

Report

AHB Box Girder Vibration Damper Investigation

Prepared for NZ Transport Agency (NZTA) (Client)

By Beca Infrastructure Ltd (Beca)

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Revision History

Revision N°	Prepared By	Description	Date
A	s 9(2)(a)	Internal review	
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Document Acceptance

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Executive Summary

Background

The Auckland Harbour Bridge box girder structures were first observed to be excited by pedestrian induced vibrations during the Maori land march on 23 September 1975, when group of a few thousand people marched across the East Extension Bridge. In 2004 another march across the West Extension Bridge confirmed this observation and, due to similar issues with the London Millennium Bridge, this phenomenon known as Synchronous Lateral Excitation is now widely known and the causes well understood.

The box girders have been strengthened for live loads and have sufficient structural capacity for pedestrian design loadings, but the issue with transverse vibrations under pedestrian loading remains. NZTA have requested that provisions for mitigating the risk of excessive vibrations occurring during future planned or unplanned pedestrian events be investigated.

Study Purpose

The purpose of this study was to investigate options and specifications for suitable damping devices to suit either permanent or temporary (on demand) deployment for reducing the potential transverse vibrations to acceptable levels. A proposal for carrying out this initial study was submitted to and approved by NZTA in May 2009 and the study commenced in August 2009. A draft report was submitted to NZTA for comment in June 2010 but further study was postponed pending confirmation of a requirement.

Conclusions

Additional damping is required to limit accelerations to within acceptable limits. Several damping options were considered and preliminary sizing for Tuned Liquid Damper and viscous damper options have been produced. Sizing of the damper devices was based on computer analysis of the bridge and idealised pedestrian loading models.

Two options are recommended, either Internal TLD for the East box only or a viscous damper option. Key features of these two options are:

A. Internal Tuned Liquid Damper (Suitable for East Extension)

- Clusters of small liquid filled tanks (16 tonnes of liquid total) at centres of both spans 1 and 3.
- Semi-permanent system, suitable for unplanned events.
- Additional weight – not suitable for the West Extension due to traffic load growth constraints.
- Highest cost.

B. Viscous Piston Dampers (Suitable for either side)

- Demountable mechanical device connected between box girder decks and truss bridge at points already reinforced for potential contact between the structures.
- Temporary system manually deployed on demand, not suitable for unplanned events.
- Lowest cost.

Both options would require further investigation to assess costs. It is recommended that NZTA consider their operational requirements and advise which option(s), if any, should be developed further.

1 Introduction

The AHB extension box girder bridges have been observed to be excited by pedestrian loading. Transverse amplitudes of +/- 50mm were reported during a land march across the extension bridge in 1975. These large amplitudes are caused when the natural frequencies of the bridge are close to walking frequencies and inherent damping in the structure is low. Once a large number of pedestrians are walking on the bridge, the induced vibrations essentially prevent pedestrians from walking normally and are instead forced to walk at the natural frequency on the bridge causing resonance. This phenomenon is referred to as Synchronous Lateral Excitation (SLE).

The purpose of this study is to determine options for additional damping devices for the box girder extension bridges and select a preferred option. The damping devices are designed to reduce transverse amplitudes caused by pedestrian induced vibrations to within acceptable limits. It is believed that vibration frequencies having mode shapes with maxima in the midspan regions of spans 1 and 3 are the primary cause. Pedestrian loading is assumed to be the full roadway width, which requires more additional damping than proposed for Option 2 of the Box Girder Strengthening project (that has a 2.4-3.0m pedestrian lane). Preliminary sizing of the damping devices is based on achieving recommended code limits for transverse accelerations. Accelerations are estimated from computer models of the bridge and idealised models of pedestrian motion. Damper options are discussed and evaluated and a preliminary design is selected.

2 Damper options and preliminary sizing

Damping devices that can be used to provide additional damping to a system can be broadly categorised into passive and active devices. Passive devices are the most commonly used due to both their high reliability and low to modest cost. Active devices generally involve a sensor array and computer system to move actuators to control the structural response. Such systems require extensive field measurements, testing and are expensive.

2.1 Damper options

In this situation, additional damping is only required for a specific vibration mode(s) that is excited by pedestrian movements and the sophistication of active devices is not warranted. Therefore the following passive devices were investigated; Tuned Mass Dampers (TMD), Tuned Liquid Dampers (TLD) and viscous dampers.

TMD are a mass connected to the structure with damper and spring elements and are effective only over a small band of frequencies. To achieve the maximum damping effect the system must be tuned exactly to the natural frequency of the structure. In this application the damper mass was excessive and this option was not considered further.

