Use of Accelerated Bridge Construction (ABC) Techniques in a High Seismic Area - MacKays to Peka Peka Expressway Project Case Study

Jamil Khan[1], Tim Pervan[2], Matt Zame[3] and Geoff Brown[4]
[1]Technical Director, Beca Ltd, New Zealand
[2]Senior Site Engineer, Fletcher Construction, New Zealand
[3]Zone Construction Manager, Fletcher Construction, New Zealand
[4]Senior Technical Director, Beca Ltd, New Zealand

Abstract: Accelerated Bridge Construction (ABC) techniques have demonstrated significant time savings, and improved the quality of bridge construction. However, no design procedures or guidelines exist for ABC in seismically active areas. ABC utilises innovative planning, design and construction methods in a safe and cost-effective manner to reduce the onsite construction time that occurs when building new bridges. On the MacKays to Peka Peka Expressway project, the design team worked in collaboration with the constructors to develop and implement a number of ABC initiatives. These include:

- **Standardisation** of the elements for modular pre-cast bridge elements
- **Prefabrication** of bridge components or complex and heavy reinforcement cages
- **Foundation** systems for efficient, quality and speedy construction
- **Elimination** of an element or operation or dependency of elements on each other, if possible, to reduce the total number of elements/operations in the construction sequence
- **Connection** of different bridge elements for safe and durable construction
- **Installation** of bridge components in a safe and cost-effective manner.

This paper describes how the collaboration between designers and constructors enabled the use of a number of ABC techniques in a highly seismic area.

Keywords: Standardisation, Prefabrication, Foundation, Elimination, Connection, Installation

1. Introduction

Accelerated Bridge Construction (ABC) is bridge construction that uses innovative planning, design, materials, and construction methods to provide a safe and cost-effective approach to reduce the onsite construction time that occurs when building new bridges, or replacing and rehabilitating existing bridges (ABC Manual (1)).

- ABC techniques improve site constructability, quality, durability, safety and total project delivery.
- ABC techniques reduce the onsite construction time, weather-related time delays and traffic impacts.
- ABC techniques also minimise environmental impacts, impacts to existing roadway alignment and utility relocations and land requirement for the construction works.

ABC techniques have demonstrated significant time savings and improved construction quality. However, the lack of widely accepted, well-developed, and proven ABC connection details has prevented extensive application of ABC in high seismic zones. The paper describes how the collaboration between designers and constructors enabled the use of a number of ABC techniques in a highly seismic area.

2. Project Back Ground

The MacKays to Peka Peka Expressway (M2PP) is an 18km 4-lane highway that will take State Highway 1 along the Kāpiti Coast. M2PP is the first of the Wellington Northern Corridor RONS projects. M2PP will separate local and state highway traffic and result in safer and shorter trips within and through the Kāpiti Coast - with local and national benefits. It is being built by an alliance made up of the NZ Transport Agency, Beca Ltd, Fletcher Construction and Higgins Group supported by Goodmans Contractors, and Boffa Miskell.

The project site is in one of New Zealand‘s most severe seismic regions. The key role of the Expressway is to provide a modern and reliable route which safely crosses over the local roads and waterways. The project includes 17 bridges comprising multi-span and single span bridges over local roads and streams, including a new 182m long crossing of the Waikanae River.

3. Challenging Environments

3.1 Seismic

The expressway is located in proximity to the following active faults (SHA-M2PP (2)):

- The Ohariu fault is between one and three kilometres from the Expressway and has an estimated MCE (maximum considered earthquake) magnitude of M7.2 at a return period of 2000 years
- The Wairarapa fault is around 30 km further from the Expressway but has an estimated MCE magnitude of 8.2 at a return period of 1200 years.

