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Seismic strengthening Auckland's waterfront

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ABSTRACT

Seawalls were constructed in sections between 1879 and 1925 to form Quay Street on the waterfront of downtown Auckland. These seawalls have essentially remained structurally unchanged since they were first constructed and now support the transport hub for Auckland, including ferry terminals, bus services, Britomart and the current CRL development, as well as supporting Auckland's prime waterfront buildings.

Seismic assessments of the seawalls showed that Quay Street was vulnerable to liquefaction/cyclic softening induced lateral spread. Seismic strengthening was proposed to provide seismic resilience to Quay Street for the next 100 years, providing post-disaster functionality for transportation services and protecting essential utilities located landward of the proposed strengthening alignment.

Four sections of the 600 m total length of seawalls were established and design options considered to respond to the desired outcomes in each section as well as the different seawall types in these sections, the changing ground conditions, and construction considerations including a tight construction timeframe with concurrent activities, and a wide range of stakeholder interactions. The three seismic strengthening solutions that were designed and constructed are a jet grout column shear wall, anchoring the existing seawall, and a palisade wall.

This paper presents the development of the final design solutions and the technical challenges and lessons learned from the concurrent design of the four sections of the seawall. These challenges and lessons learned included understanding the liquefaction/cyclic softening and lateral spreading hazard, developing a design methodology for jet grout column shear walls, validating pseudo-static design procedures with time history finite element analysis, dealing with constructability challenges, and undertaking staged geotechnical investigations to deliver optimised design solutions.

1 INTRODUCTION

The seawalls that support Quay Street in downtown Auckland provide the foundation for the transport hub of the city and an essential transport connection through the CBD, as well as supporting multiple key service utilities and multi-storey commercial buildings. These seawalls were built between 1879 and 1925 and have essentially remained structurally unchanged since they were first constructed. Seismic assessments of the seawalls showed that Quay Street is vulnerable to liquefaction/cyclic softening induced lateral spread (T+T, 2012, 2014) and therefore a decision was made by Auckland Council (AC) and Auckland Transport (AT) to seismically strengthen Quay Street, developing the Quay Street Strengthening Project.

As part of the Downtown Infrastructure Development Programme (DIDP), AT embarked on a revitalisation of the waterfront of downtown Auckland through a number of interconnected projects that would ready the area for the America's Cup. The Quay Street Strengthening Project was a fundamental project in the DIDP, providing seismic strengthening to Quay Street to enable an upgrade of the streetscape, a redevelopment of the ferry terminals and wharves, and the development of Te Wananga, a new downtown public space over the water.

The objective of the Quay Street Strengthening Project was to provide seismic resilience to Quay Street for the next 100 years, providing post-disaster functionality for transportation services and protecting essential utilities located landward of the proposed strengthening alignment. Quay Street and the services within it were considered essential facilities with post-disaster function, which meant that the Quay Street Strengthening works were designed to Importance Level 4 (IL4) in accordance with the New Zealand Loadings Standard (AS/NZS 1170).

This paper presents the seismic strengthening options that were selected, designed, and constructed. Explanation of the key technical challenges and lessons learned are then presented and discussed.

2 QUAY STREET SEAWALL AND HISTORIC RECLAMATION

The Quay Street seawall extends 600 m from the western side of Lower Hobson Street, adjacent to Princes Wharf, to the western side of Marsden Wharf in central Auckland. The seawall forms the harbour edge of an historic reclamation, which supports Quay Street, as well as the utility services contained within the road corridor. Figure 1 presents the location of the existing seawall and the four sections that represent different wall types and different connections with Quay Street and other projects within the DIDP. The four sections of the seawall were Princes Wharf, Ferry Basin, Ferry Building, and Queens Wharf to Marsden Wharf.

Figure 2 presents the different wall types for the sections of the seawall, determined from historic construction drawings (T+T, 2012). Princes Wharf and the Ferry Basin had the same wall type, likely constructed in the early 1920s and consisting of a mass concrete wall founded on a basalt boulder bund. The Ferry Building seawall was likely constructed around 1906 in front of an old dry dock wall that ran beneath Quay Street and is a much more substantial structure than the other sections of the seawall, being approximately 9 m high, founded on rock, and constructed of mass concrete with boulder inclusions. It also forms part of the Ferry Building foundations, going around the northern side of the building. The Queens Wharf to Marsden Wharf section is the oldest section of seawall, likely built between 1879 and 1886. This 300 m section of the seawall comprises masonry basalt blocks that were likely originally quarried from the nearby Albert Park volcano.

