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Renforcement parasismique d'un aqueduc en Nouvelle Zélande

Seismische Verstärkung eines Aquädukts in Neuseeland

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SUMMARY
The Kaitoke Flume Bridge near Wellington, New Zealand, is a reinforced concrete aqueduct built in the early 1950s which carries 50% of Wellington's water supply. The 51 m long bridge spans a 16 m deep ravine and is supported by two high reinforced concrete piers. Water is carried inside a 1.1 m square in-situ concrete flume. The bridge site is close to the Wellington Fault and the structure lacked the ductile detailing necessary to survive the expected M7.5 earthquake. The paper describes the various methods considered for improving seismic performance. Design for elastic response was favoured.

RÉSUMÉ
Construit au début des années 1950, l'aqueduc en béton armé de Kaitoke près de Wellington, Nouvelle-Zélande, assure 50% de l'approvisionnement en eau de Wellington. Le pont d'une longueur de 51 mètres enjambe un ravin d'une profondeur de 16 mètres et est soutenu par deux piliers en béton armé. L'eau est acheminée à l'intérieur d'une section carrée de 1,1m en béton coulé sur place. Le pont est situé à proximité de la faille de Wellington, mais la construction ne présente pas la ductilité nécessaire pour résister au tremblement de terre attendu d'une magnitude de 7,5. Le document décrit les différentes méthodes envisagées pour améliorer la performance sismique. Le projet de dimensionnement élastique a été retenu.

ZUSAMMENFASSUNG
Bei der Kaitoke Flume Bridge in der Nähe von Wellington, Neuseeland, handelt es sich um ein Stahlbetonaquädukt, das am Anfang der 50er Jahre gebaut wurde und über welches 50% der Wasserversorgung Wellingtons geleitet wird. Die 51 Meter lange Brücke überspannt eine 16 Meter tiefe Schlucht und wird von zwei Stahlbetonpfeilern getragen. Das Wasser wird in einem 1,1 Meter quadratischen Betongerinne geführt. Die Brücke liegt nahe der Verwerfung Wellington und die Bauart der Konstruktion verfügte nicht über die nötige Duktilität, um ein zu erwartendes Erdbeben der Stärke 7,5 zu überstehen. Diese Arbeit beschreibt verschiedene Methoden zur Verbesserung der seismischen Leistung. Das Projekt mit elastischer Berechnung wurde bevorzugt.

1. Introduction

Wellington, New Zealand's capital city, is in one of the country's most seismically active regions and is built astride the Wellington Fault. This fault is capable of producing a M7.5 earthquake with a probability of occurrence of more than 10% in 50 years. (500 year return period approximately). The City's engineering lifelines are all under threat from strong earthquake shaking and/or fault displacement, and their vulnerability to earthquake prompted a region-wide study in 1990 and 1991. (Reference 1).

Wellington's water supply was shown to be particularly vulnerable in places and has been the subject of closer examination by the controlling authority, the Wellington Regional Council (WRC). In 1993, a major inspection of all bulk water lines was made in order to identify vulnerabilities more detail and to estimate the costs and programming of mitigation measures. This has been the subject of a paper by the author. (2)

The Kaitoke source is one of four serving Wellington and supplies 50% of the region's needs. A 30km long, 900mm diameter water main from Kaitoke to Wellington City crosses the Wellington Fault twice and delivers water to a natural reservoir at Karori and to prestressed concrete reservoirs located throughout the region.

The Kaitoke Flume Bridge was recognised as being a critical element in the bulk water network and was known to lack ductile detailing required by current earthquake standards. In mid-1991, the Wellington Regional Council commissioned a structural assessment from the author's firm in order to address the unacceptably high earthquake risk to this bridge.

2. General Description

The bridge was built in the 1950's to a design prepared by the New Zealand Ministry of Works to unknown seismic design standards. It is likely that it was designed for a static load of 10% of gravity. The bridge is approximately 45m long over 3 spans with a 23m central span. The flume cross-section is a concrete box 1140mm x 1060mm inside with 150mm to 200mm thick walls. The four reinforced concrete piers vary markedly in length, the two central ones being 11.2m high. The short south pier is hinged top and bottom in the longitudinal direction to allow temperature movement. The flume is free to move independently of the abutment. At the north end the flume is built integrally into the intake spillway structure which is keyed into the solid greywacke rock which forms the foundations for all the piers.

An unusual feature of the flume section is that the base slab has been cast in separate units each approximately 5.7m long and with no positive connection shown to the sides. Its ability to behave as a box girder was therefore questionable.