Figure 1: Critical active faults around the site

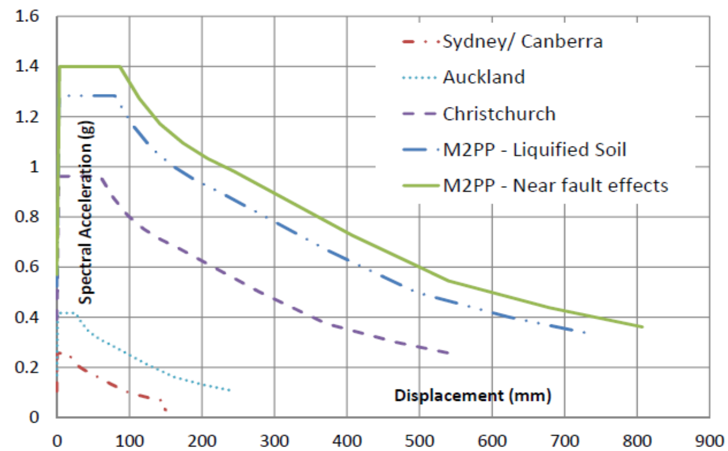

Figure 2: Spectral Acceleration of different cities and the Project site for 2500 years return period events.

To appreciate the high seismicity of the project site, the M2PP design spectral acceleration curve, based on the study (SHA-M2PP (2)) is compared against other locations in New Zealand and Australia in Figure 2.

The performance of the Expressway (NZTA BM-13 (3)), during and following earthquake design events, was a key design challenge. The bridges are designed to:

- Have no damage under Service Limit State SLS1 (a return period of 25 years) seismic events
- Have some minor damage under SLS2 (a return period of 100 years) seismic events. Damage to such components is to be cleared and access restored within 24 hours for full traffic use.
- Have some damage to the structure under Ultimate Limit State design (1/2500 years) earthquake events. The bridge should be useable by emergency traffic within three days. Permanent repair to reinstate the design capacity for both vehicle and seismic loading should be feasible and should be economically viable and able to be accomplished within 12 months.
- Prevent total collapse under the maximum credible earthquake (MCE) by ensuring sufficient ductility of the yielding elements, and/or the provision of redundant load paths such as alternative or secondary load paths to provide vertical support (NZTA BM13 (3), NZS1170-2006 (4)).

3.2 Geotechnical

The Expressway alignment traverses through sand dunes and inter-dune peat deposits. The peat deposits are very soft and highly compressible and may be up to six meters thick. The dune deposits are fine, single sized sand, with a high liquefaction potential where saturated. These conditions present the following challenges to the Expressway design:

- Peat deposits can cause significant post construction settlements due to high compressibility which, without treatment would have resulted in poor rideability, settlement of services and adjacent properties, altered surface drainage patterns and increased maintenance.
- The dune and sandy alluvium present significant challenges due to their liquefaction potential and associated settlement and lateral spreading, particularly to bridge structures due to the high ground water level.

3.3 Urban Environment

The Expressway is a new feature in the landscape, both rural and urban, and by nature largely horizontal. Challenges from an Urban Design perspective included (RCC-M2PP (5)):

- The Expressway should achieve; a sensitive fit within the built, natural and community environment, good connections for communities, be attractive and fit for purpose and maintain social and cultural values
- Fundamental aesthetic qualities to be achieved for bridges: elegance - form, proportions and scale/ shape, relationship to the surrounding natural and built landscape, expression of technology, strength and durability, use of texture and colour
- The Resource Consent for MacKays to Peka Peka (RCC-M2PP (5)) Expressway Project came with a condition of providing a 35m clear waterway channel under the Waikanae River Bridge, requiring a span length of about 39m. This led the Alliance team to think outside the square and develop some innovative ideas to overcome the span restriction problem.

4. Innovative Design approach

One of the benefits of an Alliance project delivery is the opportunity for innovation - the integrated project team comprising the client, designers and constructors are able to actively collaborate and put existing concepts together in a new way. As risks and responsibilities are shared and managed collectively the final ‘product’ represents an agreed risk-based approach and methodology to design and construction. To meet the seismic, geotechnical and urban challenges posed, innovative design and construction solutions were developed to achieve an acceptable balance between ground improvement, structural design, construction, performance, risks and cost (Jamil K, Nickolas C, Philip C, and Geoff Brown (6)).

