Omāroro Reservoir: A Case Study. It's Cheaper to Work with Nature.

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ABSTRACT

By all accounts, Wellington, New Zealand is a challenging seismic environment for the design and construction of infrastructure. In recent years, this challenge has increased with our deeper understanding of Aotearoa's seismic environment and reflected in the recently updated National Seismic Hazard Model. Larger seismic loads are typically leading to complex designs which result in more demanding material requirements. The result is further increased cost to local authorities in an already burdened economy.

The infrastructure industry has an urgent need to address embedded carbon, and as such, one of the designers' goals was to reduce the amount of material used to construct the tank without compromising structural resilience. This paper presents a case study where the designers "worked with nature" to develop an elegant, simple and sustainable design that resulted in cost and material savings, and constructability improvements. The paper describes the engineering philosophy that enabled these outcomes: the innovative use of a foundation system that cooperated with seismic loads rather than resisting them.

Nearing the end of its construction, and a recent addition to the water supply network, the Omāroro Reservoir is a critical piece of infrastructure, bolstering water supply to several suburbs in Wellington. The 35 million litre capacity reservoir will serve 70,000 residents in central Wellington, Thorndon, Newtown, Mount Cook, Hataitai, Kilbirnie, Miramar, Strathmore and Seatoun including Wellington Hospital. Also of importance, the Omāroro Reservoir will increase the emergency supply of water from 24 to 48 hours' if the main supply from the Hutt Valley is cut.

1 SETTING THE SCENE

1.1 Seismic Environment

The seismic environment is one of the most challenging in the world, particularly as it pertains to an engineering design perspective. Routinely, designers are having to design for PGAs of over 0.6g in New

Zealand. For comparison, all of the horizontal PGAs recorded during the Canterbury Earthquake Sequence were less than 1g and most were less than 0.3g.

In 2020, the PGA for geotechnical design for the Omāroro Reservoir was calculated to be 0.59g for a 2500-year return period as per the MBIE/ NZGS Modules 2016 (Holmes, 2020). In 2021, the MBIE / NZGS Module 1 was updated along with recommended PGAs for all Site Subsoil Classes, and today, that value would be 1.27g; an increase of 114%. Note that at the time of the 2021 update of the MBIE / NZGS Module 1, it did not include the results of the National Seismic Hazard Model 2022 (NSHM 2022) as it had not yet been completed. Based on the authors experience, it is likely that a PSHA (Probabilistic Seismic Hazard Assessment), based on the current NSHM22, and carried out today in the Wellington Region, would result in a similar or higher value of PGA.

Most simplified calculation methods that are used by engineers in New Zealand, are not applicable for accelerations greater than 0.7g. Additionally, even if more complex calculations or analytical tools were used, there is not a great body of case history for structural performance at these high values of PGA. Designers are often left to engineer from first principles in an area of little precedence. Such was the case for the Omāroro Reservoir.

Our understanding of the seismic hazard has improved and increased significantly. However, regarding the design aspect, we still work with simplified and partially outdated methods. To face the challenge, understand and mitigate new issues we need to step up the analytical complexity before we are able to accept newly developed design methods that are suitable for these high magnitudes of acceleration.

The Navy Seals have a resilience motto: improvise, adapt, overcome – this also makes sense for engineering challenges. If we don't adapt the design to the new seismic hazard then this will result in overly conservative designs at the cost to affordability and sustainability.

1.2 The Omāroro Reservoir

The Omāroro Reservoir is a reinforced concrete tank which is approximately 70 m in diameter and 14 m in height (top of roof to top of slab) and holds about 35 megalitres of water. For comparison to a volume that we're typically more familiar with, that's about 14 Olympics sized swimming pools.

The tank was constructed by cutting a platform into the ridgeline at Prince of Wales Park, constructing the tank and then completely burying it. The main purpose of burying the tank is to preserve the aesthetic of the Wellington Town Belt.

The purpose of the reservoir will be to make water supply more resilient for both normal operational needs and in the event of a natural disaster or disruption in Wellington. The tank is Importance Level 4 (IL4) and the design ULS (Ultimate Limit State) is equivalent to a 5000-year return period. The ULS requirement for the reservoir means it may suffer some damage following a 1 in 5000-year seismic event and may no longer retain water but will not collapse or allow a catastrophic release of water that could cause harm to people.

