Sustainability in enhancing the resilience of major route in Wellington

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ABSTRACT

A case study of the design to enhance the resilience of two large retaining walls along a 220 m long alignment on Chaytor Street along a key arterial route in Wellington is presented. The paper highlights how the issues of uncertainty in the seismicity and the need for sustainability were addressed. The relative importance of the three sustainability pillars (environmental, economic, and societal/functional) were key drivers in the development of the design.

The design was carried out to the current standards based on the Bridge Manual, but also addressed uncertainty as the seismicity of Wellington, by verifying the performance of the walls under larger seismic loads based on recent studies, and incorporated features to provide resilience of access, albeit with some damage, if even larger earthquake loads are experienced.

Designing for sustainability is emerging as a key issue in design. The design provided for sustainability through two measures. (1) Building a 3-dimensional digital twin of the retaining wall comprising an integrated 3-dimensional ground and superstructure model to facilitate ongoing sustainable management of the asset. (2) Carrying out a sustainability assessment to minimise the carbon emissions associated with materials used to achieve an optimal design that reduces the impact on the climate. The design made use of the capacity of the existing unreinforced and lightly reinforced concrete acting together with a new reinforced concrete overlay to minimise concrete use, supported by post-grouted rock anchors with ductile bars to reduce the number of anchors, to both allow for uncertainty in seismicity and minimise carbon emissions.

1 INTRODUCTION

Wellington City Council has a strategy to manage the risks to its road network from natural hazards and to deal with such hazards in an integrated manner on the basis of priorities, feasibility of mitigation and the benefit/cost. Investigations, assessment and detailed strengthening design have been developed for two existing retaining walls up to 7.5 m high, along a continuous 220 m long alignment, along the critical Chaytor Street route serving Karori, a major suburb of Wellington.

The previously developed strengthening scheme comprised a reinforced concrete overlay supported by a large number of rock anchors. The detailed strengthening design considered the relative importance of the three sustainability pillars (environmental, economic, and societal/functional) in selecting the best option for strengthening the wall. Major innovations were adopted from investigations through detailed design, consultation, and provision for maintenance of the asset.

2 RETAINING WALL DESCRIPTION AND EXPECTED PERFORMANCE

2.1 Characteristics of Chaytor Street Retaining Walls

Two distinct retaining walls along a continuous 220 m long alignment are located along Chaytor Street, and support Northland Tunnel Road and Raroa Crescent above, see Figure 2.1.

Figure 2.1: Retaining Walls along Chaytor Street

The southern wall supporting Northland Tunnel Road is about 100 m long and is of reinforced concrete counterfort construction (South Wall) and was constructed in 1925, see cross section on Figure 2.3. The characteristics of the two walls are summarised in Table 2.1.

Table 2.1: Characteristics of retaining walls identified for resilience strengthening

Wall	**Location**	**Wall Type**	**Max Height (m)**	**Length (m)**	**Constructed**
South Wall	Below Northland Tunnel Road	Reinforced concrete counterfort wall	7.5	100	1925
North Wall	Below Raroa Crescent	Mass concrete gravity wall	7.5	120	1940

The northern extension supports Raroa Crescent and is an approximately 120 m long mass concrete gravity retaining wall (North Wall) that was constructed in 1940. The heights of the retaining walls vary to a maximum 7.5 m at the middle section.

The walls are bound by Chaytor Street on western side at its base with Raroa Crescent and Northland Tunnel Road and associated footpaths being supported above the wall. Chaytor Street along this section has a dedicated southbound bus lane at the base of the wall, two lanes to cater for other traffic (one each way) and a bus and car parking lane and footpath adjacent to Appleton Park on the western side. The southern portion of the wall is below a water pumping station and electrical substation on the eastern side of Northland Tunnel Road (Figure 2.2). A significant number of large utility pipes and cables are present under the Northland Tunnel Road carriageway.

Figure 2.2: Site Constraints

The retaining walls are old, and one is unreinforced and the other is lightly reinforced.