It is anticipated that under the ULS seismic load case the bridge structures will be subject to ground shaking and also movement of the embankments. The combined exposure of the bridges to inertia loading as well as embankment movement presented a scenario where standard design approaches were considered inadequate. Appropriate design methods have therefore been developed for this project as outlined in the following sections.

The structural design follows the recommendations in the Draft Amendment to the Bridge Manual "Proposed Provision for Deflection-Based Design", dated 23rd February 2013 (NZTA Draft DBD-2013 (7)) with modifications agreed with NZ Transport Agency during the project. This methodology largely follows the proposed approach by Priestley et al. "Displacement-Based Seismic Design of Structures", 2007 ((Priestley, Calvi and Kowalsky (8)).

Direct displacement based design methods allow structures to be designed to more realistic levels of performance. The method allows for limit states to be defined through material strain levels as opposed to the more traditional force-based approximate method of limiting structural ductility, giving the designer greater control, and the client greater confidence in how their structure will perform under a specific design event.

5. ABC Techniques

On the Mackays to Peka Peka Expressway project, the design team worked in collaboration with the constructors to develop and implement a number of ABC technologies in a high seismic zone. There is no one ABC technique used on the M2PP project. Instead, there is a family of ABC construction techniques that are used which cover the majority of multispan bridges on the project. Figure 3 shows the most common forms of ABC technologies implemented on the project.

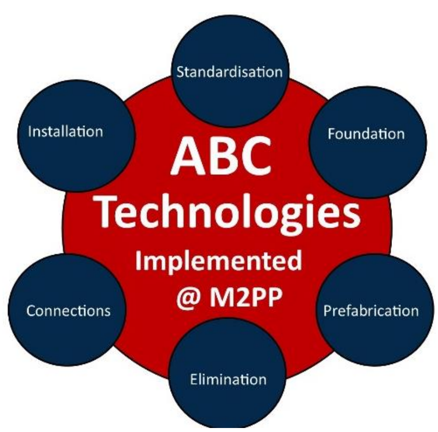

Figure 3: ABC Techniques

5.1 Standardisation

The confinement of longitudinal reinforcement and restriction on splicing the longitudinal reinforcement within the potential plastic hinge zone severely limits the implementation of standardisation in high seismic areas. Recent research by US Domestic Scan Program (Scan Team Report (12)) showed that there an inverse correlation between the level of seismicity and the level of implementation of ABC practices. However, the Alliance team used innovative planning to standardise the bridge components for efficient and cost effective design. As a result of this planning, the team standardised the number of bridge components, which were used repeatedly on the project. Some of these elements are listed below:

5.1.1 Pier types

The bridge piers on the project were standardised by adopting only two types of piers. A portal frame pier was adopted for bridges having only two spans and a hammer-head pier for bridges having three or more spans. There are 28 piers on the project, 24 of them are hammer-head piers and four of them are portal frame type piers.

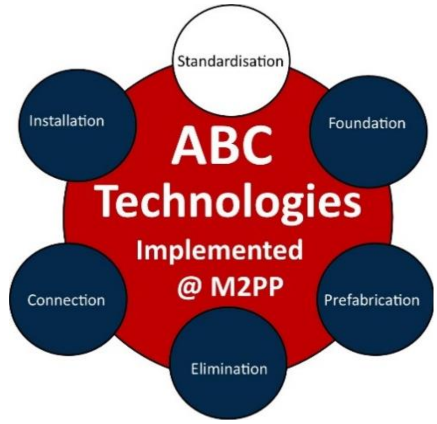

Figure 4: ABC Tech. Standardisation

5.1.2 Pier columns

The pier columns are an architectural shape, which is an elongated hexagon for the lower half portion then it gradually change to a rectangular shape at the top. Two sizes of columns were adopted for the project, these sizes were identified by the width of the columns; 1.5m wide columns for portal frame piers and 2.1m wide pier columns for hammered-head piers. There are 24 of the 2.1m wide pier columns and 8 of the 1.5m wide pier columns. Figure 5, shows both types of piers adopted on the project.

