EFFECTIVE USE OF CONCRETE TO ACHIEVE THE DESIRED HIGH QUALITY URBAN DESIGN OUTCOMES FOR THE MACKAYS TO PEKA PEKA EXPRESSWAY PROJECT

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PROJECT BACKGROUND

The Mackays to Peka Peka (M2PP) Expressway is an 18km, four-lane highway that takes State Highway 1 along the Kāpiti Coast north of Wellington. The M2PP Expressway separates local and state highway traffic and results in safer and shorter trips within and through the Kāpiti Coast, with local and national benefits. It was built by an alliance made up of the NZ Transport Agency (NZTA), Beca Ltd, Fletcher Construction and Higgins Group, supported by Goodmans Contractors and Boffa Miskell.

The key role of the expressway is to provide a modern and reliable route, safely crossing over local roads and waterways. The project included 17 multi-span and single-span bridges, including a new 182m long crossing over the Waikanae River. The bridges are designed to achieve a consistent form and adopt consistent architectural elements that create a family of bridges that are visually appealing and flow naturally within the landscape in which they sit.

URBAN DESIGN CRITERIA OF THE PROJECT

The urban design criteria of the M2PP Expressway Project was directed by project objectives as established by the Project Alliance Board which included Kāpiti Coast District Council (KCDC) on its joining the Alliance. These objectives and their application were further outlined in the Urban and Landscape Design Framework (ULDF). The ULDF broke the M2PP Expressway ‘urban design’ discipline into 15 distinct categories outlining the key design considerations and/or design principles for each.

Over/Under Bridge Options Design

In urban areas, the expressway crosses over each local road via an overpass bridge. In rural areas, the local road crosses over the expressway via an underpass bridge. This decision was based on:

- The local roads and larger watercourse corridors are used by people moving frequently in an east-west direction. For walking, cycling and people with impaired mobility maintaining flat grades assists with their connectivity and accessibility between the east and west sides of the Expressway.
The dune landforms naturally allow the Expressway to be located across the tops of dunes (Raumati and Mazengarb Road) and in other places the Expressway needs to be raised in part on embankments.

Local roads going over the Expressway would have required long ramps to provide reasonable grade slopes and this would have impacted on the ability to access properties beside those ramps within urban areas.

Due to the existing alignment of local roads, to carry them over the Expressway in urban areas would have required substantial realignment to address curves and sight lines on the local roads. This would have required both additional properties to be acquired, as well as changes to the scale and pattern of the existing local road network.

Local Road Interface Design

In urban areas, the concept for the local road interface design is that the public space within roads and streets should take primacy over the Expressway user experience. The local road users, who will be walking, cycling and driving on the local road, will interact with the spaces leading up to and under the Expressway. These spaces need to be designed and treated as public open spaces in their own right.

Bridge Design

The Expressway is a new feature in both the rural and urban landscapes, and by nature largely horizontal in form. It was desirable that the Expressway should achieve a sensitive fit within the built, natural and community environment, provide good connections for communities, be attractive and fit for purpose and maintain social and cultural values. In relation to bridges, this required:

- Fundamental aesthetic qualities were 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, and use of texture and colour.
- Where bridges interfaced with local roads, the concept was to translate its supporting armature of columns and beams into a single and fluid shape to simplify the appearance of the structure, rather than drawing attention to it. Therefore, the bridges should be:
  - consistent in their form so they registered as a ‘family’ and provided some visual continuity within the local environment
  - expressed as simple forms that sat across the changes in the landscape and were not seen as strong statements in their own right
  - consisted of elements like piers, cross heads, decks and barriers, which when united created one sculptural form and ensured services were concealed from view
  - of a form such that the underside was visually appealing, to recognise the primacy of the local road user’s experience in the design considerations
  - designed in such a way that the intersection of the piers with the ground was in concert with the abutment forms and materials
  - designed to enhance the quality of the space beneath the bridges, including the use of natural light penetration between bridges.

CHALLENGES

Urban Design Challenges - Holding Onto the Intent Outlined by the ULDF

Early design directives, key project outcomes, design principles and preliminary concepts are often the easier items to establish. The challenge of any designer is holding on to the intent established at the project onset, delivering on what was promised at the project inception and navigating the design through a myriad of competing factors. These include the opinions of
key stakeholders and peer reviewers, the aspirations of other design and construction disciplines, and the discovery of new information in regards to ground conditions, seismic demand, structural requirements, value engineering, construction methodologies, phasing, programme and procurement challenges, to name a few.