The seawalls were constructed to facilitate land reclamation that was undertaken in a number of stages from the late 19th to the early 20th century. Figure 3 presents an extract from an Auckland Harbour Board drawing of the dates and areas of reclamation in the vicinity of the Quay Street seawall. The extents of the different reclamations are consistent with the three different types of seawall along Quay Street shown in Figure 2.

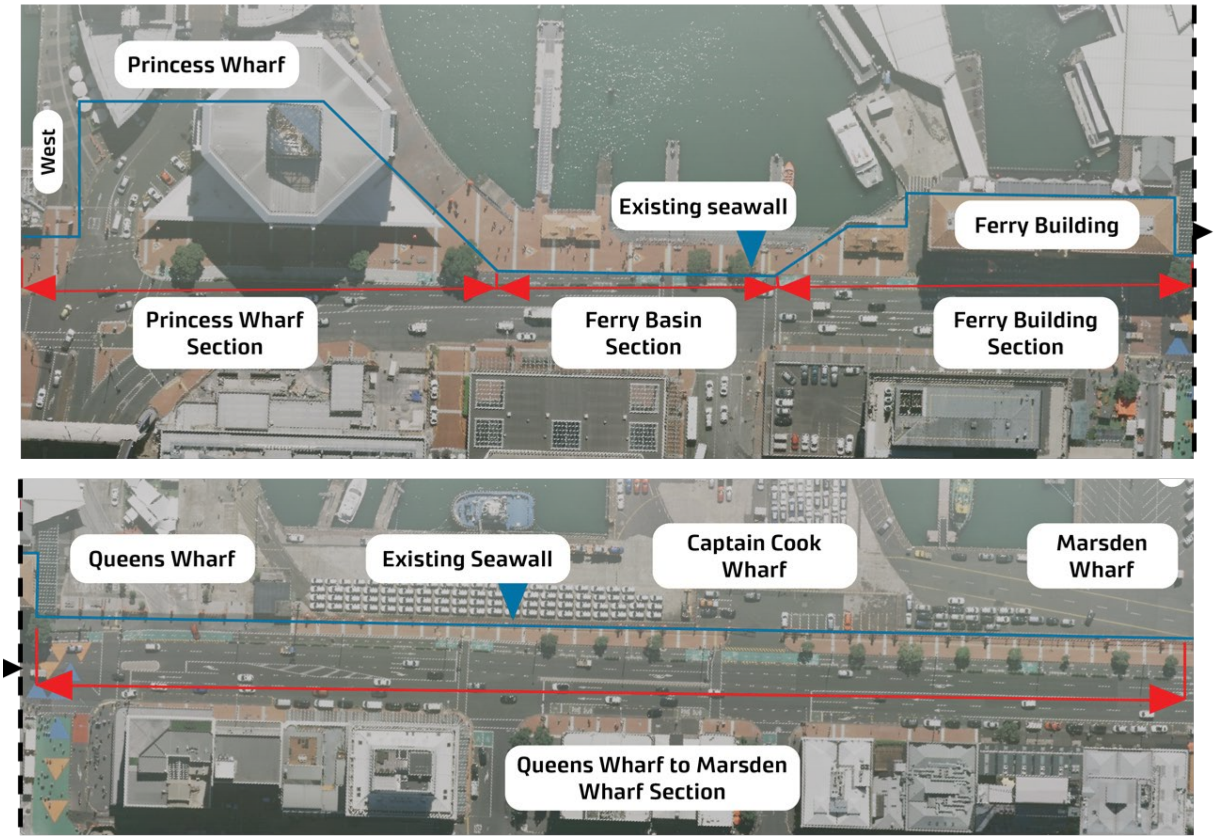

Figure 1: The Quay Street seawall in Downtown Auckland with the different sections of the seawall shown.