TLD are partially filled shallow tanks of liquid that 'slosh' under large excitation to dissipate energy from the system. Due to the complex nature of the sloshing motion, the damper system is usually tested to determine its performance. The effectiveness of the additional damping is limited to a small frequency band and tuning is required. Preliminary sizing confirms that this type of device would be feasible.

Viscous dampers use a piston to displace a fluid to dissipate energy from the system. These devices don't require specific tuning to frequencies.

2.2 Preliminary damper sizing

Preliminary damper sizing was based on computer analysis of the bridge and idealised models of pedestrian motions. An existing computer model of the bridge was updated to include the strengthening works commencing in 2008. Table 1 gives the measured and computed frequencies, unstrengthened and strengthened, for the 2nd and 3rd transverse modes. Good agreement, within 10%, was obtained between measured and computed natural frequencies. Measured frequencies were obtained from the Wood and Fowler (1976) Ministry of Works and Development dynamic study. It is reasonable to assume that the computed frequencies of the strengthened bridge are also in good agreement with actual values and analysis proceeded on this basis.

Table 1. Measured and computed frequencies for transverse modes.

Transverse mode number	Measured (Unstrengthened)	Computed (Unstrengthened)	Computed (Strengthened)
2	0.58Hz	0.64Hz	0.65Hz
3	0.62Hz	0.68Hz	0.71Hz

Damping in the bridge from Wood and Fowler (1976) was estimated at 1% critical equivalent viscous damping for the 1st transverse mode and results for modes 2 and 3 were unable to be obtained. A field investigation in 2008 using ambient vibration data concluded 1% damping for the 1st vertical mode (Beca Report, 2008). In this study, a value of 1% damping was adopted for the transverse modes.

Dynamic pedestrian load models are prescribed in several international codes (CEB-FIP, 2005) and in this study the Eurocode approach was adopted. In this approach three loading cases are analysed, a single pedestrian, a group of pedestrians and a continuous stream of pedestrians. The continuous stream of pedestrians is the critical case and is based on the full length and width of the bridge being loaded with a density of 0.6 persons/m². Pedestrian densities above 0.6 persons/m² cause restricted movement and densities higher than 1.0 persons/m² are considered to be dense crowds (CEB-FIP, 2005). Sinusoidal varying loads in the vertical and transverse directions are applied to model the pedestrian motion with factors to account for synchronisation. Using the most unfavourable positions of loading, transverse amplitudes of +/- 58mm and +/-45mm were obtained for midspan regions of spans 1 and 3 with corresponding peak accelerations of **0.96m/s²** and **0.73m/s²** respectively using 0.6 persons/m². Acceptable horizontal vibration limits for comfort were also determined from Eurocode and a value of **0.19m/s²** was adopted. This requires peak amplitudes to be reduced by a factor of 5 and equates to approximately 5% additional damping needing to be provided.

A preliminary design for a TLD from Dr Barry Davidson (Compusoft Engineering) was obtained and a viscous damper option was sized. These options are discussed in the following section.

3 Preliminary damper options

3.1 Option 1A – Internal TLD

A TLD system located internally in Boxes 7 and 37 in spans 1 and 3 respectively of the box girder bridge would be used, see sketch S001 in Appendix 1, located near a diaphragm. This would consist of a modular multi-cellular arrangement of tanks of dimensions L = 0.8m, B = 0.5m and H = 0.25m (sized to enable modules to fit through the box girder entrance). A total of 270 and 300 cells would be required for spans 1 and 3 with a total liquid mass of 16 tons and 17 tons respectively. Two modules of 2 wide x 12 long x 6 high (1.0m x 9.6m x 1.5m) and 2 wide x 13 long x 6 high

(1.05m x 10.4m x 1.5m) would be sufficient for spans 1 and 3 respectively (4 in total). Final cell arrangement will depend on access requirements. The cells, constructed from plastic/fibreglass or similar, would be bought in empty, assembled into modules and fixed to the diaphragm/bottom flange of the box girder. The cells would remain unfilled until required for an event when filling would take place. An automated system would be used to equalise levels in the cells. Once the event was finished the cells would be emptied. Filling time could be several hours or more depending on the automated system used, two commercial irrigation pumps operating at 150m³/hour (2x100mm diameter pipes with flow rate of 2.7m/s) would complete the task in 2 hours. Emptying could also take several hours.

It is important to note that a permanently filled sub-option of the internal TLD system is feasible. The significantly lower live loading for the East Extension compared to the strengthening design loading would permit a system to be permanently installed in the East box.