3. Initial Structural Assessment

Analysis

The initial structural assessment was based on an equivalent static analysis to evaluate the bridge's performance in earthquake. A three dimensional static analysis was carried out in which the flume was assumed to be an inverted U section. The strength of critical sections was determined in accordance with normally accepted concrete theory taking account of details on the drawings and assuming the concrete was 3000 psi (20 MPa) and the reinforcing steel 40,000 psi (275 MPa).

The vertical steel at the inside face of the flume walls was not adequately anchored into the base and it was therefore neglected. The horizontal steel in the central piers was also not adequately anchored at the ends and was neglected in strength calculations.

Earthquake Performance

Three references (3, 4, 5) were consulted to determine an appropriate design coefficient, resulting in base shear coefficients ranging from 0.4 to 1.0g, corresponding to peak ground accelerations of between 0.5 and 0.7g.

Table 1 summarises the assessed ultimate strengths of bridge elements in terms of the equivalent static base shear coefficient. A wide variation can be seen, with notable inadequacies in the flume and in the piers for overturning. In order to set these figures in context, the probabilities of earthquakes exceeding the various levels of shaking intensity are given..

Table 1 : Comparative Strengths of Bridge Elements

Element	Structural Action	Base Shear (g) at Ultimate Strength	50-yr Probability
Flume	Flexure at midspan	0.16	90%
	Flexure at pier	3.43	1%
	Side wall flexure at pier	0.04	100%
	Shear at pier	0.48	30%
	Torsion at pier	0.04	100%
Central Piers	Shear at top	0.37	50%
	Flexure at base	0.81	10%
	Overturning at base	0.22	80%

Conclusions and Recommendations

The initial structural assessment concluded that the bridge was in reasonable physical condition but that there were some unusual detailing and design characteristics which were unacceptable in a structure of this importance. Some basic strengthening measures to the flume itself were identified, but further analysis was recommended in order to provide greater insights into the likely earthquake performance of the bridge and the costs of remedial work.

4. Follow-up Evaluation

In November 1991, a closer study was made using response spectrum dynamic analyses. The analyses carried out were based on two separate structural models, the first representing the structure as it stood at the time and the second in its partially strengthened and stiffened state. A site-specific earthquake response spectrum was used, scaled to correspond to a 475-year return period, the results of which confirmed the basic findings of the initial structural assessment. However it was found that even with the basic strengthening measures initially recommended, the bridge would be capable of withstanding only about 12% of the seismic load recommended for the design of modern structures of similar importance. This raised the prospect of more extensive strengthening, full replacement or base isolation to improve the performance of the bridge.

5. Strengthening Options

Table 2 summarises the strengthening options considered, and estimated costs.

Table 2 : Summary of Strengthening Options, Strengths and Costs

Strengthening Option	Strength/Current Code (Ratio)	Cost Estimate ($NZ)
1. Leave as existing	0.04	0
2. Strengthen flume only	0.12	60,000
3. Strengthen flume, piers (partial)	0.39	175,000
4. As for Option 3 plus base isolation	1.00	260,000
5. Strengthen flume and piers fully	1.00	200,000
6. Construct replacement bridge	1.00	700,000

Base isolation (Option 4) was to be achieved by either controlled rocking of the piers or controlled sliding of the flume at the top of the piers. A particular difficulty with this concept was the relatively large horizontal movements of the flume which would need to be accommodated, and the necessity to decommission the aqueduct. There were no cost advantages.

6. Bridge Strengthening

The strengthening scheme selected (Option 5) involved the following main items:

- Construction of steel frames bolted to each pier.

- Construction of a foundation beam, extending beyond the original one and anchored to the rock foundation material.

- Installation of horizontal trusses underneath the flume base.

- Installation of yokes above each pier to reduce the vertical bending in the walls of the flume under lateral loads.

Details are shown in Figure 1.

A design base shear of 0.96g was used corresponding to elastic response of the structure.

7. Tendering and Construction

The strengthening work was tendered in early 1993 on a selected competitive basis. Interestingly, one bidder offered an alternative involving base isolation, but this confirmed the earlier costings and was not competitive with design for elastic response.