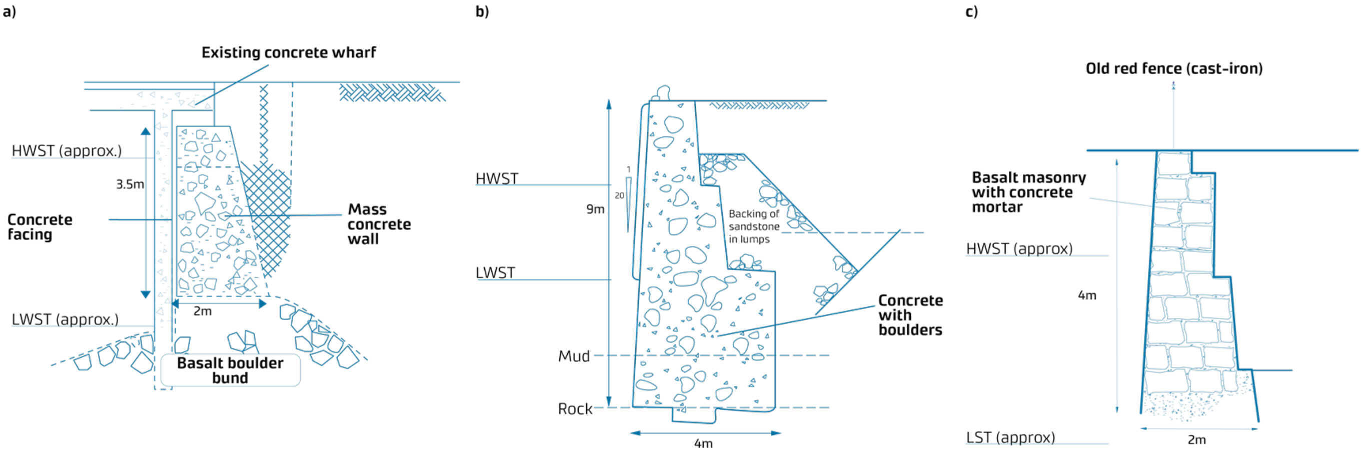

Figure 2: The different types of Quay Street seawall – a) Princes Wharf and Ferry Basin section, b) Ferry Building section, and c) Queens Wharf to Marsden Wharf section (dimensions are approximate) (T+T, 2012b).

The rock contour beneath Quay Street also likely influenced the types of wall constructed along Quay Street as it also likely influenced where the different wharves were built. Figure 4 presents a geological long section along the Quay Street seawall, developed using Leapfrog software and recent and historic geotechnical investigations. In the vicinity of Queens Wharf and the Ferry Building, the rock is at a shallow depth, diving off to the east and gradually dropping off to the west, which likely made it a favourable location for Queens

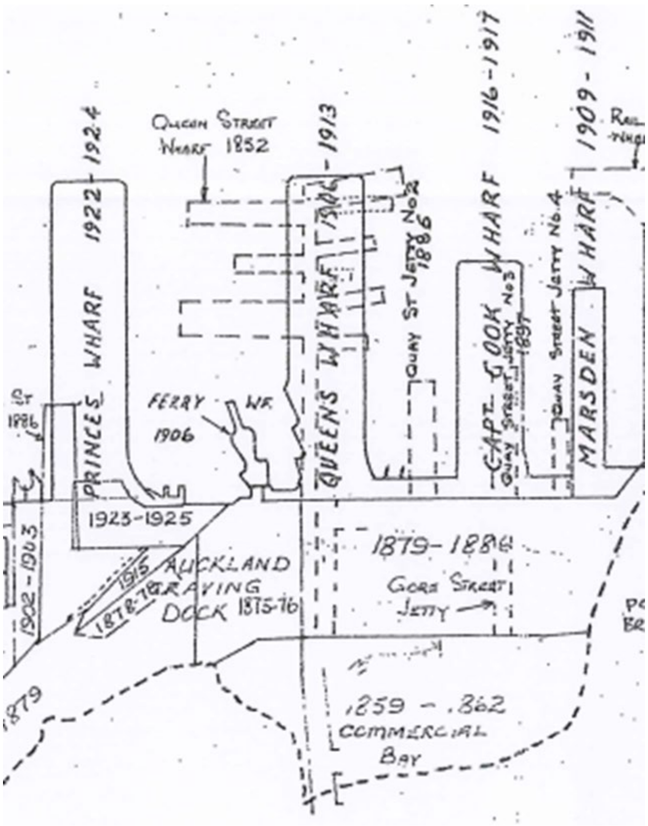

Figure 3: Dates and extents of reclamation undertaken in Downtown Auckland (T+T, 2012a).

Wharf and meant that the large seawall founded on rock could be located in the Ferry Building section. Where the rock contour was deeper, basalt boulder bunds had to be formed and smaller seawalls were built.

The geological units shown in the long section in Figure 4 and present across the site, from shallowest to deepest are:

- Reclamation fill
- Upper Tauranga Group (UTG) soils
- Lower Tauranga Group (LTG) soils
- Weathered East Coast Bays Formation (ECBF)
- ECBF Rock.