**Engineering Challenges**

**Challenging Soil Conditions**
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 6m thick. The dune deposits are fine, single-sized sand, with a high liquefaction potential where saturated. These conditions presented 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 presented significant challenges due to their liquefaction potential and associated settlement and lateral spreading, particularly to bridge structures due to the high ground water level.

**High Seismic Demands**
The expressway is located in proximity to the following critical active faults (SHA-M2PP (2)):

- The Ohariu fault is between 1-3km 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 30km further from the Expressway but has an estimated MCE magnitude of 8.2 at a return period of 1200 years.

**Use of Slender Members**
The high seismicity and soft soil conditions presented unique challenges to the designers, as the combined exposure of the bridges to inertia loading, as well as embankment movement due to liquefaction, presented a scenario where slender members could not be used on the project, to meet the required structural performance.

**Limiting Standardization**
The confinement of longitudinal reinforcement in bridge pier columns, and restriction on splicing the longitudinal reinforcement within the potential plastic hinge zones, severely limits the application of standardised bridge components in high seismic areas.

**Connections of Concrete Elements**
Stich/coupler connections are not permitted within plastic hinge zones in high seismic regions. The lack of widely accepted, well-developed, and proven pre-cast element connection details for use in high seismic zones was a challenge to the team.

**DEVELOPMENT OF URBAN DESIGN**

Urban design in highway projects involves creating infrastructure that is sensitive to its context, serves communities well, and has a unified architecture. The high seismicity and complex geotechnical conditions presented a number of unique challenges to the Alliance, along with ensuring urban design requirements were able to be incorporated. The M2PP Expressway has
been integrated into the landscape of the Kapiti Coast, and is located in both rural and urban landscapes. Through effective use of concrete, and refinement of the design concept to balance the aesthetic form with the local environmental and structural requirements, elegant and functional bridge forms were developed.

**Expressway Bridges**

The expressway bridges faced many challenges through the design and construction process. The urban design of the expressway bridges was established at the scheme design stage, by assessing the needs for each bridge location – urban, rural, road users, pedestrians and cyclists. Initial span arrangements and high level structural forms developed with input from hydraulic and geometric design. The architect developed initial architectural options, with an iterative process used to further develop options and discount those that were too expensive or structurally unsuitable. Urban design and landscape framework were also developed.

Once the ground conditions, seismic demands, structural and geotechnical requirements were identified, the next task was to ensure that the bridges could be constructed to the established budget and programme, while ensuring the bridge designs met the objectives and principles established in the ULDF.

During the preliminary and detailed design stages, the importance of retaining the scheme concepts was recognised by the Alliance. The structural designs were developed and detailed for seismic detailing and constructor preferences. Practical compromises were made, but overall forms and concepts were retained. Council approvals were obtained for each bridge through urban design and landscaping plans.

Figure 2. Urban design development journey of bridges from scheme stage to the construction stage

Figure 3. Shaped piers to provide continuity between superstructure and substructure with crossheads shaped to match edge of column and fascias covering the full depth of beams

Figure 4. Full height folded fascia units to outside of edge barriers to give clean elevation and reduce visual bulk
Concrete is one of the most cost-effective, durable and aesthetic construction materials, and can provide advantages over other construction materials in order to achieve desirable urban design and durability outcomes. The durability, ease of maintenance and minimal whole-of-life cost confirmed the selection of concrete for this project.

For expressway bridges, the concrete is used to achieve a consistent form, by selecting similar architectural elements that create a family of bridges that are visually appealing from all aspects, and flow naturally within the landscape in which they sit.

These common architectural features consist primarily of faceted precast-concrete facia panels that provide horizontal consistency along the length of the bridge, and architecturally-shaped concrete bridge piers that provide connectivity between the superstructure and substructure.

An additional key feature to the urban design included the textured precast-concrete facing panels provided at each of the abutments. With an exposed aggregate finish they allow the bridge form to blend into the expressway embankment and are sloped where local roads pass under the expressway to improve the openings for pedestrians and cyclists.

Spill-through abutments with more gently sloping panels are used in areas of high pedestrian and cyclist use, and more steeply sloping facing panels are used in more rural locations with fewer pedestrians and cyclists.

The bridge abutments were designed to anchor the bridges to the landscape. Rather than over designing/patterning the bridge abutments, the design used clean simple lines and angles to create interest while staying true to the design language of the bridge structure and fascia panels. The bridge approaches along local roads were designed to lead users up to, beneath, and then beyond the bridge space, so it reads as a continuous experience. An exposed
aggregate finish, using earthy aggregate colours found in the district, and in surrounding rivers, allowed the abutments to have a strong, but subtle reference to place. The use of exposed aggregate and patterned finishes to abutments was also selected to deter graffiti.