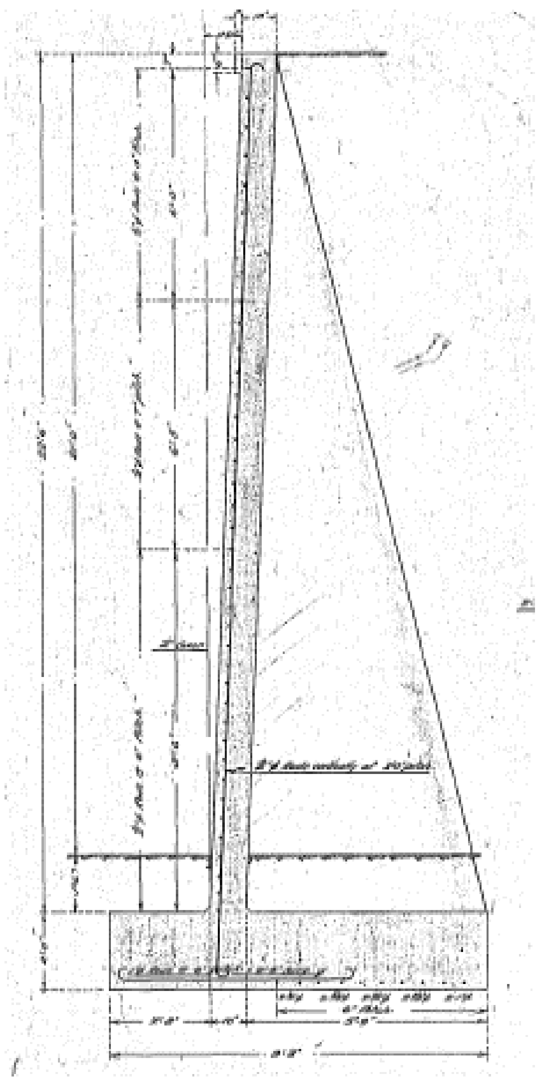
2.2 Condition of the Walls

Based on some available historic drawings for southern wall, the wall is lightly reinforced and there are no tie backs. The walls are in reasonable condition except some cracks and some depressions of the footpath above the wall, due to settlement of the backfill. Sub-vertical cracks, 30 mm to 50 mm wide at the top were observed in the South Wall opposite the pump station and substation. These appear to have led locally to a lean of the wall towards to Chaytor street. Similar but less extensive sub vertical cracks were observed on the North Wall too. Shallow depressions at the crest of the wall, opposite the junction of Raroa Crescent and Northland Tunnel Road was also observed.

Overall, the risk of significant reinforcement corrosion was assessed to be low. Chloride analyses were carried out on the concrete core samples to understand risk of corrosion of the reinforcement. The results show chloride contamination poses low reinforcement corrosion risk, given the age and wide construction joints and there is a possibility that carbonation-induced corrosion may be occurring where concrete cover depths are low.

2.3 Expected Performance

The wall has gone through various major earthquakes during its life, such as the 1942 Wairarapa Earthquakes, 2013 Cook Strait Earthquakes and, 2016 Kaikoura earthquake. Existing cracks or aggravation of existing cracks possibly associated with these ground shaking. Engineered walls with high redundancy and robustness and flexible walls for tolerance to larger displacements



survived well in Canterbury/Darfield earthquakes. However, there were a large number of retaining walls that failed in the 2010-2011 Canterbury and 2016 Kaikoura earthquakes (Wood, 2014).

1942 Masterton earthquakes caused MM VI to VII shaking in the Wellington area (Downes et al, 2001), and given the shallow rock, the shaking at this site would have been at the lower end compared to in the CBD with deeper soils and reclamation fills but may have led to the large cracks and lean of the retaining walls observed even under the modest levels of shaking. However, the reason and timing of the cracks have not been recorded. The recent 2013 Cook Strait and 2016 Kaikoura earthquakes only gave up to about 0.2g shaking in the bedrock or shallow soil areas. These levels of shaking are quite low compared to that expected in a large local earthquake.

The assessment of the retaining walls indicated that retaining walls could fail in a large earthquake event by sliding and rotational failure. The walls also have inadequate structural capacity. Such failure will remove the road platforms of Raroa Crescent and Northland Tunnel Road and debris from the 7.5 m high walls could completely inundate Chaytor Street, leading to closure of access along these three roads. Reconstruction of these walls will take a long time given the large retaining walls and a lot of utility services.