In general, the reclamation fill and UTG consist of very soft to firm silt and clay and very loose to loose sand; the LTG consists of stiff to very stiff clays and silts grading to very loose to medium dense sand and bouldery sand; and the ECBF consists of interbedded, extremely weak to weak sandstone and siltstone, which is common across Auckland.

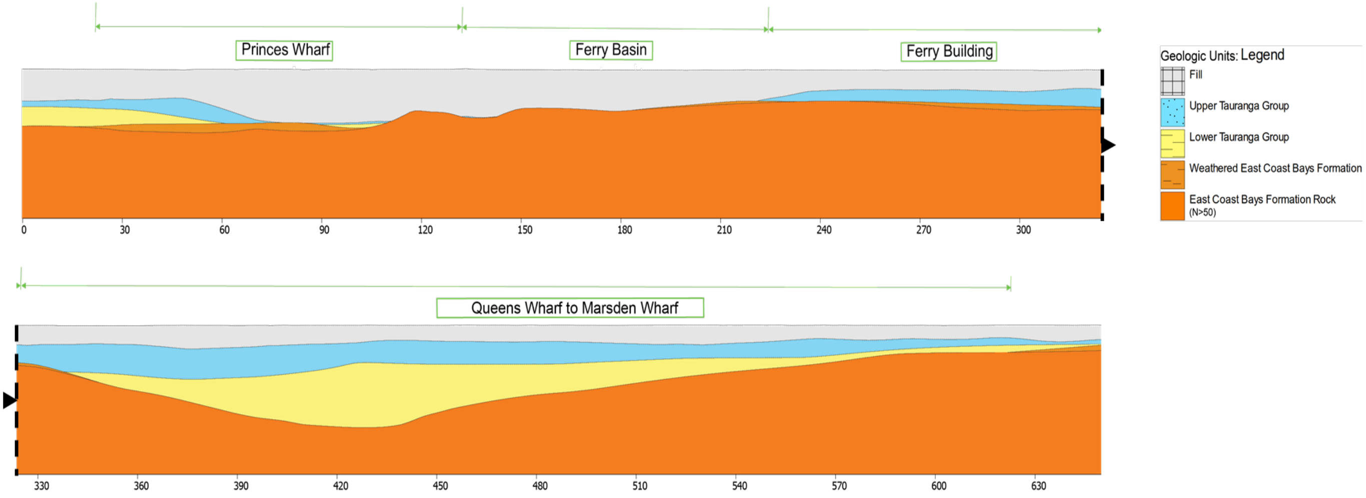

Figure 4: Geological long section along the Quay Street seawall

2.1 Liquefaction, cyclic softening and lateral spreading vulnerability

Silts and sands in the reclamation fill and predominantly in the UTG were assessed to be susceptible to liquefaction and very soft cohesive soils in the UTG were assessed to be susceptible to cyclic softening (T+T, 2019).

The triggering procedure proposed by Boulanger & Idriss (2014) was used to assess liquefaction triggering, and the triggering procedure proposed by Idriss & Boulanger (2008) was used to assess cyclic softening triggering, utilising the available CPT data along Quay Street. Seismic input parameters were determined for the project using the Waka Kotahi New Zealand Transport Agency (NZTA) Bridge Manual (NZTA, 2016) as well as a one dimensional site response analysis (T+T, 2018), which gave an ultimate limit state (ULS) design peak ground acceleration of 0.28g and magnitude of 5.9.

At the ULS design levels of shaking, triggering of liquefaction and cyclic softening was predicted to occur within lenses of the UTG soil layers and reclamation fill. Reduced soil strengths for triggered soils were estimated for each geological unit. For soils predicted to liquefy, a liquefied strength ratio was estimated to range from 0.09 – 0.095. For soils susceptible to cyclic softening, a softened shear strength of 80% of peak undrained shear strength was considered for the entire thickness of cohesive UTG, which was considered conservative for the design level of shaking given only lenses were predicted to trigger. The slope stability software program Slope/W was used to model geological sections along Quay Street and the results showed lateral spreading was likely to occur, following the triggering of liquefaction and cyclic softening.

