Innovative design methodology for secant pile walls

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ABSTRACT

Many infrastructure projects in New Zealand (NZ) require deep excavations in unstable granular, soft or liquefiable soil below the water table. The use of secant piles to form temporary or permanent retaining walls that support the ground during excavation and mitigate ground water inflow is becoming very common in NZ. Secant pile walls can also be used as permanent structural foundation systems. Recent developments in drilling equipment and construction procedures allow cost-effective construction of secant pile walls to tight tolerances. Optimal design of the secant pile walls increases design efficiency, reduces construction costs and reduces carbon footprint. Simplified secant pile wall design methods do not adequately capture the complex stress-strain state of secant pile walls and cannot be used for design optimisation. An innovative design methodology for secant pile walls has been developed and applied on a major wastewater project in Wellington. Non-linear steel, concrete and soil models were used in a 3D finite element analysis of the secant pile walls under static and seismic loads. The design methodology, material models and results of the 3D analysis as well as design optimisation process are described.

1 SECANT PILE WALLS APPLICATIONS

Deep excavations are often necessary for the construction of infrastructure projects and urban development. Nonetheless, deep excavations can present major risks on sites where soils are unstable, soft, liquefiable or below groundwater level. Risks include soil instability, changes to the groundwater regime, ground movement, and potential impacts on surrounding structures. These risks can result in settlement, tilting, or damage to adjacent structures, along with health and safety risks during construction. In such circumstances, implementation of some form of excavation support and groundwater control measures is required to mitigate these risks. Secant pile walls are one of the techniques commonly used to support deep excavations due to their effectiveness in stabilising excavation perimeters and their versatility in serving both as temporary lateral support during construction and as part of a permanent foundation system.

Secant pile walls can be constructed by continuous flight auger (CFA), bored cast-in-situ or micropiling techniques. The technique involves constructing secant, alternate primary (typically low-strength concrete and unreinforced) and secondary piles (typically high-strength concrete and reinforced), with the secondary piles cutting through the primary piles either side. This interlocking pattern results in a continuous, wall-like structure that forms the perimeter of the excavation area.

The design of secant pile walls depends on project-specific performance requirements. These may include requirements in terms of function (temporary or permanent), design life, surcharge loads, seismic resilience, structural capacity of the wall, deflection limits, water tightness, constructability and reducing the carbon footprint.

2 DESIGN ASPECTS

Secant pile walls may be used as temporary or permanent earth supporting systems for deep excavations. They may also be integrated as part of structural foundation systems. Therefore, all construction stages, load cases and potential failure mechanisms should be considered in the design process.

2.1 Secant pile walls as earth retaining structures

When supporting deep excavations, secant pile walls function as retaining walls constructed from ground level, with retention demands mobilised as the excavation proceeds and initially concealed beneath ground surface, thus, unsighted until exposed.

A key characteristic of secant pile walls is the interlocking joints between adjacent piles. If the interlock between piles is insufficient, it may compromise the stability of the excavation and the supported ground, thereby endangering both workers and nearby structures. Therefore, construction tolerances are key for the construction of secant pile walls. The interlock of adjacent piles and construction staging is what guarantees structural continuity, effective load transfer, water tightness and adequate support to soil excavation.

On one hand, conservative assumptions in terms of construction tolerances can lead to oversized piles and unnecessary concrete usage, which in turn results in increased costs and a less sustainable/efficient design. On the other hand, designers need reassurance that a minimum effective interlock is achieved to guarantee intended performance and durability. Designers should, therefore, allow for construction tolerances when positioning the piles while keeping in mind that restrictive tolerances may not only lead to increased costs but may also prove impractical. Collaboration between designers and contractors in the early stages facilitates a more integrated approach to the design and construction and ensures that specifications are fit for purpose. A minimum effective interlock, reinforcement requirements and pile embedment depth (below the base of excavation) are the key outputs from the design stage.

2.2 Stability of excavation

Another aspect to consider is the safety against failure at the base of the excavation due to changes in stress state of the in-situ soils during and after excavation. Should the natural groundwater level be above the base of the excavation, water ingress might occur from the base of the excavation if the secant pile walls do not extend to impermeable strata, or if a confined aquifer is present below excavation level. This ingress occurs due to the differential in water head, inducing groundwater flow towards the base of the excavation from the surrounding ground. This phenomenon increases porewater pressures at the base of the excavation, reducing effective stresses in these soils and can lead to the generation of ground heave. Additionally, inflow of water into the excavation may also cause soil erosion, in a phenomenon called piping.