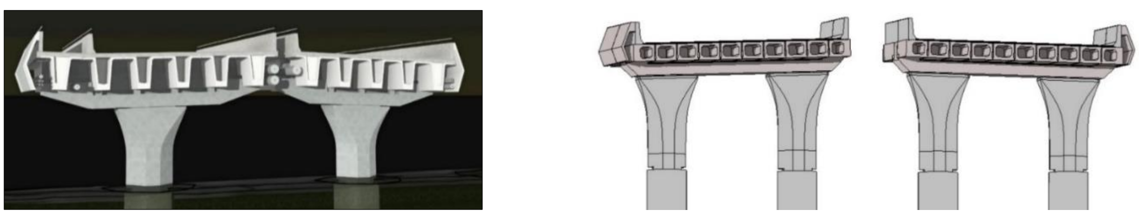

Figure 5: Pier and Column types

5.1.3 Bored piles

A large diameter bored pile foundation system was adopted for pier column supports. There are 32 bored piles on the project; 24 are of 3m diameter bored piles for hammered head pier columns and the remaining 8 are 2.1m diameter bored piles for portal frame pier columns,

5.1.4 Crosshead beams

The crosshead beams adopted for the project are pre-cast inverted-T reinforced concrete beams. The following four sizes of crosshead beams are used:

- Portal frame crosshead beam for 900mm SHC beams (4 Nos)
- Hammerhead crosshead beam for:
  - 900mm SHC beams (12 Nos)
  - 1225mm Super T beams (4 Nos)
  - 1825mm Super T beams (8 Nos)

Figure 6: Cross-head beams types

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5.1.5 Abutments types

In order to fit the bridges into the urban design framework of the project, two types of bridge abutments were adopted in the design:

- Spill-through type abutment (7 Nos)
- Vertical abutments (7 Nos).

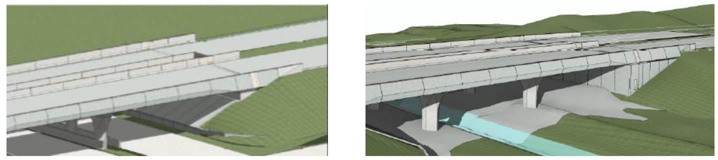

Figure 7: Abutment types

5.1.6 Bridge beams

Pre-cast bridge beams adopted for the project were:

- 1825 Super Tee Beams (55 Nos)
- 1225 Super T beams (66 Nos)
- 900 SHC beams (245 Nos)
- 650 SHC Beams (30 Nos)

Figure 8: Pre-cast bridge beam types

5.1.7 Pre-cast fascia panels to barriers

The visual appearance of bridges has been developed to form a family of bridges along the Expressway. This primarily consists of faceted precast concrete facia panels attached to the outer edges of the traffic barriers, and architecturally shaped bridge piers that provide the bridges with a common appearance to the superstructure and substructure.

5.1.8 Pre-cast facing panels to abutments

The key feature of urban design under the overpass bridges is the textured precast panel facings to the sloping embankment. Where the embankment has been built up to lift the expressway above the local road, the exposed aggregate facing panels taper down with the embankment side slopes.

5.2 Foundations

The bridges sit in an urban environment, where the quality of the space and aesthetics are very important. The bridges are designed to enhance the quality of the local road beneath the overpass by maximising natural light penetration. Hammerhead/portal frame piers have been used because they are aesthetically appealing, occupy less space and provide more light and room for the pedestrians and traffic underneath the bridges.

A detailed investigation indicated that 3.0m diameter piles are needed to support each hammer head pier using a monopile system and 2.1m diameter bored piles for portal frame pier columns (Jamil K, Philip C, Matt Z, Ian S, Amit C and Geoff B (9)). The pier core reinforcement cage and pile reinforcement cage were detailed as a circular cage, to allow the plunging of the architectural-shaped pier reinforcement into the piles top concrete. The adopted system has flexibility to accommodate the pile construction tolerances.