The stability modelling suggested the likely failure mechanism would be due to the propagation of a slip surface between liquefied and cyclically softened lenses of the UTG sediments, during ULS levels of earthquake shaking. This slip surface was assessed to have the potential to extend to the southern side of Quay Street. Lateral spreading could result in evacuation of land, ground cracking, and settlement on Quay Street. It is unlikely the land would be completely lost but the movement was likely to cause damage to Quay Street, services, and buildings within and adjacent to the evacuated land. As such, seismic strengthening was proposed to resist the lateral spreading movement, protecting Quay Street and the services within it, and providing post disaster functionality.

3 DESIGN SOLUTIONS

Assessment of seismic strengthening options for Quay Street was undertaken in different stages and details of those assessments are available in a range of T+T option assessment reports (T+T, 2014, 2018b, 2018c). The first stage of options assessment involved considering whether the status quo ("do nothing") option was acceptable. That is, whether the risk of failure of the seawall and the consequences of that failure would be acceptable given current and anticipated future conditions. AT and AC concluded that the risk associated with the status quo option was not acceptable and a decision was made to address the seismic vulnerability of the Quay Street Seawall to protect the road and services within it.

The second stage was to consider the different options for the seawall upgrade once it was determined that the status quo option was not acceptable. Upgrade options were thoroughly considered through multi-criteria assessment (MCA) processes and a subsequent post-MCA option development phase. A total of 22 options were initially considered that fit into options landward and seaward of the existing seawall as well as replacing the wall.

The options were considered further with a focus on achieving the seismic strengthening within the required timeframes, being mindful of constructability considerations, and providing a robust and cost-effective solution that minimised environmental effects. Three seismic strengthening solutions were proposed in the different sections, which have been designed and constructed:

- Jet grout column shear wall – Princes Wharf section
- Anchoring the existing seawall – Ferry Basin and Ferry Building sections
- Palisade wall – Queens Wharf to Marsden Wharf section.

3.1 Jet grout column shear wall

A jet grout column shear wall solution landward of the existing seawall was chosen in the Princes Wharf section. A landward option was chosen because it protects Quay Street and the services within it and constructing an option that strengthened or was built seaward of the existing wall would be challenging beneath the existing wharf. The jet grout column solution provided advantages over other options when working around the extensive array of utilities present where the strengthening option had been proposed.

The jet grout option comprised of rows of overlapping jet grout columns forming barrettes that extended approximately 110 m along the Quay Street road reserve to form a block of improved ground, as shown in Figure 5. The design comprised 1 (No.) 1.7 m diameter seaward column and 3 (No.) 1.4 m diameter landward columns (i.e. 4 (No.) columns total per row) constructed at a maximum 1.2 m centre-to-centre spacing in the north south direction, with each row at 3 m centre-to-centre spacing in the east west direction.

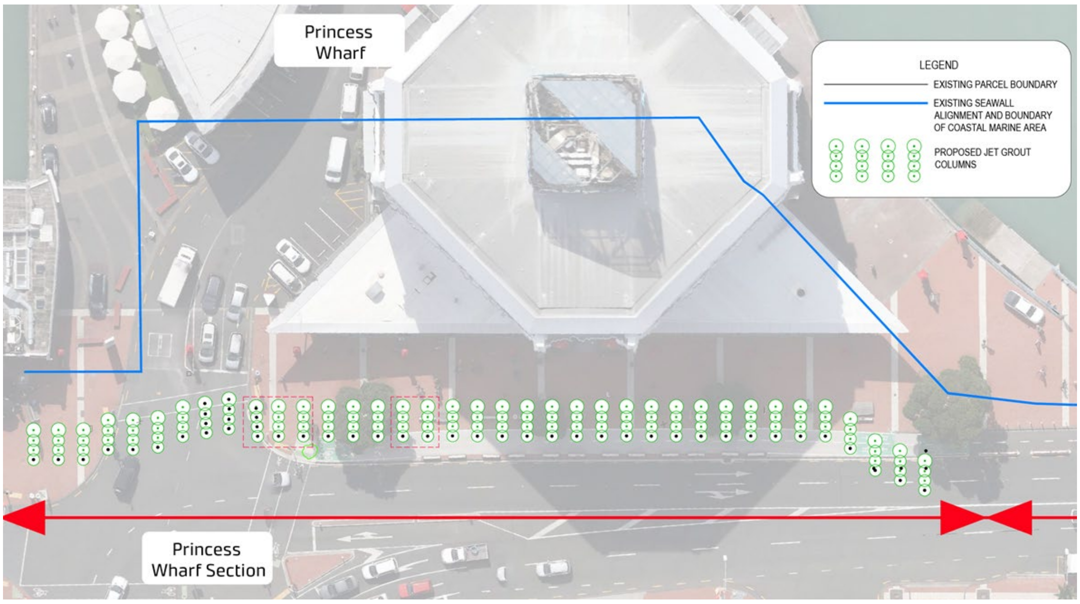

Figure 5: Jet grout column configuration for the shear wall constructed in the Princes Wharf section.