A comprehensive understanding of both ground and groundwater conditions is essential to mitigate these risks. Therefore, phenomena related to changes in stress-state of soils and water regime should be carefully evaluated. Several methods are available to consider evaluation of porewater pressures, effective overburden pressures and hydraulic gradients.

If water inflow is predicted, dewatering may be required during construction. Also, buoyancy forces on permanent underground structures should be accounted for.

3 LIMITATIONS OF EXISTING DESIGN METHODS

The design of secant pile walls traditionally involves a combination of geotechnical and structural engineering principles. Limit equilibrium methods are widely used to assess the stability of secant pile walls for different construction stages and loading scenarios. This assessment involves analysing the forces acting on the wall and surrounding soil to evaluating its resistance against potential failure modes, such as sliding, overturning, bearing capacity failure and global instability. In this process, static equilibrium equations are used to determine the minimum pile embedment depths to achieve target factors of safety.

Structural design of the piles typically involves estimation of the lateral earth pressure distribution acting on the wall and calculation of resulting bending moments and shear forces. In some circumstances, such as integration of the secant pile wall into a structure's foundation system, axial loads may also be present. Beam theory is commonly used to estimate pile force envelopes used in the design of the structural elements.

Although the design approach described above is valid and suitable in certain contexts, it is important to recognise that analytical methods often rely on simplified assumptions which may not capture the complexity of the analyses required. This often includes assumptions on the use of simplified geometries, homogeneity of soils, equivalent materials in lieu of composite materials (i.e. use of homogeneous materials that approximate the mechanical response of a composite as if it were a solely uniform material), and potentially overlooking effects of construction sequence, non-linear behaviour of materials, and complex loading conditions (such as spatial distribution of loads). Also, analytical approaches often simplify the way loads are transferred to and distributed across structural elements. This can result in inaccurate assessments, particularly in structures where load paths are complex and governed by interactions between various structure elements.

Numerical modelling such as finite element or finite difference analysis is also widely used to design secant pile walls. Common practice is to represent steel-reinforced concrete element in analyses by the means of defining a shell or plate element with equivalent mechanical properties. A limitation of this approach is that it overlooks the complementary properties of steel and concrete: steel provides tensile strength and ductility, whereas concrete excels in compressive behaviour. By merging these materials into one, models may inadequately represent either tensile or compressive strength, or both, leading to an inaccurate representation of the structural behaviour, especially under complex stress-strain conditions where the load distribution between the concrete and steel elements is critical.

Furthermore, linear elasticity of structural elements is often assumed. However, this assumption may not be valid if plastic deformation of steel or cracking of concrete occur. The use of non-linear material models provides a more realistic assessment of stress-strain state of secant pile walls and enables design optimisation. Non-linear modelling of secant pile walls requires the use of numerical methods and has many advantages compared to analytical solutions in engineering problems that involve complex 3D effects, plastic deformation, extreme seismic loads, complex ground conditions etc. Another significant advantage of numerical methods is the ability to assess interaction of the superstructure, the foundation system, the ground as well as construction sequence.

4 PROPOSED DESIGN METHODOLOGY

A new design methodology has been developed for secant pile walls with steel reinforcement (wide flange H-beams) in the secondary concrete piles, instead of reinforcing cages. The concrete of the pile is represented as a 'material cluster', which consists of a group of volume elements defined by a material with a non-linear constitutive model. In Finite Element models, these groups of volume elements can be iteratively meshed and refined to achieve the desired level of discretisation, as illustrated in Figure 1. H-beams are modelled as embedded beam elements, non-linear elasto-plastic model is used for the steel (small blue dots on Figure 1).

This approach enables the designer to model non-linear properties of concrete and steel and to assess elastic and plastic deformation of steel and concrete, axial and shear stresses, bending moments, and cracking within concrete.