3.2 Option 1B – External TLD

A TLD system with similar total mass to Option 1A but fewer, larger modules to reduce costs would be placed externally on the deck surface of the box girder in Boxes 7 and 37, see sketch S002. The cells would be arranged into modules fitting inside a modified shipping container to be transportable by truck for deployment, filled to correct levels and stored. Once required for an event the modules, fitted inside the containers, would be placed on the deck surface and removed once finished. To minimise obstruction to pedestrians the modules would be placed near the edge of the box girder and traffic safety implications would determine how close. Standard size containers are either 2.4m wide x 6.1m long x 2.6m high or 2.4m wide x 12.2m x 2.6m high, either two small or one large container would be used to house the modules for spans 1 and 3 respectively. Traffic safety devices would be incorporated into the modules and crash attenuators may be required to mitigate the hazard for vehicles in the adjacent live lane.

3.3 Option 2 – Viscous damper

Viscous dampers would be installed at the touchdown cross girder locations in Boxes 7 and 37 of spans 1 and 3 respectively, see sketch S003. Two 15kN devices would be required, one in each span. The damper would be demountable, to maintain gantry access along the spans, and only attached prior to an event. A mechanical 'ball joint' type connection with a quick release mechanism would be required to allow relative movement between the box girder and truss in all three spatial dimensions, e.g. accommodate max crowd load deflections.

4 Preliminary damper option evaluation

In this section, the three options introduced above are evaluated and a preliminary design selected on the following categories; performance/robustness, deployment/operation, maintenance, constructability, traffic safety implications, bridge operational constraints, structural implications and cost. We have assessed weightings for each category based on anticipated importance to NZTA, giving highest rankings to safety and operational aspects. Each attribute is scored on a 1 (worst) to 5 (best) scale. The results are presented below in Table 2 and Table 3 shows the final scoring.

Table 2. Preliminary damper option evaluation.

Attribute	Option 1A - Internal TLD	Option 1B – External TLD	Option 2 – Viscous damper
Performance/Robustness ■ effectively reduce vibrations	Effective. Level of damping can be altered by adding/removing cells.	Effective. Level of damping can be altered by adding/removing cells.	Effective. Change in level of damping requires new damper. No tuning

Attribute	Option 1A - Internal TLD	Option 1B – External TLD	Option 2 – Viscous damper
<ul style="list-style-type: none"> ■ adaptability ■ mistuning 	Requires tuning.	Requires tuning.	required.
Deployment/Operation <ul style="list-style-type: none"> ■ setup time ■ process involved 	Filling/emptying required for each use – could be lengthy. Automated filling system required.	Modules stored off bridge and remain filled. Transported to/from bridge for each use. Deployed using container truck.	Damper de-mountable and installed prior to use. Installation should be quick and simple. Damper removed after use. Compact system.
Maintenance	Calibrating the automated filling system. Algae build-up in tanks may need chemical inhibitor – disposal issue.	Algae build-up in tanks may need chemical inhibitor – disposal issue.	Damper requires periodic servicing. Connections may require inspections.
Constructability	Cells must be assembled into modules on racks inside box girder and braced to floor and diaphragms.	Simple.	Simple. Mechanical 'ball joint' required to permit relative movements between bridges – damper stroke +/- 75mm. Device weight 40-50 kg. Quick release system.
Traffic safety implications	Nil.	Management plan. Traffic safety devices required.	Nil.
Bridge operational constraints	East box - permanent system feasible. West box - Heavy Traffic restrictions whilst filling/emptying/full.	Two lane closure while deploying and in use.	Traffic Nil. Maintenance gantry travel may be restricted.
Structural implications <ul style="list-style-type: none"> ■ effect on box girder bridge ■ effect on truss bridge 	Heavy Traffic restrictions apply during filling/emptying for West box only.	Only present with pedestrian loading. Load effects not significant.	Forces applied to strengthened parts of the box girder and truss node point and cross frame. Load effects not considered to be significant.
Cost <ul style="list-style-type: none"> ■ Device costs ■ Ongoing costs ■ Usage costs 	Plastic/fibre glass tanks. Bracing system to fix to box girder. Automated filling system – pumps, hosing etc. 33m ³ of water per use. Associated labour costs.	Plastic/fibre glass tanks. Bracing system to fix to container. Container to house. 33m ³ of water. Storage when not in use. Transportation. Traffic management and safety device costs. Associated labour costs.	Damper device and connections with quick release system. Installation and removable each use. Associated labour costs.

Table 3. Final scoring for damper options.