3.2 Anchoring the existing seawall

Strengthening the existing seawall by anchoring was the adopted option in the Ferry Basin and Ferry Building sections. Anchoring the existing seawall allowed for protection of Quay Street and the services within it while providing improved resilience in relation to scour effects arising from vessels manoeuvring within the Ferry Basin, and was preferred in terms of constructability and cost considerations.

The anchoring solutions in the Ferry Basin and Ferry Building sections were different due to the different wall types and cross sections of the two solutions are shown in Figure 6. In the Ferry Basin section the solution comprised approximately 45 degree anchors socketed into ECBF rock, which were connected to the face of the existing seawall using concrete encased steel corbels. In the Ferry Building section sub-vertical anchors were socketed into ECBF rock immediately beneath the existing seawall and connected to the top of the existing seawall using a recessed anchor head. In both sections rock armour was designed and constructed to prevent scour and undermining of the wall as well as provide stability to the wall.

3.3 Palisade wall

A palisade wall was designed and constructed immediately landward of the existing seawall in the Queens Wharf to Marsden Wharf section. A landward wall was preferred as it was cost-effective and could be delivered within the available programme while achieving the project objectives.

A single row of reinforced concrete piles, extending approximately 300 m along the Quay Street road reserve, formed the palisade wall. The piles were 1200 mm in diameter and spaced at between 2.4 and 3.6 m centres, socketed a minimum of 3.6 m into the underlying ECBF rock.

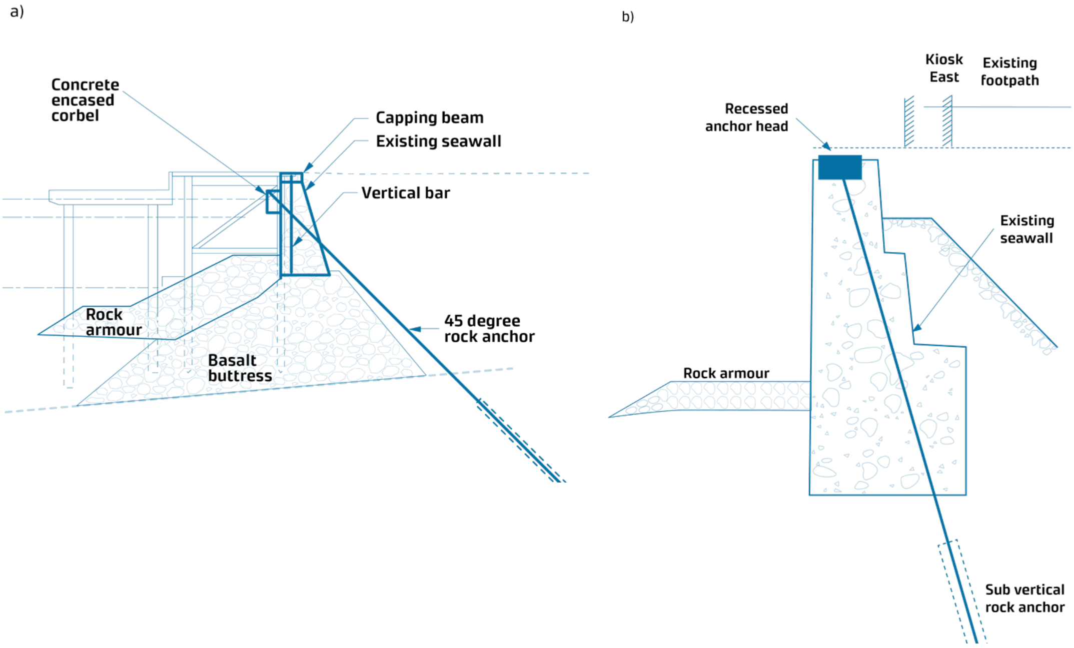

Figure 6: Cross sections of the a) Ferry Basin, and b) Ferry Building seawall anchoring solutions.