The design of the bridges as a series of concrete elements that together form a whole, allowed for the bridges to be conceived as single kits of parts. It also allowed the components to be repeated, and the same approach reused at the multiple crossings to register as a ‘family’ of bridges.

**Noise Walls**

Noise walls along the expressway are another feature that enhance the urban design of the project. Noise walls have the potential to be the most visually dominant and obtrusive elements along an expressway or road corridor, and every effort needs to be made to ensure they fit into their intended setting.

High quality concrete was selected for the noise wall on account of concrete acoustic performance, durability, weathering, ease of maintenance and vandal and graffiti resistance. Noise walls are designed to retain their noise attenuation performance for a minimum of 20 years.

The concrete walls were designed to be visually appealing and accommodate the various locations along the project while keeping a standardised element for construction efficiency. The visual appearance was created by adopting an etched design, which was recessed during the precast process using a concrete curing retarder, enabling a visually appealing pattern to be exposed on the concrete panel surface.

![Figure 6. Flexible noise wall with an etched design to accommodate different site conditions](image)

**Te Kakakura Retaining Wall**

The Te Kakakura retaining wall is one of the stand-out urban design features that is located halfway along the Expressway. The wall was completed and blessed in February 2017. The M2PP Expressway and wall bisects culturally significant land including the Grace Whānau and Ahu Whenua Trust land blocks. These comprise the last vestiges of the estate of Wiremu (Wi) Parata Te Kakakura.

The retaining wall uses patterns on the precast concrete panels to express the cultural values of the surrounding area. These panels are patterned to reflect local cultural narratives and enable the wall to be a contextually relevant feature that provides context to the local community. The lower and upper sections of the Te Kakakura retaining wall display motifs that demonstrate the cultural values of the region using the concept of a kaitaka (cloak). The motifs are embossed into the precast panels to expose the locally sourced river stone for contrast. The patterns were developed through consultation with local Iwi and community groups.
Pedestrian Bridges

The design philosophy for both the Rongomau Lane and Makarini pedestrian bridges was conceived of as sleek, fluid and sculptural in its architectural expression. The geometry of the bridges was designed as simple, yet graceful, to create a subtle sculptural quality. The cross section of the deck is trapezoidal to form a sharp leading edge to the exterior and create a sense of slenderness. The structural depth of the bridge is sloped back under this leading edge, making it appear recessive and in shadow. Both bridges share a structural system, which is comprised of a concrete slab deck supported by an internal twin steel I-beam core. These engage with concrete columns at varying spans and land on earth bunds at each end.

The superstructure of the bridges was conceived of as a high gloss black finish in contrast to the road bridges and resembles the shiny nature of black eel skin, an allusion that the bridges make. The abutments, where the bridge meets the ground, were finished with an exposed aggregate precast finish, with a black stone finish to contrast in texture with the sleekness of the bridge deck. Concrete columns were conceived as matte black, expressing an earthier and recessive aesthetic, again in contrast to the sweeping superstructure above.
Construction Challenges

Consistence Quality
Achieving the high and consistent quality, finishes of the concrete products was a challenge to the construction team. The final finish can vary significantly with a small variation in concrete mix, formwork quality, concrete pouring and curing methodology. Therefore, it was essential to develop a fluent methodology that could adapt to the changes in the process to accommodate the change in weather conditions, and keep the consistency in the finished product. The use of steel formwork, and monitoring and adjusting the mix design to suit the weather conditions, were a few key initiatives taken to keep the consistency in the finished product.

Non-Consistence Elements
Achieving the desired architectural or urban design outcomes for concrete elements, which are not consistent across the project, was another challenge. The cross-head beams with an upward tapering cantilever soffit, were not consistent across the project. A 3D model of the cross-head beams was developed to design the formwork. The reinforcement of the cross-head beams was detailed in 3D using Revit and high flow-able self-compacted concrete was used to achieve the desired urban design finish on the pre-cast cross-head beams.

High Quality Finishes
For the Te Kakakura retaining wall, the challenges were to create seamless patterns, and eliminate any unsightly rework or damage through the installation process. This was done by detailed planning, drawing the panel installation sequences in a 3D space, and adjusting the gaps and the tilt angle of each panel. The cultural significance of the wall, created a motivation in the construction team to take extra care and produce an exceptionally high quality concrete product to achieve the design urban design outcomes.