	Option 1A - Internal TLD		Option 1B – External TLD	Option 2 – Viscous damper
	West	East		
Performance/Robustness (15%)	5	5	5	5
Deployment/Operation (15%)	1	5	3	4
Maintenance (5%)	2	3	4	5
Constructability (5%)	2	3	5	4
Traffic safety implications (20%)	5	5	1	5
Bridge operational constraints (20%)	1	5	3	5
Structural implications (10%)	5*	4	5	2
Cost (10%)	1	2	3	5
Totals	2.90	4.40	3.25	4.50

* Provided bridge operational constraints are met.

5 Recommended damping option

Based on the preliminary weightings and scores assigned in Table 3 two options are recommended, either Internal TLD for the East box only or viscous damper option. For the West box only the viscous damper option is recommended. Both these options place minimal operational constraints on the bridge and also have no traffic safety implications. A further consideration is which extension bridge NZTA prefers to adopt for “major events”.

6 Development to final design and implementation

Development of the preliminary design would require a dynamic field investigation of the box girder extensions. The dynamic investigation would capture natural frequencies, mode shapes and equivalent viscous damping ratios. Forced vibration testing using shaker devices would allow the most certainty in results. This would confirm the frequencies likely to be excited by pedestrians and the final damper sizing.

Developed designs would be necessary to assess total costs of the two short listed options, though preliminary inquiries for the viscous dampers confirm they are relatively low cost.

It is recommended that NZTA consider their operational requirements and advise which option(s), if any, should be developed further.

7 References

Beca Infrastructure (2008). Auckland Harbour Bridge Extension Bridge Strengthening – Ambient vibration testing of Span 2.

CEB-FIP (2005). FIB Bulletin 32: Guidelines for the design of footbridges. International Federation for Structural Concrete (FIB), Lausanne, Switzerland.

Wood, J.H. and Fowler, G.F. (1976) Auckland Harbour Bridges Extensions, Dynamic Studies. Ministry of Works and Development. Report No. 5-76/5. Lower Hutt, New Zealand.

