at least one or two major structures a year, as a result of this work.

7 CONCLUSIONS

The purpose of this paper was to outline current progress on the seismic assessment and retrofitting of New Zealand's state highway bridges, and to present and discuss the results of the detailed seismic assessment of 24 of the bridges.

Transit has made steady progress on the assessment and retrofitting of the state highway bridge stock and the problem has been approached in a logical manner, starting with a screening process and then concentrating more detailed attention where it was needed. Inter-span linkages have been upgraded on Priority 1 routes and a start has been made on detailed assessments to identify other structural vulnerabilities and risks of damage. However, the bulk of the physical retrofit of these vulnerabilities has yet to begin and much else remains to be done. Decisions are needed on the appropriate rate of expenditure on seismic retrofitting, how best to allocate the available resources for the work and what balance should be struck between the needs of this work and those of other risk management projects (for example scour risk) and new works.

The detailed assessments undertaken have shown that the many variables that influence the results of a structural analysis require input of a significant amount of judgement, both in deciding the input parameters for the analysis and in interpreting the results. The two peer reviewers found, however, that in most cases it was possible to reach a consensus on the appropriate degree of retrofit and priority ranking for the structures involved. The interaction that was possible as a result of using two peer reviewers working together was also found to be valuable in weighing the assessments and making recommendations.

8 ACKNOWLEDGEMENT

The permission of Transit New Zealand to publish the information contained in this paper is acknowledged with thanks.

REFERENCES:

Chapman, H.E., Kirkcaldie, D.K., Lauder, M.K. & Oakden, G.J. 2002. Seismic security of state highway bridges: screening and retrofit – progress summary. *Proceedings of NZSEE 2002 conference.*

Priestley, M.J.N., Seible, F. and Calvi, G.M. 1996. *"Seismic design and retrofit of bridges",* New York: Wiley.

Smith, W.D. 2003. Criteria for strengthening buildings: cost-benefit analysis is misleading. *Bulletin of the New Zealand Society for Earthquake Engineering.* 36 (4). 260-262.