Figure 2.3: Cross section of South Wall with buttress

2.4 Consequences

The short-term impact is that access from Karori and Northland to the central business district and the regional hospital and airport will be disrupted. There are some alternative routes such as through local streets and Birdwood Street, but these would not have the capacity to serve the traffic demand and Birdwood Street itself is likely to be closed in such an event due to the steep slopes along that route. Therefore, collapse of the wall could adversely affect the resilience of access along this critical route. Using the NZTA risk management process manual, the consequence is assessed as major, because loss of access in the event of an earthquake could lead to several fatalities due to the inability to access emergency services to treat likely serious injuries or could cost \$ 1 M to \$ 10 M to replace or repair the damaged retaining walls. The rare to unusual likelihood and the major consequence of failure, gives a high risk associated with failure of the retaining walls.

3 INVESTIGATIONS

Additional Site investigations were planned and carried out along the busy route considering sustainability to minimize impacts to live traffic, dust, noise and the overall cost. An innovative approach was taken for investigation of the site, using three longitudinal lines of MASW survey carried after peak hours, supplemented by minimum number of boreholes and associated laboratory testing. The locations of the lines were critically thought through to understand the ground variability along the wall with minimum intrusive investigations.

A 3D laser scan survey supplemented by topographical survey of the site were carried out to understand the variable slope of the wall and horizontal curvature to enable 3D modelling of the walls, footpaths, adjacent structures – water pumping station and electrical substation and roading furniture like lamp poles, electrical boxes and road markings.

A ground penetration radar (GPR) survey was carried out to capture the underground services and mark-up at the site for surveying the as-built existing information.

4 DEVELOPMENT OF GROUND AND STRUCTURE MODEL

4.1 Development of Ground Model

Leapfrog – 3D ground modelling software was used to develop a ground model of the site using the topographical survey, 3D Laser Scan survey, geology of the site, borehole information and MASW geophysical ground survey. A ground and groundwater model were developed fast and effectively in full 3D using this approach. New data and interpretation were added when available and the model was updated again using originally set rules and parameters. Geological data was visualized in 3D and enabled the design team to gain visual insights for interpretation. Cross sections were cut at multiple locations using the 3D model for design. The ground model and sections were shared with the design team for design collaboration with confidence, to carry out the design and understand future construction issues.

4.2 Analyses of Failure Modes

Global slope stability was assessed without and with rock anchors using SlopeW software using the ground model and sections developed. Global stability was not critical and would be further improved significantly by the rock anchors. Local wall stability analysis was completed to check sliding, overturning and bearing type of wall failures, and to derive the design loads on rock anchors and foundations for various design cases.

Static (active) and seismic earth pressures on the retaining wall were considered. Seismic soil loads were estimated assuming a "stiff" wall, as defined in the Road Research Bulletin 814. Frictional resistance at the base of the wall and the passive resistance of the ground in front of the foundations were not considered with limited or no as-built information available.

The factored demand (axial forces) on the anchors were calculated to satisfy the sliding and overturning requirements for both static and seismic cases.

Structural detailed design of strengthening works was carried out using the loads derived from earth pressures aseismic loads.

4.3 Combined Superstructure – Ground Model

A superstructure 3-dimensional model was developed using the Revit software. Architectural features and imprints were incorporated in the Revit Model.

Finally, the Revit structural model was incorporated into the Leapfrog ground model to develop an integrated model of the walls and the proposed strengthening works in 3D (see Figures 4.1 and 4.2), and this facilitated the optimisation of the design.