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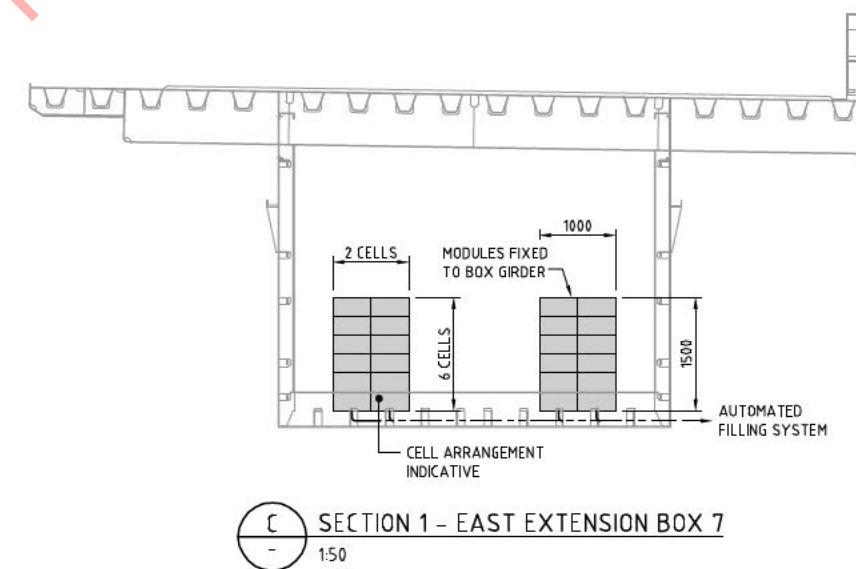
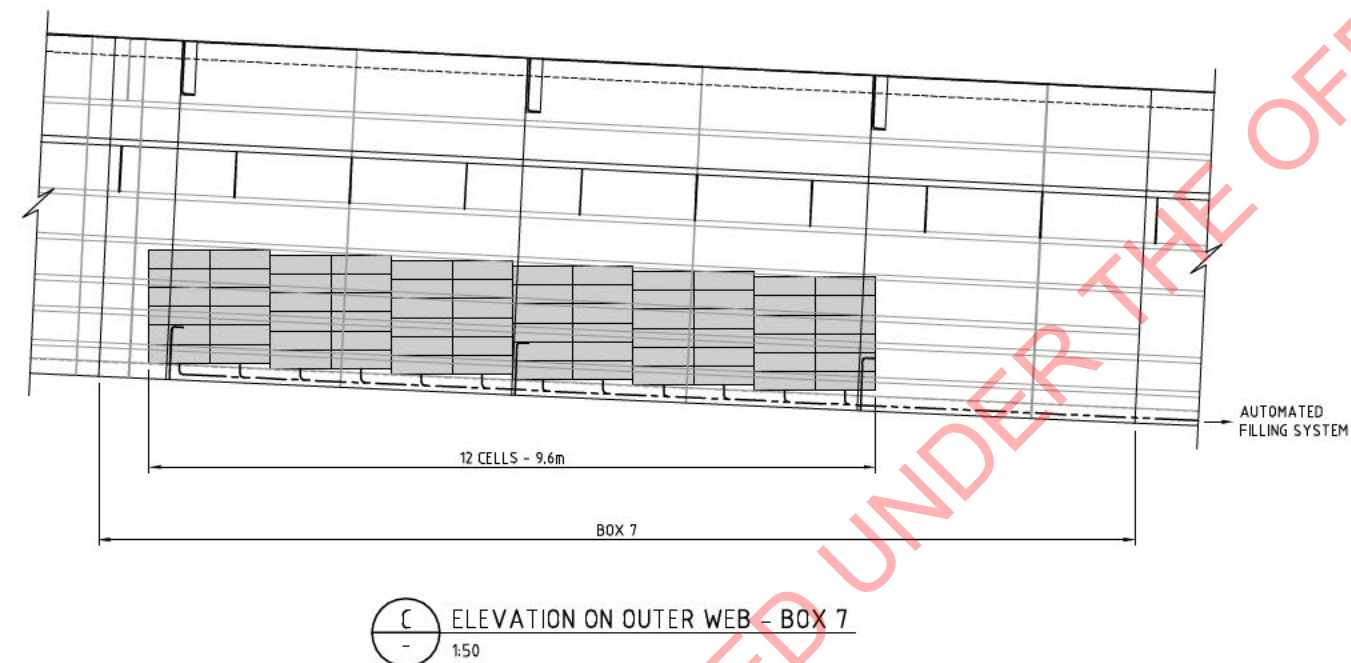
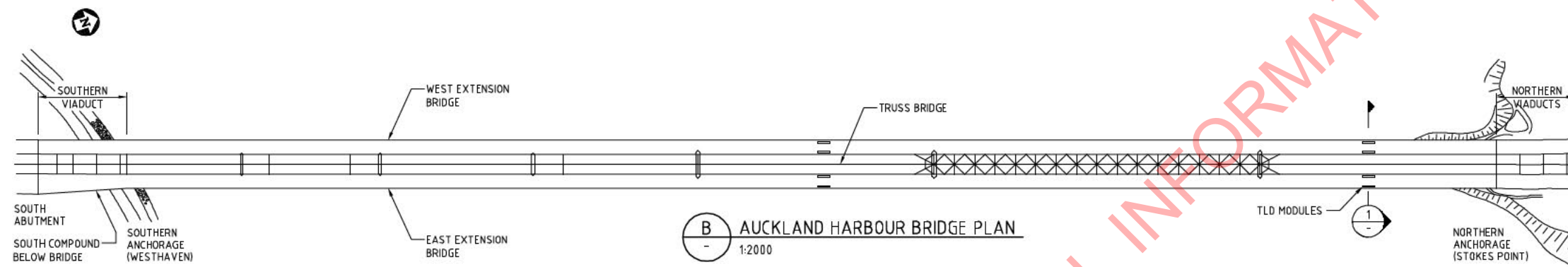
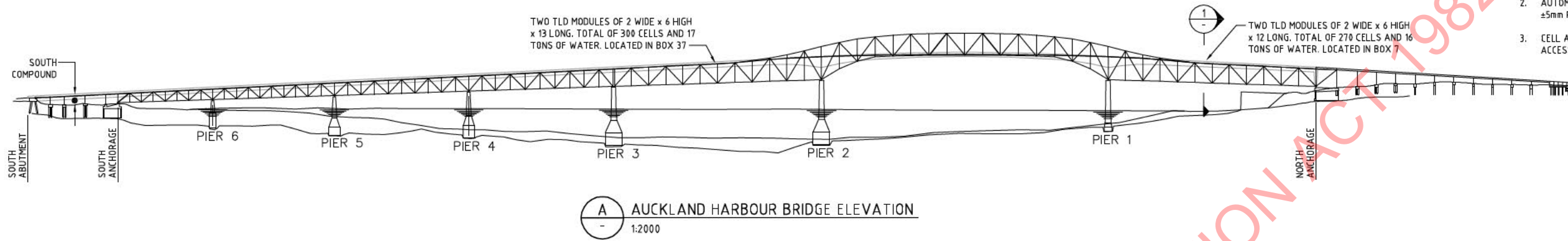
Appendix 1

Sketches of preliminary
damper options

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NOTES:

1. MODULES REQUIRE RIGID FIXINGS TO WEB AND BOTTOM FLANGE TO ENSURE DAMPER EFFECTIVENESS.
2. AUTOMATED FILLING SYSTEM REQUIRED TO FILL TANKS TO ±5mm REQUIRED LEVEL.
3. CELL ARRANGEMENT INDICATIVE. ARRANGEMENT DEPENDS ON ACCESS REQUIREMENTS AND STRUCTURAL CONSIDERATIONS.