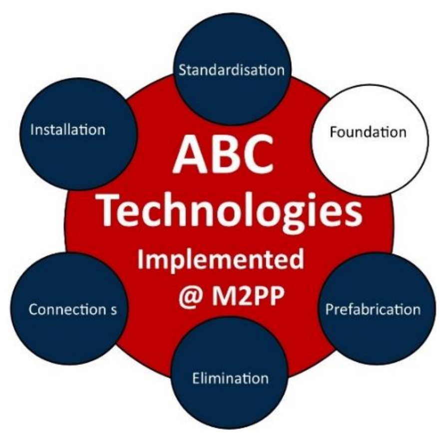

Figure 9: ABC Tech. Foundations

The bridge abutments are cast-in-situ concrete structures supported on two rows of 310UBP149 steel H-piles. The steel piles may develop plastic hinges under seismic inertial forces. Under earthquake induced permanent embankment movements, it is expected that the abutment and their piles will deform with the ground movements in the longitudinal and transverse direction forming plastic hinges in the piles (Jamil K, Philip C, Ronald W, Anton K and Geoff B (10)). To provide a secondary load path the soil between the H-piles with MSE embankment was reinforced with geogrid.

5.3 Prefabrication of Bridge Elements

The use of pre-cast beams in bridge construction is very common. The Alliance team planned to maximise the prefabrication of bridge components for efficient, cost effective and quality construction including:

- Pre-cast bridge Super T/Single Hollow Core beams
- Pre-cast cross-head beams
- Pre-cast approach/land span slabs
- Pre-cast fascia panels to barriers
- Pre-cast facing panels to abutment
- Pre-fabricated steel cages for:
  - Pier columns.
  - Bored piles
  - Large abutment pilecaps
  - Traffic barriers.

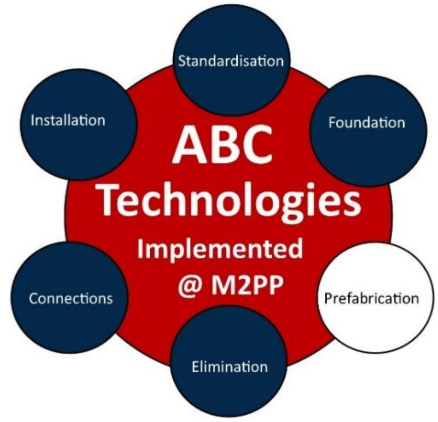

Figure 10: ABC Tech. Prefabrication

Figure 11: Prefabricated reinforcement cage for a 29m by 9m pile cap

5.4 Elimination

The Alliance team worked in collaboration to eliminate an element, an operation or dependency of elements on each other in the construction of the bridges. This helped in making the bridge construction efficient and improved the quality of work at the site.

5.4.1 Elimination of pile caps

The bridge piers are supported directly on large mono-piles, which eliminated the need for a pilecap. The piers act as cantilever structures supporting static and seismic inertia loads as well as resisting lateral ground movement loads under extreme seismic loads (9). The absence of a pilecap reduces the lateral loads applied to the piles from the laterally spreading ground in the liquefaction design case.

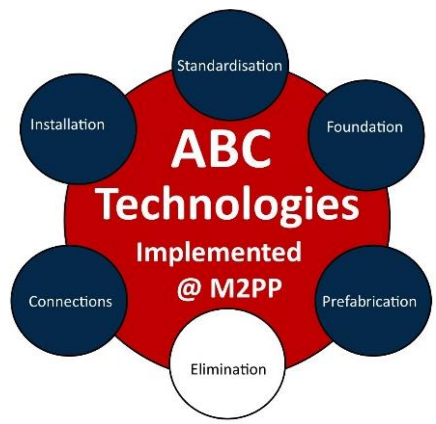

Figure 12: ABC Tech. Elimination

5.4.2 Elimination of second stage concreting for pile-column interface

Plunging the fully assembled column reinforcement cage into the wet pile concrete eliminated the installation of the starter bars or second stage concreting to splice the columns to the piles. This reduced the programme and saved 210 days in preparation and forming column pour connections and 175 days in fixing steel at height across the project. It also made things safer by eliminating confined space work and reducing work at height (Jamil K, Philip C, Matt Z, Ian S, Amit C and Geoff B (9)). The primary risks associated with this approach were:

- Maintaining concrete workability for around 5 hours.
- Achieving design tolerances (horizontal 20mm, vertical 20 mm) on fixing the column cage.
- High bleed water from a high slump concrete.