At the time of writing this paper, the 'practical completion' milestone of the Omāroro Reservoir was recently achieved, and the reservoir has been completely covered over with engineered fill and landscaped for park use. A 3D View of the Omāroro Reservoir is show in Figure 1.

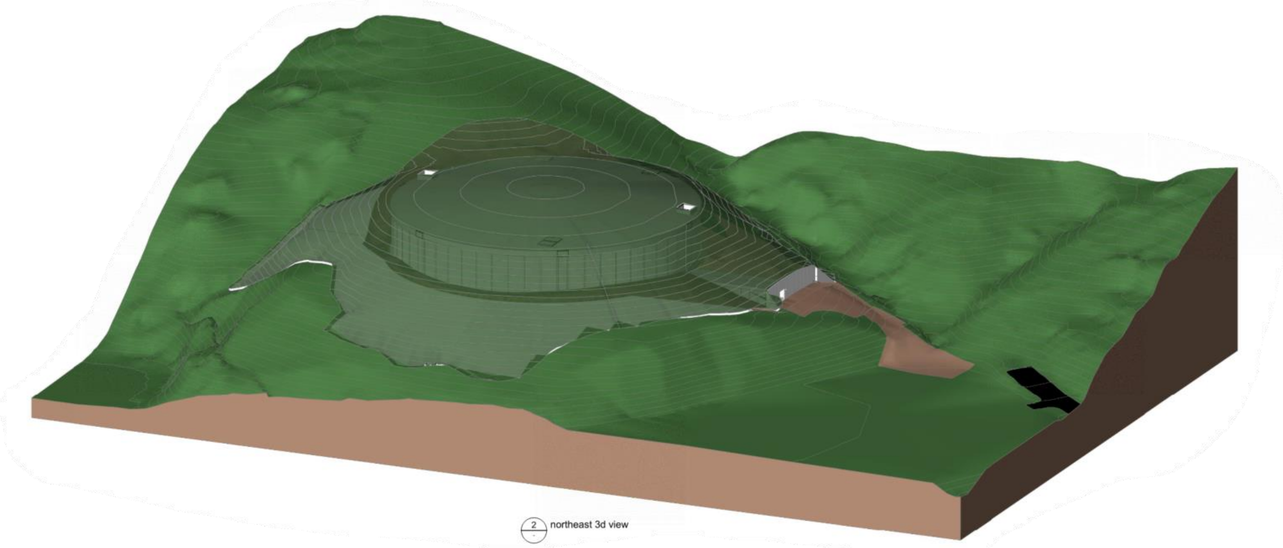

Figure 1: Northeast 3D View of the Omāroro Reservoir (Holmes, 2020)

1.2.1 Ground Conditions

The ground model (Moniz et al. 2020) for the Omāroro Reservoir shows that the ground conditions generally consists of Greywacke bedrock with various degrees of weathering. Site visits between November 2020 and June 2021 by Holmes confirmed that the founding conditions for the tank comprise moderately to slightly weathered greywacke bedrock.

2 THE DESIGN

The Client's Consultant's Design for the Omāroro Reservoir proposed that the reservoir should be founded on a grid of ground beams and shallow pad foundations. The intention of the Client's Design was that the lateral loads on the reservoir would be transferred through the shear keys to the underlying and surrounding Greywacke rock. This would essentially create a 'locked-in' structure where the seismic resistance is dependent on the integrity of the foundations. As such, these foundations would be rigid, and all actions, including dynamic load peaks, would be captured by the structure and transferred into the foundations. A sketch to describe the seismic resistance mechanism is presented in Figure 2.