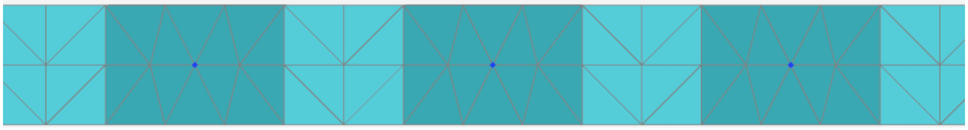

Figure 1: Example of discretisation of a concrete 'material cluster' into finite elements

As illustrated in Figure 1, the secant circular shape of the piles has been converted into an equivalent rectangular shape with thickness defined as the effective interlock thickness of the secant pile wall. The effective interlock thickness is a conceptual parameter that represents the minimum thickness of the secant pile wall, and it is calculated based on the geometric arrangement and diameters of the piles, as illustrated in Figure 2. This approach ensures computational efficiency while capturing the global response of the wall under various loading conditions without significantly compromising accuracy in the results.

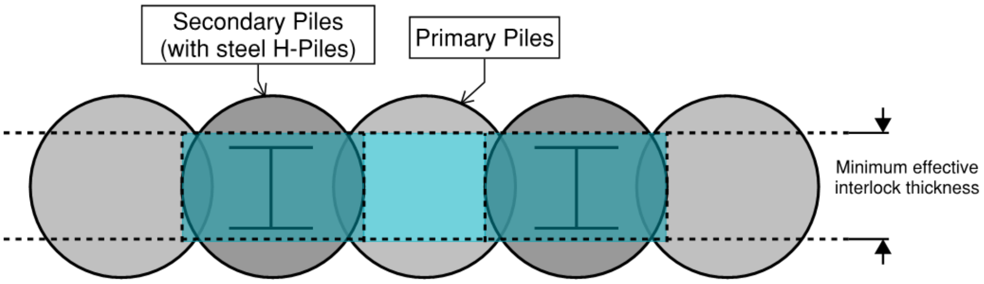

Figure 2: Effective interlock thickness of secant pile walls

The primary rationale for this modelling approach is its ability to separately evaluate the contributions of concrete and steel within the secant pile wall. This distinction is important for good understanding of the stress distribution within the piles, identification of the location of potential failure points, and ensuring that materials are effectively utilised. The methodology also enables better understanding of complex interaction and load distribution between steel and concrete and provides an opportunity for optimisation of secant pile wall design in terms of H-beam reinforcement and concrete pile sizes, lengths, spacings, and concrete strengths.

Optimising material usage not only reduces costs but also decreases embodied carbon – the CO_2 emitted during the manufacture, transport, and construction of building materials. Reducing embodied carbon emissions is crucial for combating climate change by lowering greenhouse gas emissions. Therefore, adopting optimised design practices allows the construction industry to contribute to sustainability goals and reduce its environmental impact.

5 PRACTICAL APPLICATION OF THE PROPOSED METHODOLOGY

5.1 Project context

The proposed design methodology was used to design secant pile walls on one of the Wellington Water projects. The Porirua Central City Wastewater Storage (PCCWS) development project is intended to increase the operational resilience of the wastewater network as part of Wellington Water's Wastewater Network Improvement Programme. New structures include a Storage Tank, a Pump Station, two Weir Chambers, an Access Road and Kenepuru Access Bridge. The site is located to the east of Porirua Stream and, although the area has been considerably man-modified by highway and railway construction, the low-lying western part of the site is a naturally developed wetland with high groundwater level.

5.2 Description of structures

5.2.1 Wastewater Storage Tank

The proposed Wastewater Storage Tank is a new 7ML-capacity partially buried concrete structure located at the Northern end of the site, with approximately 74 m in length and 21 m in width. The proposed foundation system comprises shear keys (reinforced concrete piles) at the northern end of the tank and a grid of CFA secant pile walls at the southern end supporting the ground slab, as illustrated in Figure 3. The secant pile wall comprises alternating unreinforced lower-strength concrete piles (primary) and reinforced with steel H-beams higher-strength concrete (secondary) piles.