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A	ISSUED FOR INFORMATION ONLY	FMR	DAC	IJB	24-06-09

Drawing Originator:
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Original Scale (A1)	Design	ORDL	APR '10	Approved For Construction*
1:2000	Drawn	PN	APR '10	
Reduced Scale (A3)	Dwg Verifier			Date
1:4000	Dwg Check			

* Refer to Revision 1 for Original Signatures

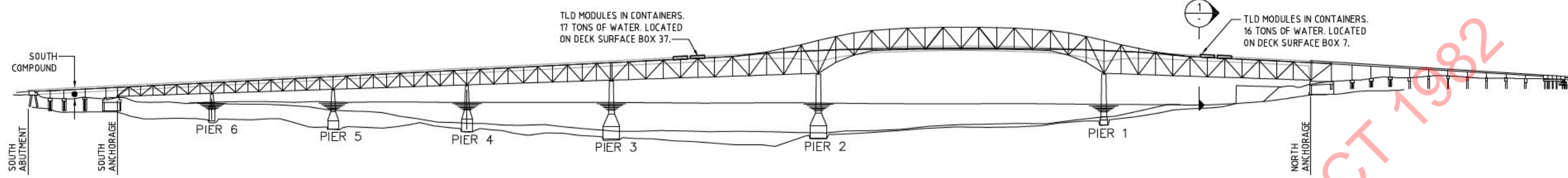
Client:
NZ TRANSPORT AGENCY
 WAKA KOTAHU

Project:
AUCKLAND HARBOUR BRIDGE
 STRUCTURAL SERVICES
 PA2980

Title:
OPTION 1A
 INTERNAL TLD

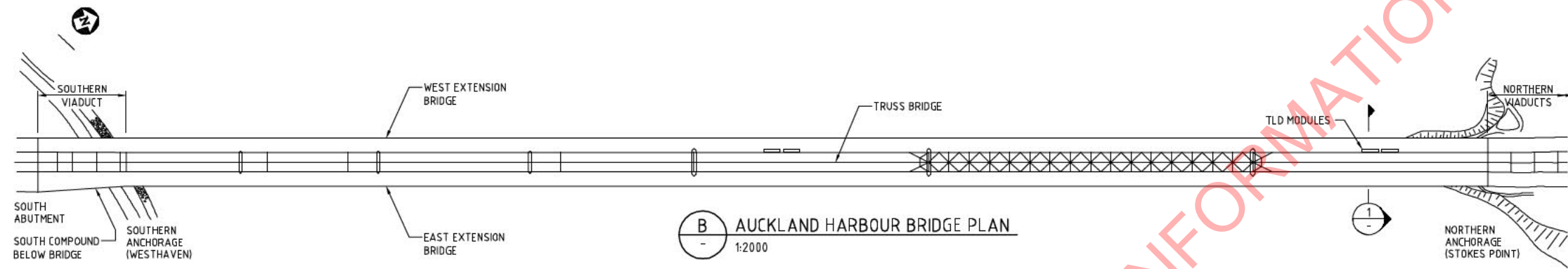
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Discipline	STRUCTURAL
Drawing No.	3910504-343-S-001
Rev.	A