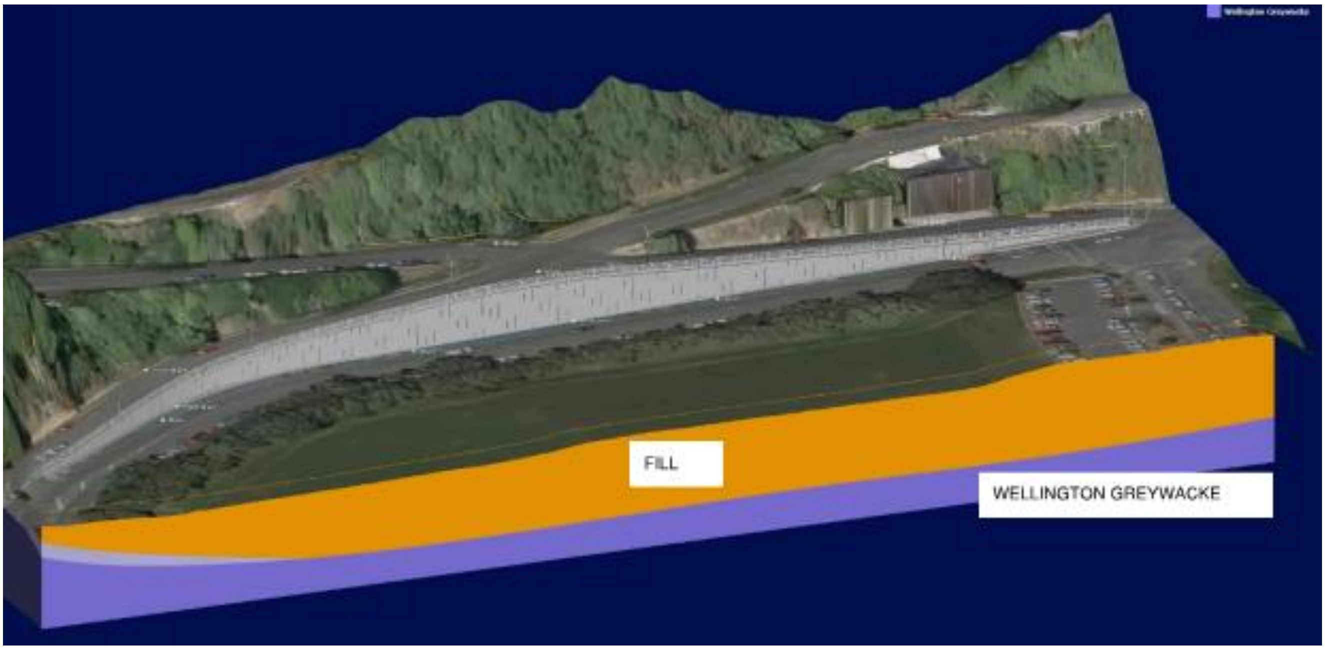


Figure 4.1: LeapFrog Ground Model

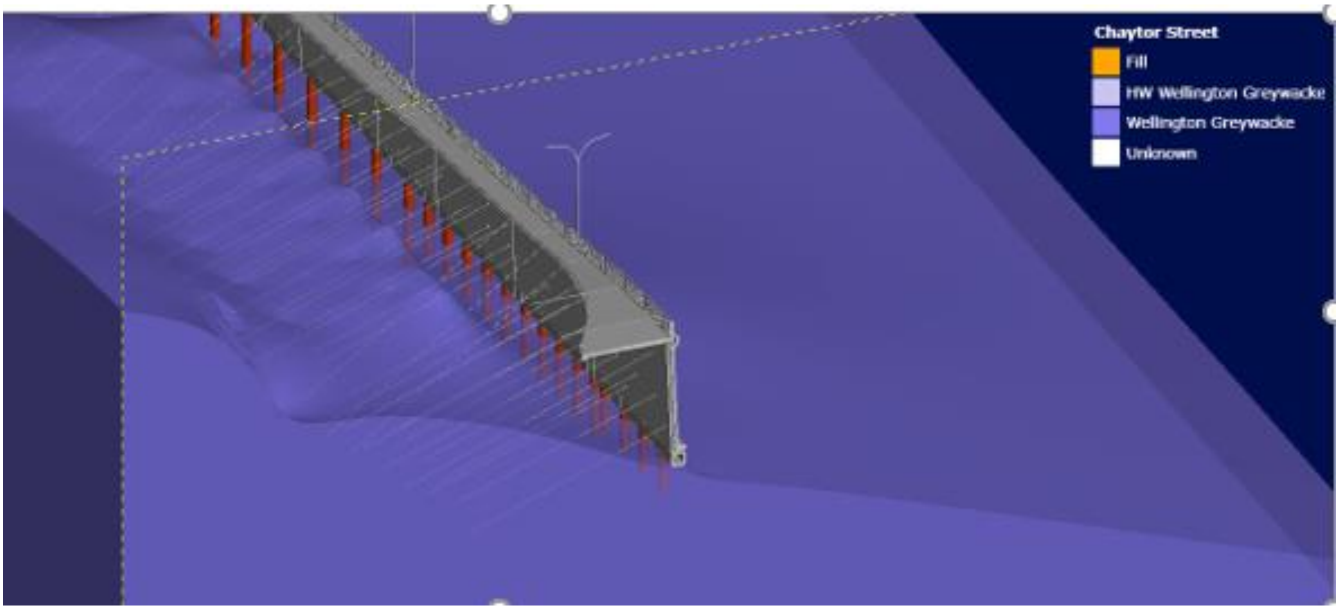


Figure 4.2: Incorporated Structural Model

4.4 Strengthening Options

Strengthening options were developed to make the retaining walls resilient to earthquakes and ensure that Chaytor Street will be protected from being inundated by debris from a failure of the wall, and the strengthened walls will protect the adjacent sections of Northland Tunnel Road and Raroa Crescent.