Time and motion trials were carried out on setting up temporary works and plunging the column cage into a dummy hole. Regular reviews of the trials and throughout piling led to refinement and continuous improvement to reduce time and increase safety and quality assurance.

Removing the top extra concrete after pile pour

Column cage plunge frame setup

Column cage lifting and slewing

Column cage introduced into plunge frame

Cage lowered to final position

Plunged column cage after removal of frame

Figure 13: Plunging the fully assembled 16T column cage

5.4.3 Eliminate the dependency of elements on each other

To speed up the construction of bridges, the Alliance team looked into to the possibility of eliminating dependency of elements in each other. The MSE block of embankment was set back form the vertical abutment and a short land span was introduced to bridge the gap between the concrete vertical abutment and MSE wall block. This eliminated the dependency of the MSE wall block and concrete abutment construction on each other. Both MSE wall block and concrete abutments were then constructed in parallel.

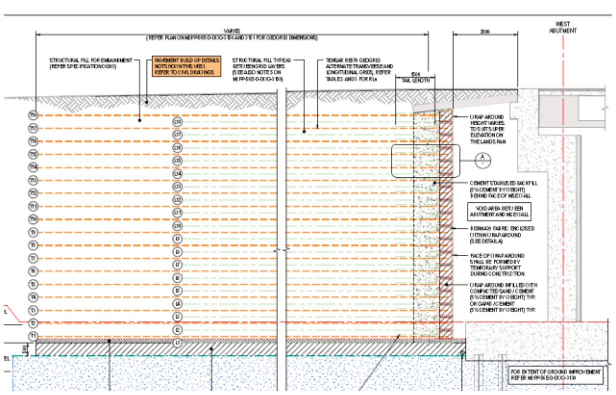

Figure 14: Short Land span to separate MSE Wall block and bridge abutment

5.5 Connections

Lapped / coupled reinforcement connections are not allowed within the plastic hinge zones in high seismic regions. The lack of widely accepted, well-developed, and proven ABC connection details in high seismic zone was a challenge to the team. Careful thought on connection details during the design, can save a lot of time and effort during construction.

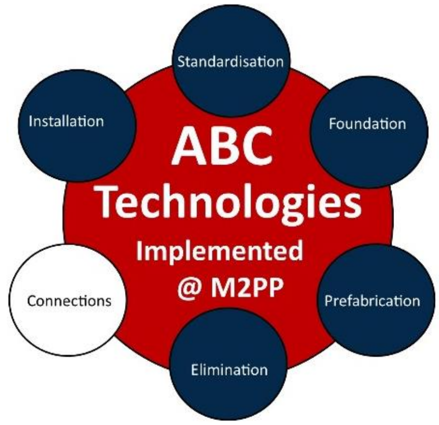

Figure 15: ABC Tech. Connections

5.5.1 Pile and pier connection

The piers are architectural shaped columns, an elongated hexagonal shape at the lower portion, which gradually changes to a rectangular shape at the top of the pier. At the pile-pier interface the short length of the column shape changes to an octagonal shape, which allows the pier main cage to be detailed as a circular cage. The pier column cages are designed as a Main Structural cage and a Secondary cage.

The main core cage was detailed as a circular shaped cage, which along with the pile circular cage provided flexibility in accommodating the pile construction tolerance (Jamil K, Philip C, Matt Z, Ian S, Amit C and Geoff B (9)). The secondary cage follows the architectural shape of the column and ties into the main circular cage for the architectural shape.