Concrete Production Challenges
Concrete mixes developed for the M2PP structures and fascia elements had to meet:

- Structural requirements - durability, strength, ability to cope with a design for high seismicity; and constructability
- Aesthetic requirements - consistency of appearance between structures, requirements for a specific surface finish or appearance and structural properties that were driven by urban design requirements

To comply with urban design demands, a mono-pile system was adopted for bridge piers that led to the construction of 3m diameter concrete bored piles to a depth up to 35m without pilecaps. To enable this, the pile concrete needed sufficient workability to allow the cage to be plunged under its own weight up to 3 hours after the start of supply; and the pier cage to be subsequently cast into the (still plastic) pile concrete. It also needed sufficient stability under pressure to resist the ingress of groundwater in the local granular soils, and to resist the egress of concrete mix water under such a high hydrostatic head. The mix proportions were developed through a series of lab trials, truck mixer trials and finally a full-scale test pile; and was at the time, the highest performing tremie pile mix developed in this region.

The operational and QA requirements to supply such large piles were in themselves stringent. Three fully staffed concrete plants, between 20 and 22 mixer trucks and three site staff were required to test concrete being supplied at a rate of 100m³ per hour.

The development of the mix formulation for reinforced concrete piers was driven by a similar set of requirements. Each pier was cast in situ without a pile cap, to integrate seamlessly with the pile below. Likewise, high seismicity required high strength concrete to be consolidated through reinforcement congestion and a uniform F5 finish was required. A high quality self-
compacting concrete mix was developed over a period of months, which went through nine trial iterations before it gave an acceptable surface finish, uniformity of colour and retention of workability.

Precast facing panels for bridge abutments and retaining walls presented an unexpected challenge in the visual density of the coarse aggregate that was required after exposing the aggregate. In other words the requirement was to see a lot of stones and very little of the sand/cement matrix that binds the concrete together. Exposed aggregate concrete mixes are not commonly pumped because pump mixes usually compromise on coarse aggregate content in favour of pumpability. In this case we explored the boundaries of both the concrete pump’s capabilities and those of maintaining a cohesive mix design, by developing a pumpable mix that had 20% more coarse aggregate than had previously been used with these materials.

ADVANTAGES OF CONCRETE USE

Originality

The complex geometry, high seismicity, soft and potentially liquefiable soils, and critical urban design demands presented unique challenges to the Alliance. This challenging environment forced the team to push for innovative solutions in design and construction of the structures along the expressway. The client, designers and constructors were able to collaborate to put existing concepts together in a new way. Some of the key innovations of the project included:

- Installing New Zealand’s first 3m diameter bored piles
- Plunging a 16-ton fully assembled column cage into the wet pile concrete to form the splice
- Installing New Zealand’s first 1,825mm deep Super T beams to span 39m on the Waikanae River Bridge – the longest precast bridge beam in New Zealand
- Prefabricating a reinforcement cage for a 29m long by 9m wide and 1.5m deep pile cap
- Creating special concrete mix designs to achieve high flow-able self-compacted characteristics, whilst controlling the heat of hydration and preventing the loss of water from the concrete due to highly permeable soil around the piles.

Sustainability

The structural form of the bridges along the Expressway was established to optimise whole-of-life costs. This was achieved using low maintenance materials such as durable high quality concrete, combined with sound engineering detailing practice and ease of constructability, to produce durable structures. Pre-cast and pre-fabricated concrete elements have been incorporated to maximise off-site fabrication, improve construction quality, reduce health and safety risks, improve durability and assist with the overall construction schedule. Exposed aggregates or feature finishes are used to reduce graffiti and to help the structures blend into the landscape.

Durability and Weathering

The durability, ease of maintenance and minimal whole-of-life cost led to the selection of concrete for this project.

The exposure environments for the project site was “B1 – Costal perimeter” in accordance with Table 3.1 of NZS 3101. The concrete cover to reinforcement/pre-stressed strands was provided for exposure classification “B2 – Costal frontage”. The concrete cover for exposure environment B2 is 10mm thicker than for exposure environment B1. The flow-able concrete mix with a high cement and fine particles content produced a dense concrete with low permeability/porosity. A dense concrete with thicker concrete cover than required for the exposure environment enhanced the durability of the structures and will minimise potential
weakening effects. The concrete members should achieve a 100-year design life and should require minimal maintenance during the in-service life of the bridges.