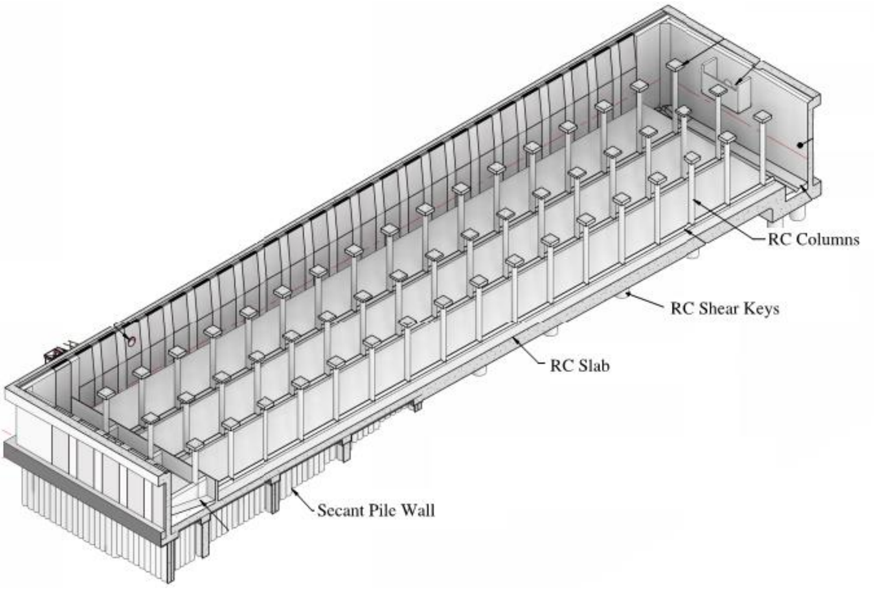

Figure 3: 3D view of the Storage Tank

Both shear keys and secant pile walls are embedded into greywacke sandstone rock. A Leapfrog® ground model is shown on Figure 4. The top 2.0m of in-situ soils have been replaced with well-compacted structural hardfill.

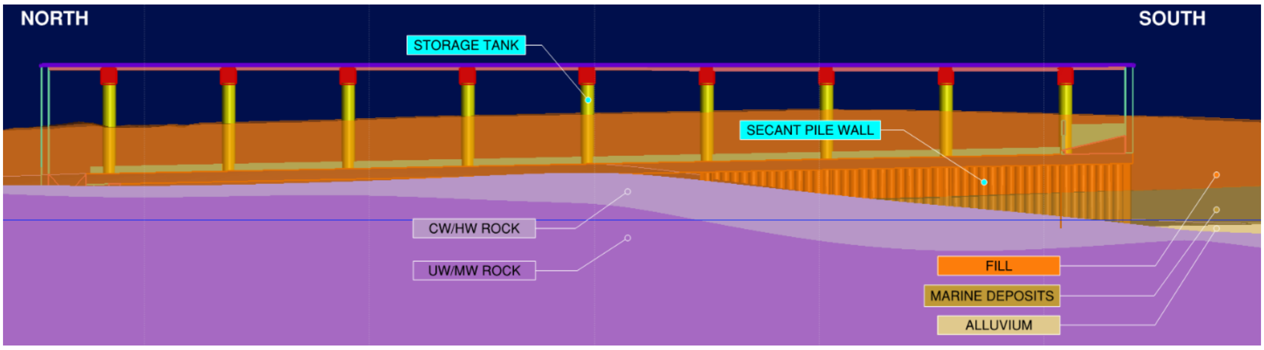

Figure 4: Ground conditions at the Storage Tank site

5.2.2 Pump Station

The proposed Pump Station comprises a 13m x 10m reinforced concrete building with a fully buried wet well underneath. The foundation system comprises of a 13m diameter circular secant pile wall founded on rock and enclosing the wet well to approximately 10m below ground surface level. There is a capping beam at the top of the secant pile wall and a wet well reinforced concrete plug slab, as shown on Figure 5. The wet well is approximately 6.6m deep and the space between the secant shaft and the wet well walls is backfilled with mass concrete.