4 TECHNICAL CHALLENGES AND LESSONS LEARNED

4.1 Jet grout column design as a shear wall

The design of jet grout columns as a shear wall in the Princes Wharf section was challenging because it is not a common design approach for addressing lateral spreading. Detailed explanation of the design approach adopted is provided in Neves et al. (2020a). In general, the design approach was an adaptation of the design guidance for deep soil mixed shear walls provided by the Federal Highway Administration (FHWA) (FHWA, 2013) and involved the treated ground being assumed as an improved block of soil using an area replacement ratio methodology with inclusion of Newmark Sliding Block analysis to estimate design horizontal yield accelerations for the assumed range of permanent displacements. The design team was able to develop a successful approach using this methodology, working closely with the specialist contractors, and this was facilitated through a thorough and iterative peer review process.

4.2 Design validation using time history finite element analysis

All of the pseudo-static seismic design solutions for the different sections of the seawall were validated using time history finite element (FE) analysis using Plaxis 2D software. This was an important aspect of the design as it allowed simplified pseudo-static approaches to be validated and adopted, enabling the range of design analysis to be carried out without extensive finite element analysis, and gave insight to the expected seismic performance of the different solutions. For each of the design solutions, the time history FE analysis provided a different validation aspect that assisted with the successful design outcomes.

The design of the jet grout column shear wall used the FE analysis to confirm the likely range of permanent displacements and check internal tensile and shear stresses within the rows of jet grout columns (Neves et al., 2020b). For anchoring the existing seawall, the FE analysis was used to validate pseudo-static methodologies and estimate the likely evacuated profile seaward of the existing seawall, as well as the seawall’s displacement and potential settlement of backfill during a seismic event to assist with structural design. The palisade wall FE analysis was primarily intended to confirm the extent of evacuation seaward of the wall so that potential retention of the piles could be allowed for in the design. However, the FE analysis also provided important validation of the pile design in terms of loads, deformations, and input parameters in the simplified analysis (Neves et al., 2020c)

4.3 Constructability challenges

Challenges were encountered during construction due to the nature of the reclamation fill and the uncertainty around the extent of the existing seawall structures. These challenges were primarily for the jet grout column and anchored existing seawall solutions.

When undertaking jet grout columns, a trial is typically undertaken before construction commences to confirm jet grout parameters that can be achieved and adopted in design. However, there was not time or space to undertake a trial and so this was carried out as part of the initial phase of construction. Design parameters were initially based on jet grout columns that had been constructed at the nearby CRL development and confirmation of these was required in the early production phases. A redesign had to be undertaken during construction to allow for lower jet grout strengths achieved, reduced column diameters, and difficulties treating stiffer soils at depth. Close collaboration between designers, contractors, and the client enabled a constructed solution that achieved the project objectives.

The primary technical challenge with the anchoring solution was understanding the geometry and expected performance of the existing seawalls as well as the interaction with the streetscape upgrade and the new public space wharf. Geotechnical investigations were done through the existing seawall where access became available to confirm the dimensions of the seawall and strength of the concrete as well as to understand the founding conditions of the seawalls. Confirmation of parameters and geometry were made during construction and changes to design managed through close collaboration between designers and constructors.

4.4 Quality of historic geotechnical investigations and targeted additional investigations

The importance of quality and targeted geotechnical investigations and testing was a key lesson in the design and construction of the palisade wall in the Queens Wharf to Marsden Wharf section. The concept design included a capping beam and anchors. This was because in a critical section a thick layer of liquefying material was predicted using historical CPT data. However, this outcome was inconsistent with findings across the rest of Quay Street where liquefaction was predicted to occur within isolated lenses. Additional CPT investigations were undertaken along with additional targeted laboratory testing from boreholes, and these showed that the thick layer of liquefying material was not predicted in these investigations. The ground models were refined, liquefaction triggering analysis updated for site specific parameters, and the anchors could be removed for the next phases of design.

4.5 Palisade wall capping beam removal

The capping beam for the Queens Wharf to Marsden Wharf palisade wall was going to be challenging to construct within the project timeframe due to the presence of a large number of utility services, including high voltage power, in the vicinity of the proposed wall alignment. A decision was made to remove the capping beam on the proviso that a detailed suite of proof drill boreholes were undertaken so that the design of each pile could be confirmed.

Cored boreholes were undertaken at every third pile location and wash drilled boreholes were undertaken at every other pile location to confirm the depth to ECBF rock and critical layers predicted to trigger liquefaction and cyclic softening. Figure 7 presents a comparison between the original geological long section issued for construction and the final geological long section following the completion of proof drilling. A design check was undertaken on each pile as proof drilling results were received and updates to design zones, pile spacing, and reinforcing requirements were undertaken as required. The proof drilling also allowed for efficient construction, with the depth to rock accurately known at each pile location meaning less changes on site.