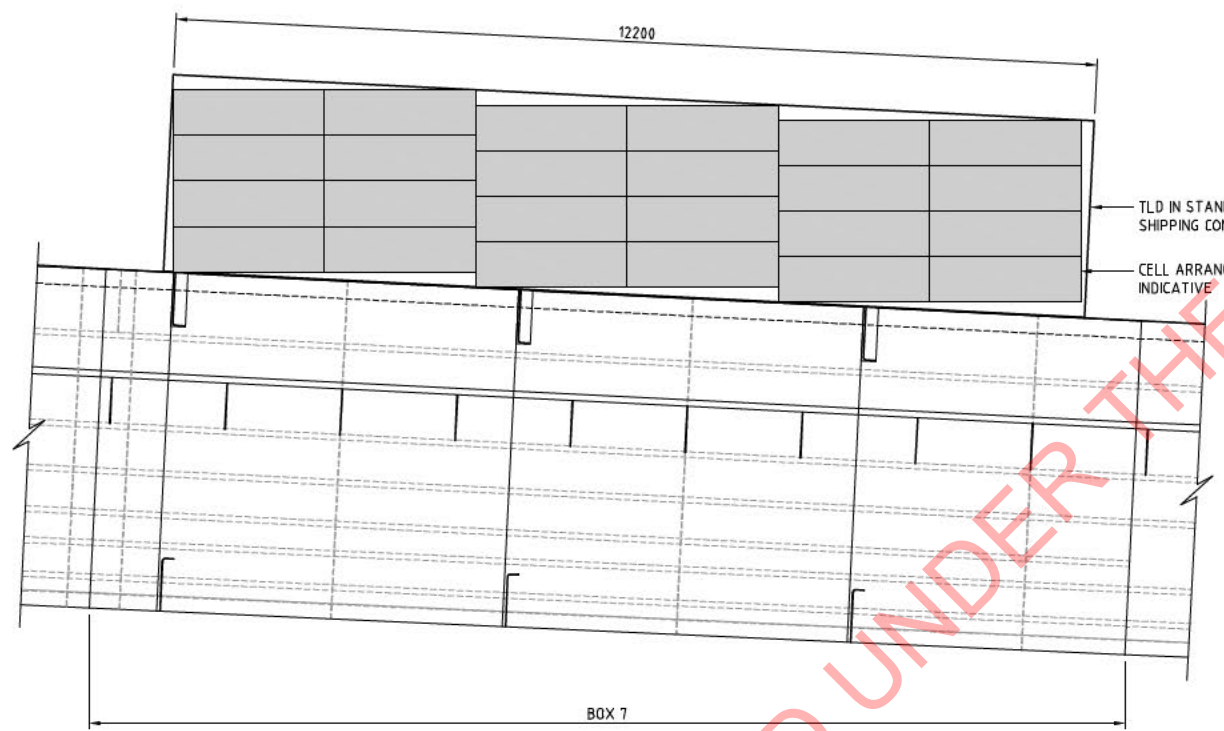


A AUCKLAND HARBOUR BRIDGE ELEVATION
1:2000

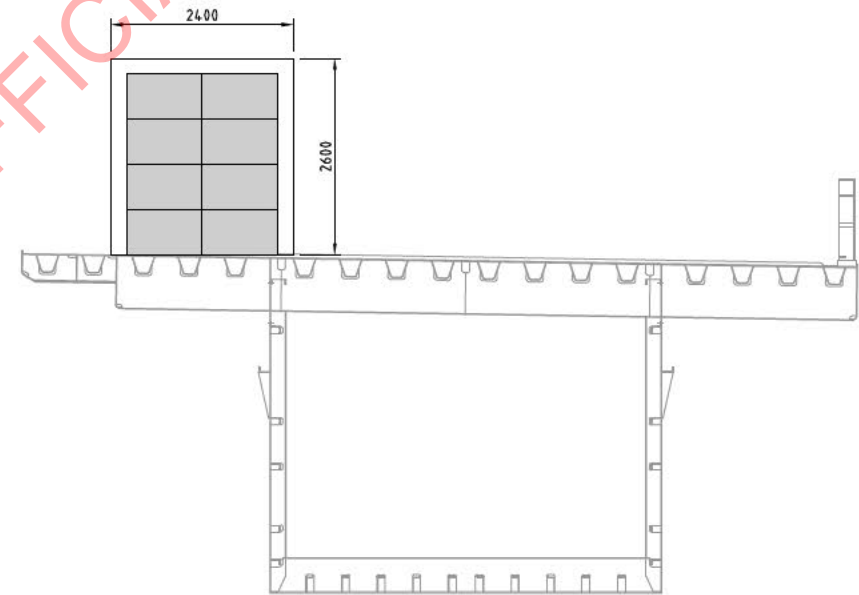
- NOTES:**
1. CELL ARRANGEMENT INDICATIVE. SIZE OPTIMISED TO MINIMISE NUMBER OF CELLS.
 2. CONTAINERS DEPLOYED BY TRUCK.
 3. TRAFFIC SAFETY DEVICES TO BE INCORPORATED INTO OPERATIONAL PLAN.