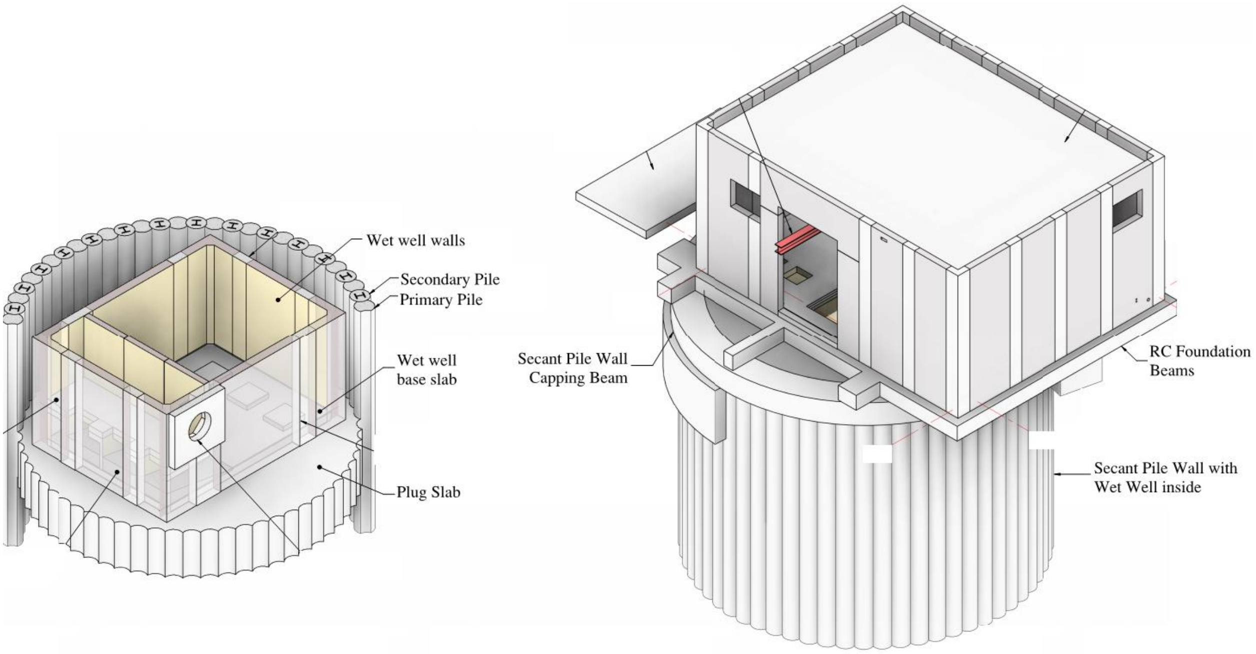

Figure 5: 3D view of the Pump Station

Piles extend deeper than the wet well base slab to anchor into the rock and provide uplift and lateral resistance. The secant pile wall has been designed for a construction phase earthquake, to allow for excavation within the wall perimeter to construct the wet well structure. A Leapfrog® ground model for the Pump Station is shown on Figure 6.

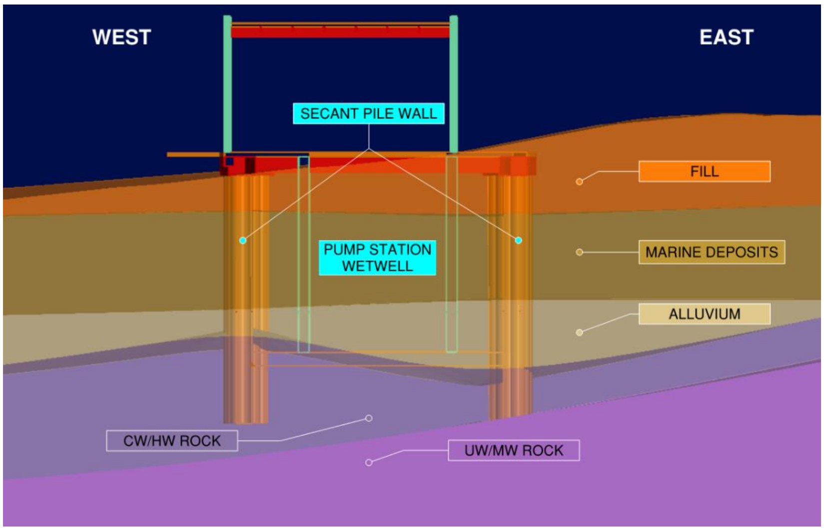

Figure 6: Ground conditions at the Pump Station site

5.3 Design requirements

The Storage Tank and the Pump Station have been designed for both Serviceability (SLS and SLS2) as well as Ultimate Limit State (ULS) earthquakes. SLS1 criteria requires that water retaining structures should not only retain its contents but also remain operational with very minor or no damage. SLS2 criteria requires that water retaining structures should remain operational immediately following a design seismic event, resulting in minimal loss of content. For the ULS event, Wellington Water requires that water retaining structures should not collapse or cause harm to people. The structures may suffer damage, but only minor leakage is acceptable, the structures should retain their content and be repairable.

The Pump Station secant pile wall should be capable of resisting active and seismic soil pressures while the excavation work for the wet well is in progress and the base slab is being poured (temporary condition consideration to ensure life safety during construction).