A sustainability and resilience-based design approach has been used. Some displacement of the walls following a design seismic event, has been accepted with some limited cracking of the road possible, however the retaining wall will provide continued support to the road in a design earthquake event and will provide continued access. The Council's strategic objective is to enhance the resilience of its road network, so that access is available for emergency services, response and recovery after significant natural hazard events.

The original strengthening option comprised forming a cast in situ wall facing with shallow footing supported by closely spaced rock anchors. This was critically investigated, in terms of the environmental, economic and functionality pillars of sustainability.

Two shortlisted detailed design options were considered to strengthen the wall:

Option A – Forming a cast in situ concrete wall facing supported by rock anchors only. Piles would be used locally where the overburden soil was deep.

Option B - Forming a cast in situ reinforced concrete wall facing supported by a combination of short piles embedded into rock and fewer rock anchors.

Typical section of the proposed design is illustrated in Figure 4.3.

Cost estimates and sustainability assessments were further carried out for the options.

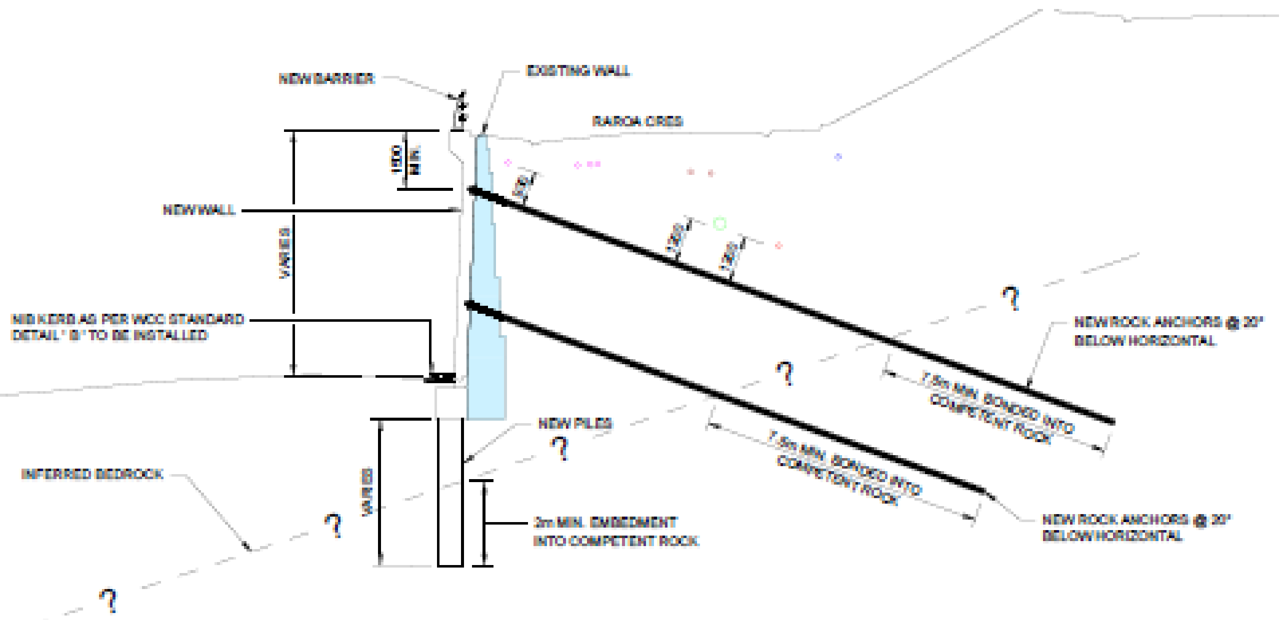


Figure 4.3: Typical Cross sections of Strengthening Details

4.5 Options Comparative Analysis on Embodied Carbon

A comparative analysis of the embodied carbon emission was carried out for the key components with a focus on the building materials like grout, concrete and steel.