B AUCKLAND HARBOUR BRIDGE PLAN
1:2000



C ELEVATION ON INNER WEB - BOX 7
1:50



C SECTION 1 - EAST EXTENSION BOX 7
1:50

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A	ISSUED FOR INFORMATION ONLY	FMR	DAC	IJB	24-06-09



Original Scale (A1)	Design	ORDL	APR '10	Approved For Construction*
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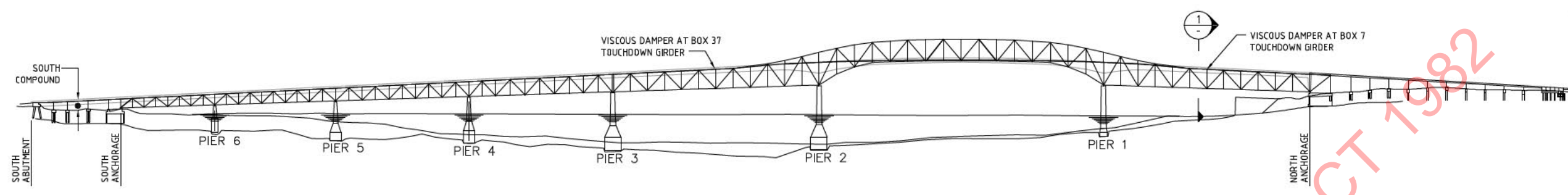
Project: AUCKLAND HARBOUR BRIDGE
STRUCTURAL SERVICES
PA2980

Title: OPTION 1B
EXTERNAL TLD

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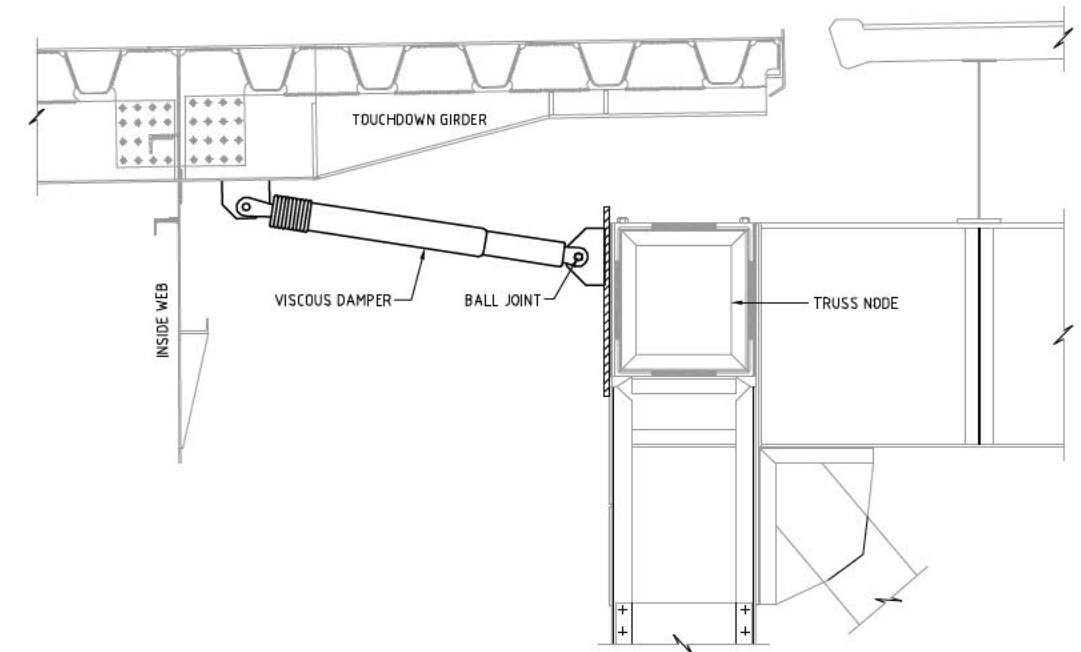
Discipline	STRUCTURAL
Drawing No.	3910504-343-S-002
Rev.	A

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- NOTES:**
1. VISCOUS DAMPER TO BE 15KN DEVICE.
 2. STROKE TO BE ± 75 mm.
 3. BALL JOINT TO PERMIT RELATIVE MOMENTS BETWEEN BOX GIRDER AND TRUSS.
 4. QUICK RELEASE SYSTEM INCORPORATED INTO DESIGN.

A AUCKLAND HARBOUR BRIDGE ELEVATION
1:2000



1 SECTION
1:20

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A	ISSUED FOR INFORMATION ONLY	FMR	DAC	IJB	24-06-09

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Client:
NZ TRANSPORT AGENCY
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Project:
AUCKLAND HARBOUR BRIDGE
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Title:
OPTION 2
VISCOUS DAMPER

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Discipline	STRUCTURAL
Drawing No.	3910504-343-S-003
Rev.	A