Construction commenced in August 1993 and was completed in January 1994. During construction, the generally good condition of the bridge was verified, and although awkward in places, the installation proceeded according to plan. The bridge, which is situated in a regional

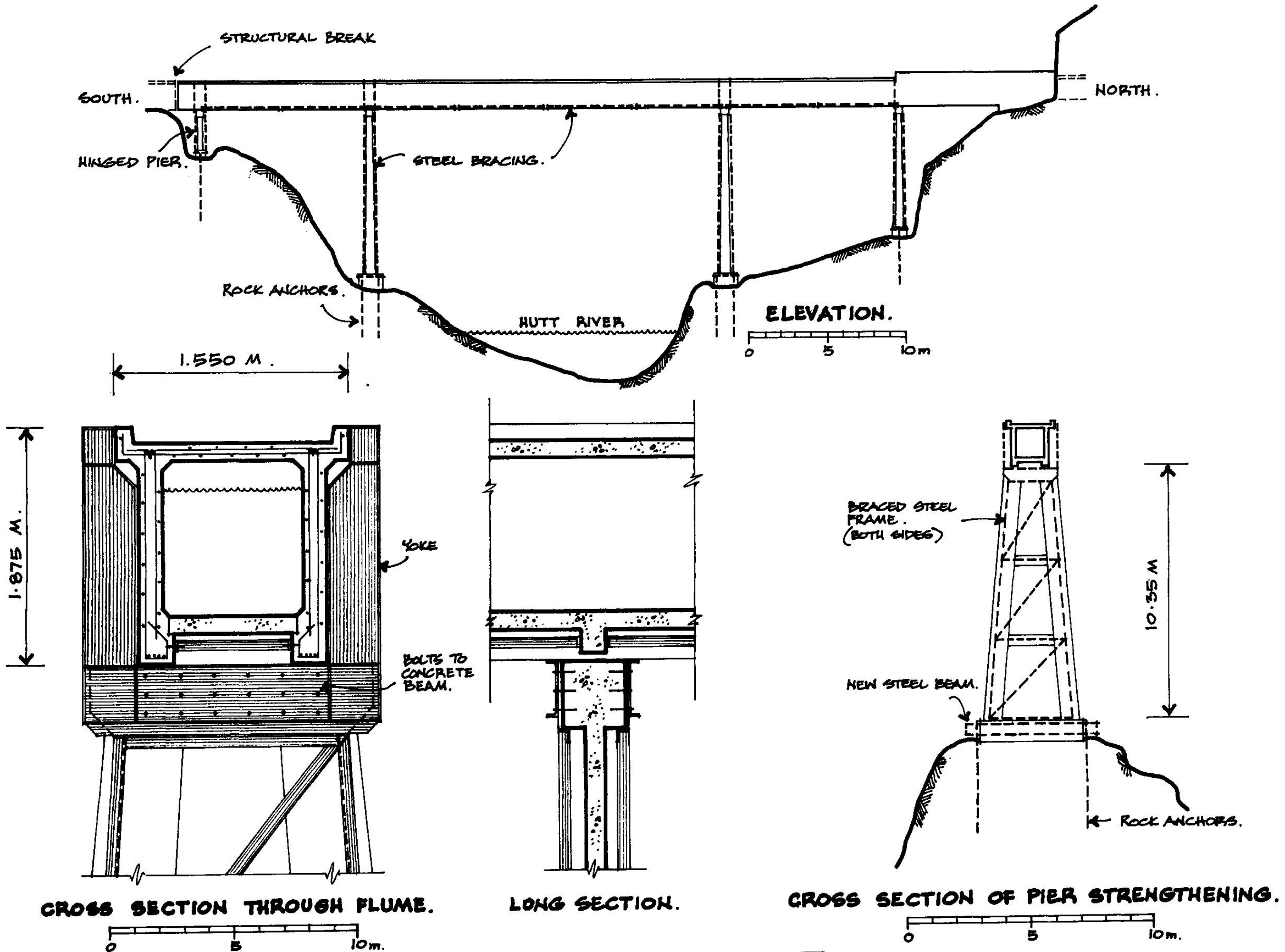

FIGURE 1 : KAITOKE FLUME BRIDGE - STRENGTHENING DETAILS.

recreational park, was strengthened without being decommissioned at any stage and without significant restriction to public access.

8. Conclusions

Initial structural assessments followed by more detailed dynamic analyses indicated that the Kaitoke Flume Bridge had an unacceptably high risk of failure in earthquake at several critical locations.

Examination of design options, which included consideration of base isolation, led to the adoption of design for elastic response to control deflections and reduce ductility demand.

The strengthening work, which brought the bridge to a condition similar to that for a new structure, was achieved at a cost of 30% of a replacement structure.

References

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