The fundamental principle of an embodied carbon calculation is to assess the emissions associated with the proposed construction options. The focus of this assessment was on the embodied carbon in the materials used for the strengthening options, which was assessed by multiplying the quantity of each material by a carbon factor for the life cycle modules being considered:

material quantity (kg) × carbon factor (kgCO2e/kg) = embodied carbon (kgCO2e).

This is the carbon emissions associated with the extraction and processing of materials, the energy and water consumption used by the factory in manufacturing the products, transporting materials to site, materials wasted on site and energy used due to construction activity (also referred to as ‘upfront embodied carbon’). Suggested embodied carbon factors (ECFs) (Table 2.3, IStructE Guide – How to calculate embodied carbon) of common construction materials were used to in the assessment. The results of comparative analysis in Table 4.1 shows that Option A has about 25% higher emission than Option B. During the life cycle of the wall structure, it consumes energy and resources as well as emits carbon dioxide. This initial comparison in deciding the option is a key start on sustainability considerations.

Concrete and steel are among the most widely used resources in civil engineering, but efficient use is not always a significant consideration in design. The global production of cement has grown very rapidly in recent years, and after fossil fuels and land-use change, it is the third-largest source of anthropogenic emissions of carbon dioxide (Andrew, 2018).

Despite this, because of the longevity of these materials the whole-of-life carbon cost can be lower than other, initially less carbon emitting alternatives. Careful design with a focus on resilience and sustainability can reduce the embodied carbon associated with these materials.

Table: 4.1: Comparison of Embodied Carbon Emissions for options

Building materials	Quantity Option A	Quantity Option B	Total Embodied Carbon emission of option A ($kgC0_2e$)	Total Embodied Carbon emission of option B ($kgCO_2e$)
Rock anchors (m)	2,660	1,696	54,800	35,000
Grout for anchors (m^3)	48	31	12,900	8,200
Concrete for wall (m^3)	468	374	115,600	92,500
Concrete Strip footing/beam (m^3)	141	141	34,800	34,800
Concrete to piles (m^3)	15	31	3,700	7,700
Steel reinforcement to all the elements (kg)	93,075	73,234	185,200	145,700
Total			407,000	323,900

There are a few tools that allow a robust comparison between different design alternatives in civil engineering. The BRANZ "Whole-building whole-of-life framework" provides tools, data and information to support decision making for sustainable building design. It assists calculation of the climate change impacts and other environmental impacts of our buildings and infrastructures (BRANZ). This tool does allow a comparison between concrete and other building materials using data valid for New Zealand, but it focusses on building elements, and does not directly consider foundations, and has no data for earthworks or other geotechnical structures.

4.6 Selected Option

Option B had a lower embodied carbon compared to Option A. A comparison of the cost estimates for the strengthening using the two options also indicated that Options B would have a lower cost than Option A. Based on the comparisons, Option B was chosen for strengthening, and the final design was completed.

5 STAKEHOLDERS CONSULTATION

The Wellington community has been overwhelmingly supportive of the resilience enhancement of the road network. Traffic will be carefully managed during construction to minimise disruption to road users. Wellington City Council together with WSP have consulted with the New Zealand Transport Agency, Greater Wellington Regional Council, NZ Bus, Zealandia, and the Council management for this project, and all are supportive of this initiative.

The Council consulted with Greater Wellington Regional Council, particularly as Chaytor Street is a key bus route for public transport. The bus route/dedicated lane will be maintained during construction. Part of the footpath along the west side will be diverted into the park to enable the use of the parking lane as outbound lane from the city during construction. Strengthening the Karori route as a key emergency access route is critical for residents in Karori and Northland and the surrounding suburbs of Wellington City.

6 CONCLUSION

Safety in design is now becoming common practice. By considering safety from project conception through to decommissioning, safety is being much more deeply considered in design. The same approach should be standard practice for sustainability in design. Engineers involved in the design process have a key role to play in materials selection and design, and this gives them an ideal opportunity to influence the whole design process. This case study illustrates how a focus on resilience and sustainability facilitated the achievement of good resilience as well as reduced embodied carbon.

The materials used in the structure could be selected, re-used or re-purposed at the end of the structure's life, and where appropriate the design can be adjusted. For example, consider how piles foundations might be reused in future strengthening. Documentation of these in design features reports and assumptions, and in particular the 3D modelling and creation of a structure-ground integrated digital twin will facilitate the use in optimisation of the design, construction, maintenance and at the point of demolition.

7 ACKNOWLEDGEMENT

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