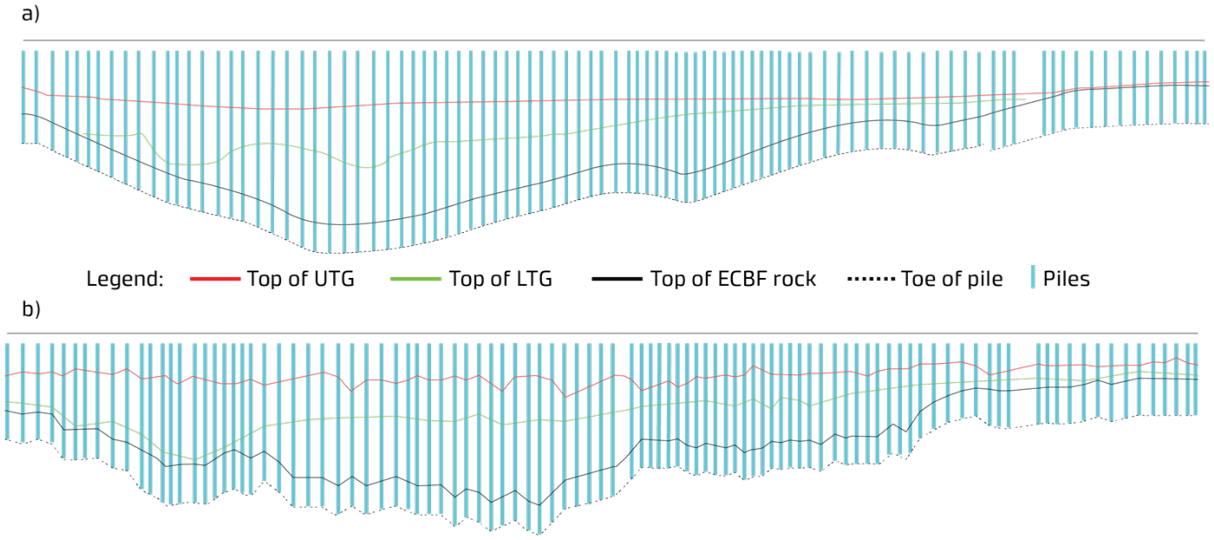

Figure 7: Geological long sections in the Queens Wharf to Marsden Wharf section undertaken a) for initial construction issue drawings, and b) following proof drilling.

5 CONCLUSIONS

The Quay Street Strengthening Project was a fundamental part of the DIDP, providing seismic strengthening to Auckland's waterfront as well as adding resilience to an essential transport connection through the CBD. The existing seawalls had essentially remained structurally unchanged since they were constructed around 100 years ago and were assessed to be vulnerable to liquefaction/cyclic softening induced lateral spread. Three seismic strengthening solutions were designed and built across the four sections of the seawall to provide seismic resilience to Quay Street for the next 100 years, providing post-disaster functionality for transportation services and protecting essential utilities located landward of the proposed strengthening alignment. These solutions were:

- Jet grout column shear wall landward of the existing seawall – Princes Wharf section
- Anchoring the existing seawall – Ferry Basin and Ferry Building sections
- Palisade wall landward of the existing seawall – Queens Wharf to Marsden Wharf section.

The key technical challenges and lessons learned in the design and construction of the three solutions were:

- Developing a design solution using jet grout columns as a shear wall – a standard approach assuming an improved block of soil was adopted with integration of a Newmark Sliding Block methodology to estimate design horizontal yield accelerations for the assumed range of permanent displacements.
- Validating pseudo-static seismic design solutions using time history finite element analysis – the different design methodologies were validated, and the likely evacuated profile seaward of the existing seawall was estimated as well as internal tensile and shear stresses within the rows of jet grout columns.
- Addressing constructability challenges – redesign was undertaken during construction to allow for in-situ jet grout column design parameters and anchored wall design adjustments made from a developed understanding of the geometry and expected performance of the existing seawall.

- Undertaking targeted geotechnical investigation and testing to address inconsistent liquefaction assessment in historic investigations – additional CPT and lab testing was undertaken to confirm expected liquefaction performance and optimise the palisade wall design solution.
- Removal of the palisade wall capping beam – proof drilling was undertaken on every pile and design zones, pile spacing, and reinforcing requirements were confirmed.

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