5.4 Liquefaction and lateral spreading

Some of the in-situ soils at the PCCWS site have been identified as prone to liquefaction and lateral spreading. Evaluation of liquefaction susceptibility and triggering indicated that the Fill (silty gravel) and Marine Deposits (silty sand) are susceptible to liquefaction with a triggering PGA corresponding to an 80-year return period event with an earthquake magnitude of 6.5 (based on MBIE Module, 2021).

Lateral spreading is expected to occur following strong earthquake shaking for both at the Storage Tank and the Pump Station sites, with estimated displacements up to 600mm in the ULS event.

5.5 Secant Pile Wall

5.5.1 Design philosophy

For the design of the foundation system, coupled SSI analysis was required for several reasons:

- Substantial complex 3D soil-structure interaction effects
- Widespread liquefaction and lateral spreading in the design earthquakes.
- Possibility of plastic deformation of steel and concrete in the seismic design cases considered.
- The need to understand post-earthquake condition of the structure.

Understanding the interplay between the ground, the foundation system and the superstructure, particularly under seismic loading conditions, was essential to develop an effective design solution and address a complex geotechnical and structural problem.

5.5.2 Design method

In accordance with the design methodology described in Section 4, finite element models of the Storage Tank and the Pump Station were developed in PLAXIS 3D® to assist the design of the foundation system and concrete slabs, understand the effects of the various construction stages, and evaluate deformations and modes of failure for the different load cases analysed. The model for the Storage Tank included the secant pile walls, shear keys and concrete slab. The Pump Station model included the secant pile wall, the capping beam (for the construction phase), plus the wet well structure (including the basement slab and walls) and concrete infill between the wet well and the secant pile wall and building slab (for the permanent case).

Steel H-beams were incorporated into the secondary piles to provide ductility and enhance the resilience of the foundation system. In accordance with the proposed design methodology, the concrete and steel of the secant piles were modelled as two different materials. Concrete of the piles was modelled as a non-linear linear material using soil volume elements ('material cluster') in accordance with PLAXIS Bulletin “Mohr-Coulomb parameters for modelling of concrete structures” (2009). Steel H-beams were modelled as elastoplastic 'embedded beam' elements with mechanical properties determined based on the manufacturer’s specifications for various steel profiles.

The geometry of the secant piles was simplified in both models to a continuous wall with effective interlock thickness, as shown in Figure 2. The structural loads provided by structural engineers for different load combinations were incorporated into the model as line loads, point loads and moments. These were applied to the structural slabs (plate elements in the models). For the Storage Tank model, hydrostatic loads acting on the slab for the full tank scenario were also considered. The performance of the proposed foundation system was analysed for permanent static and seismic load cases, and for temporary static and seismic load cases. Lateral ground displacements (induced by lateral spreading) have also been accounted for in the seismic load cases.

For the Pump Station, a temporary construction case was considered, where the secant pile wall has been constructed and excavation to the base of the wet well completed but the base plug slab has not been built. This was found to be the most critical case for the Pump Station secant pile wall.

5.6 Modelling outputs

This section highlights advantages of the proposed design methodology in terms of getting a better insight into performance of steel and concrete. For example, concrete subject to tension loads exhibited tension cut-off points where concrete elements have stresses that lie on the concrete's constitutive model tension failure envelope.

As an example of the implementation of the proposed methodology, results for the temporary construction seismic case for the Pump Station are discussed below. This stage is the most critical for the Pump Station, where the secant pile wall has been constructed and excavation to the base of the wet well completed but the base plug slab has not been built yet.

Results showed that for the seismic loading considered for the temporary construction case, concrete cracking develops in the secondary piles, with localised yielding of the H-beam reinforcement. Typical graphical outputs illustrated on Figure 7 and Figure 8 demonstrate that once concrete has failed, tensile loads are transferred to the H-beams. Figure 9 illustrates typical bending moments in the Pump Station secant pile wall H-beams for the temporary construction seismic case.

Similar shear and bending outputs were obtained for all structural components of the Pump Station and the Storage Tank foundations (e.g. piles, capping beams, shear keys).