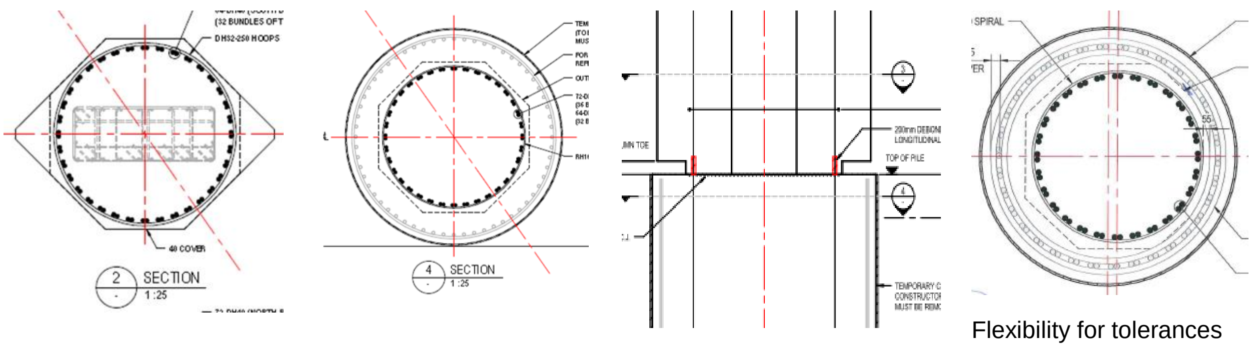

Figure 16: Pile-pier connection

5.5.2 Pier and crosshead connection

A post-tensioned connection was designed to connect the precast crosshead beam to the cast-in-situ pier. This type of connection reduced the joint reinforcement congestion and increased the construction speed. Steel anchorage plates with screwed threaded stress bars were cast into the piers. The pre-cast crosshead was lowered over the column with stress bars passing through oversize ducts, and stressing was performed. The post-tensioned connection was designed to remain elastic under all load cases. This connection allowed rapid erection of the crossheads and proved to be a cost effective solution.

Figure 17: Pier and crosshead beam connection

5.5.3 *Crosshead and deck connection.*

Linkage reinforcement is required to restrain the bridge span to the pier in the event of an earthquake. In high seismic zones, the linkage reinforcement will be subject to geometric elongation and bending of linkages in addition to conventional direct tension action. It was noticed that the conventional linkage reinforcement would yield extensively under the combined ULS action due to high rotation of pier heads. The team developed an alternative solution using 15.2mm diameter strands, individually sheathed in a HDPE duct. The use of strands reduced flexural stresses in the linkage to a negligible value. Debonding was increased significantly to control the strains in the linkage that develop due to geometric elongation. The strands are flexible enough to accommodate the rotation and axial extension without yielding/failing at both the ULS and MCE.

Figure 18: Linkage connection

5.5.4 *Barrier and fascia panel connection*

The outer face of the traffic barriers, a key aesthetic element, has a 20 degree slope and will act as the fascia of the bridge. The fascia is the precast portion of the barrier and the actual barrier is cast-in-situ. Inserts were cast in the ribs of the fascia panels and drossbach ducts were cast in the barriers. The fascia panels were lowered into place, cast-in inserts aligned with ducts in the barriers and threaded rods screwed into the inserts. Bearing plates were placed against the barriers in pockets and the bolts were tensioned by tightening the nut against the bearing plates. The ducts were grouted and the pockets in the barriers filled with protective mortar. This type of connection sped up the installation of the fascia panels on the project.