**Advances in Concrete technology**

The project used state-of-the-art concrete mixes including:

- Tremie concrete with fly ash to reduce bleeding and segregation, improve pumpability, control the heat of hydration, decrease permeability and improve durability of pile concrete in an aggressive environment
- Flow-able self-compacted-concrete (SCC) and semi-SCC mixes for pre-cast crosshead and Super T beams with highly congested reinforcement, to achieve a high quality surface finish, and address challenging shrinkage issues during construction
- A small proportion of polymers “Specrete SCX” was used in the concrete mix for the secant-pile retaining wall to retain the water in the concrete and keep it workable, so that pile reinforcement cages could be pushed into the concrete after the pile concrete was placed, using the Central Flight Auger method
- Noise walls were constructed using an etched design, which was recessed during the precast process using a SCC concrete curing retarder, enabling a visually appealing pattern to be exposed on the concrete panel surface
- Accelerated curing of the pre-stressed concrete beams by circulating hot water around the skin of the mould via tubes and pipes to achieve the required transfer strength within 16 hours of casting.

![Figure 11. Flow-able self-compacted-concrete](image1.png)

![Figure 12. Use “Specrete of polymer SCX” in concrete to retain water in concrete, which allowed pile cages to be plunged](image2.png)

![Figure 13. Noise wall: A visually appealing pattern by etched design](image3.png)

![Figure 14. Motifs to wall panels demonstrate local cultural values](image4.png)
**Surface finishes and workmanship**

High quality surface finishes were achieved to enhance the function, durability and aesthetics of the structures, and to reduce maintenance of the bridges. The following concrete surface finishes were achieved:

- **F5** to all exposed formed surfaces of cast-in-situ pier columns, pre-cast crossheads, pre-cast fascia panels and precast facing panels to abutments
- **F4** to all exposed formed surface of super T beams and single hollow core beams.

The workmanship of the project is evident from the high quality finishes achieved to both pre-cast and cast-in-situ concrete elements. The devotion and commitment to the workmanship of the team has provided the desired urban design outcomes.

**THE FINAL OUTCOMES**

The common architectural features adopted for the Expressway bridges consist primarily of faceted precast-concrete facia panels that keep horizontal consistency along the length of the bridges, and architecturally-shaped concrete bridge piers that provide uniformity between the superstructure and substructure.

We believe, the completed Expressway has demonstrated that desirable urban design outcomes can be achieved through the effective use of concrete in a soft landscape. Some people may appreciate the urban design of the M2PP expressway and some may not; it may be down to individual perception as “beauty lies in the eyes of the beholder”.

The use of high quality concrete has delivered structures that fit seamlessly into the local urban and rural landscape, while maintaining construction efficiency and allowing the project to be delivered to a very high standard.
The use of dense concrete with thicker cover enhanced the durability of the structures and minimised the potential for weathering effect. Exposed aggregate or feature finishes were adopted to reduce the graffiti and help the structures blend into the landscape.

The efficient use of high quality concrete enabled 40m spans using standard pre-cast beams to be achieved, and provided seismic resilience in soft and liquefiable ground by using large diameter bored piles up to 35m depth. The total volume of concrete used was around 70,000 cubic meters. The construction value of bridges is around $200 million.

FEEDBACK AND OWNER’S SATISFACTION

“The collaborative design-construct approach and attention to safety in design by the M2PP Team has delivered exceptional innovation by ensuring that the design was optimised not only for the high seismic forces but for the team’s ability to construct these large scale piles and pier columns in a manner that yielded significant savings.”

Tony Coulman, former NZ Transport Agency Principal Project Manager

“Through the early development of this project, and into the construction phase quality, connection with the community, integrity and resilience have been at the heart of the decision making process. The numerous structures and bridges which have been created for this community, are testament to these principles. Not only have we been able to provide a safe, and highly resilient network, but have taken the time to really listen, understand this community and the history which surrounds it. Each structure tells a story, and are iconic in their own right, leaving a legacy of pride, and something of real beauty behind.”

Craig Pitchford, Owner Interface Manager, NZ Transport Agency

“The Expressway involved the construction of numerous bridges, including the Waikanae River Bridge, giving us a second crossing of this significant local river. While there’s been a huge variation in construction size, concrete work has played a huge part in delivering all the bridge connections over our local roads and rivers. The bridges were a particular construction challenge for the project, but the end result has been road structures running through our community that look good and sit well in their environment.”

Patrick Dougherty, CEO, Kapiti Coast District Council

“The M2PP team worked with iwi on the design of the overall Expressway, which sits in an environment of cultural significance to our communities. The incorporation of Maori cultural motifs through the Expressway’s concrete structures, including under the bridges, is one of the results of that collaboration.”

Local Iwi Te Ati Awa, The Takamore Trust

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