Several secant pile wall model adjustments and iterations were required as part of the design process to develop a cost-effective design. The ability to separately evaluate the contributions of concrete and steel within the secant pile wall enabled design optimisation in terms of concrete pile sizes, H-beam reinforcement sizes, concrete pile and H-beam reinforcement lengths, rock embedment depths and concrete strength (for both primary and secondary piles). This resulted in a reduction of material usage, cost savings, and reduction in embodied carbon emissions, while meeting foundation performance requirements.

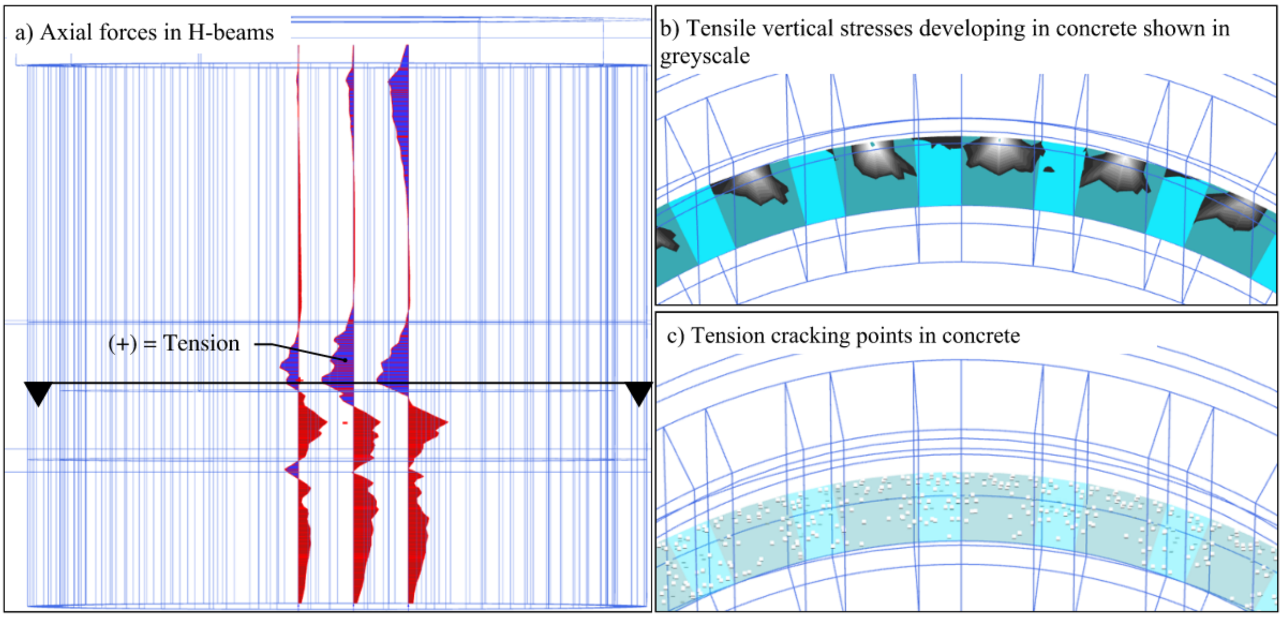

Figure 7: Typical finite element modelling graphical outputs for the Pump Station for construction seismic case: a) Axial forces in selected H-beams showing compression (red shaded) and tension (blue shaded) developing; b) Tensile vertical stresses in a concrete cross-section showing tension developing within the concrete (greyscale); c) Tension cracking points in concrete indicating middle points of finite elements where cracking has occurred