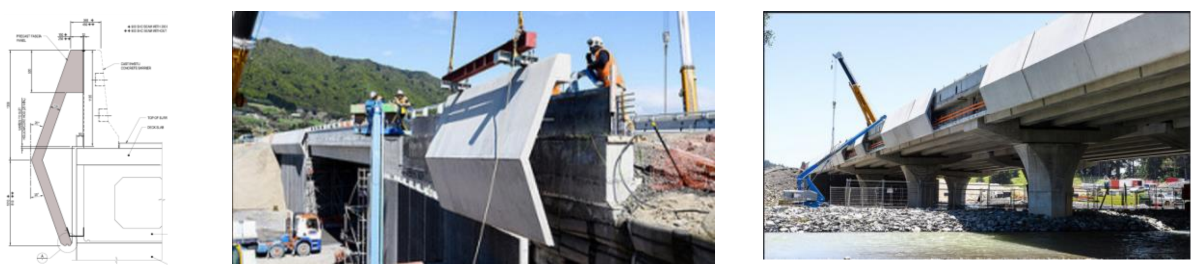

Figure 19: Pre-cast fascia connection

5.6 Installation

The erection of bridge beams, cross-head beams, facia panels and facing panels were primarily carried out using cranes. A modern high capacity 400T crane has been used on the project. This crane was transported from South Africa. The crane was able to travel over the haul road and could be set up in 2-3 hours. This allowed the installation of heavy pre-cast elements on the two largest bridges on the project, the 180m long Waikanae River Bridge and the 125m long Te Moana Road Overpass Bridge, at the same time. After preparing the ground the crane installed the Te Moana Road Bridge crossed-head beams. The crane then travelled to Waikanae Bridge to install the bridge beams to one span, while the ground work was prepared at Te Moana Road Bridge for the bridge beam installation.

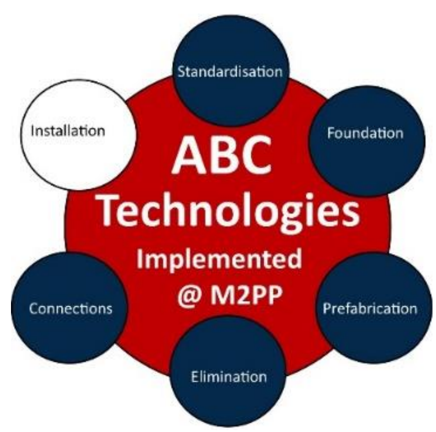

Figure 20: ABC Tech. Installation

Once the Waikanae bridge beams were installed, the crane travelled back to Te Moana Bridge to install the bridge beams, and the ground work for the next span at Waikanae River Bridge was carried out. This careful planning made the use of the crane efficient and accelerated the installation of heavy beams on the two bridges. Smaller crawler cranes were used for the installation of lighter precast elements like the fascia panels and abutment facing panels.

Ngarara Road Bridge was constructed using the top-down construction method. An innovative technique was used for installing the facing panel underneath the bridge. This low cost and efficient method, required only a 20t excavator, a dozer and some recycled steel from the yard to install the precast panels under Ngarara Bridge as shown in figure 23.

Figure 22: Installation of facing panels at Ngarara Road bridge

6. Conclusions

The high seismicity, challenging soil conditions and urban environment presented unique challenges to the Alliance team at the M2PP Expressway project. The combined exposure of the bridges to inertia loading as well as embankment movement presented a scenario where standard design approaches were considered inadequate. Appropriate design methods have therefore been developed for this project using direct displacement based design methods, which allow structures to be designed to more realistic levels of performance. The developed approach gives the designer greater control, and the client greater confidence in how their structure will perform under a specific design event.

The confinement of longitudinal reinforcement, restriction on use of lapped or coupler connections and splices to the longitudinal reinforcement within the potential plastic hinge zones severely limits the implementation of ABC techniques in high seismic areas. However, the collaboration between designers and constructors enabled the use of a number of ABC techniques for the multi-span bridges of M2PP Project. The team adopted a number of ABC techniques to improve the construction efficiencies, to make a safe working environment and to achieve a good quality product. By pushing to find ABC solutions in the design and construction of M2PP bridges, significant construction efficiencies and savings has been achieved.

7. Acknowledgement

The authors would like to acknowledge the numerous and continuing contributions of the their designer colleagues Andrew Dickson, Ronald Wessel, Anton Kivell and the constructor colleagues, Ian Stockdale, Amit Chaudhary, Dave Hoffman and many others in the development and implementation of these ABC Techniques which formed the basis for the design and construction of the M2PP Bridges.

The authors would like to acknowledge the numerous and continuing contributions of the NZ Transport Agency, other Alliance partners and suppliers in the development and implementation of the innovative approach taken on this project.

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