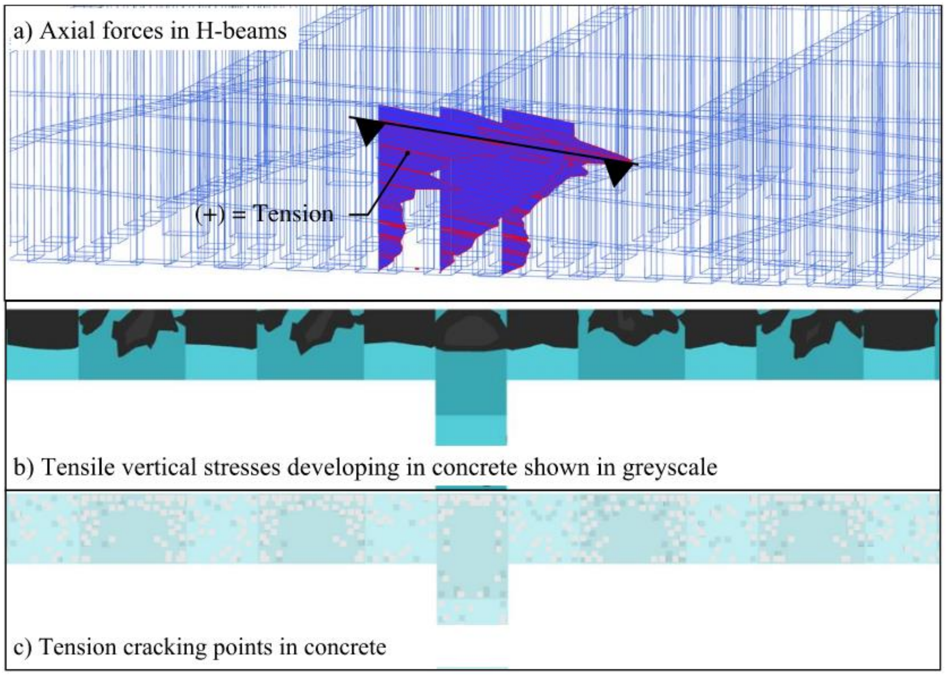

Figure 8: Typical finite element modelling graphical outputs for the Storage Tank ULS case: a) Axial forces in selected H-beams showing tension (blue shaded) developing; b) Tensile vertical stresses in a concrete cross-section showing tension developing within the concrete (greyscale) c) Tension cracking points in concrete indicating middle points of finite elements where cracking has occurred

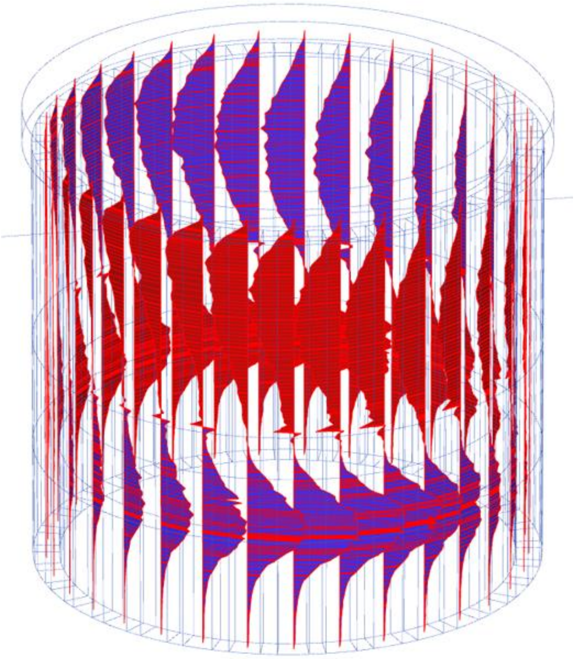

Figure 9: Typical finite element modelling graphical outputs for the Pump Station: positive (blue shaded) and negative (red shaded) bending moments in the secant pile H-beams for the construction seismic case

Analyses of the finite element modelling outputs for static and seismic construction phase, SLS and ULS cases, including wall deflections, concrete cracking and associated leakage, yielding of the steel H-beams indicated that the performance criteria were met.

6 CONCLUSIONS

Secant pile walls play an important role in infrastructure projects where retention and groundwater control are required for deep excavations. A range of design and construction risks that require careful consideration has been discussed. Existing design methods often rely on simplified assumptions, which may not capture the complexity of secant pile walls performance and soil-structure interaction effects. A new finite element design methodology for secant pile walls has been developed. One of the main advantages of the methodology is its ability to assess complex soil-structure interaction effects and separately evaluate the contributions of concrete and steel strengths.

The proposed design methodology has been successfully used on a secant pile wall project in Wellington. For the discussed project example, several secant pile wall model adjustments and iterations were required as part of the design process to develop a cost-effective design. The ability to separately evaluate the contributions of concrete and steel within the secant pile wall enabled design optimisation in terms of concrete pile sizes, H-beam reinforcement sizes, concrete pile and H-beam reinforcement lengths, rock embedment depths and concrete strength (for both primary and secondary piles). This resulted in a reduction of material usage, cost savings, and reduction in embodied carbon emissions, while meeting foundation performance requirements.

The methodology enables the designer to develop comprehensive understanding of complex interaction between soil, steel and concrete, and to optimise secant pile wall design and reduce carbon emissions.

7 ACKNOWLEDGMENTS

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