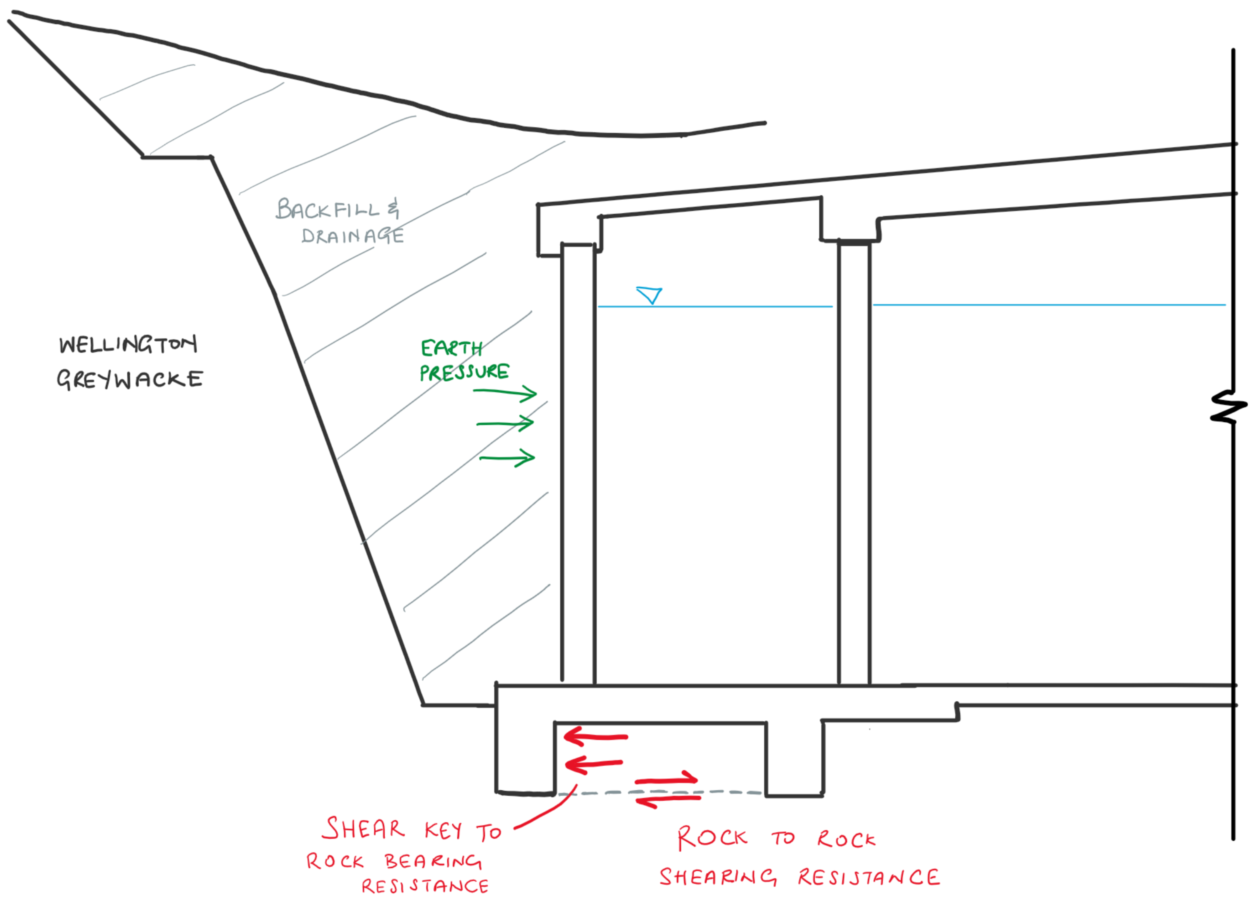

Figure 2: Client's Seismic Design Philosophy

Holmes, through the tender process of an ECI type contract, developed an alternative solution for the reservoir structure. The seismic philosophy of the Holmes design was to 'work with nature' i.e. let the tank move in a seismic event. The seismic forces from the design earthquakes are so large such that the shear forces generated along the underside of the tank would not be sufficient to prevent the base of the tank from sliding (i.e. the Factor of Safety against sliding would be less than 1). Allowing the tank to slide in these design seismic events reduced the lateral forces on the walls of the tank and allowed for a more efficient tank design. By placing the reservoir on a slab foundation and allowing the tank to move by sliding, the resulting earth pressures on the wall and roof were significantly reduced. This resulted in the need for less reinforcing and smaller sections for the walls and roof. A sketch to describe the Holmes seismic philosophy for the tank is shown in Figure 3.

To facilitate sliding at the foundation level, we placed 2 layers of High Density Polyethylene (HDPE) below the underside of the tank. The peak interface friction angle required to allow sliding in these design seismic events along the underside of the tank was calculated as 25°. It was assumed that in order for base-sliding to occur in the design seismic event (i.e. to maintain an interface friction angle underneath the tank of $\delta < 25°$) then one or multiple layers of base membrane may be required underneath the tank foundations.

Large scale in-situ tests were carried out on site to confirm this design assumption. The results of the friction tests indicated that 2 layers of HDPE would provide an interface friction angle that allows for sliding in a design ULS seismic event.

To manage the predicted sliding displacements, careful detailing of sumps and some minor adjustments to flexible connections were carried out; many of these details were already planned in the original design to pipework.

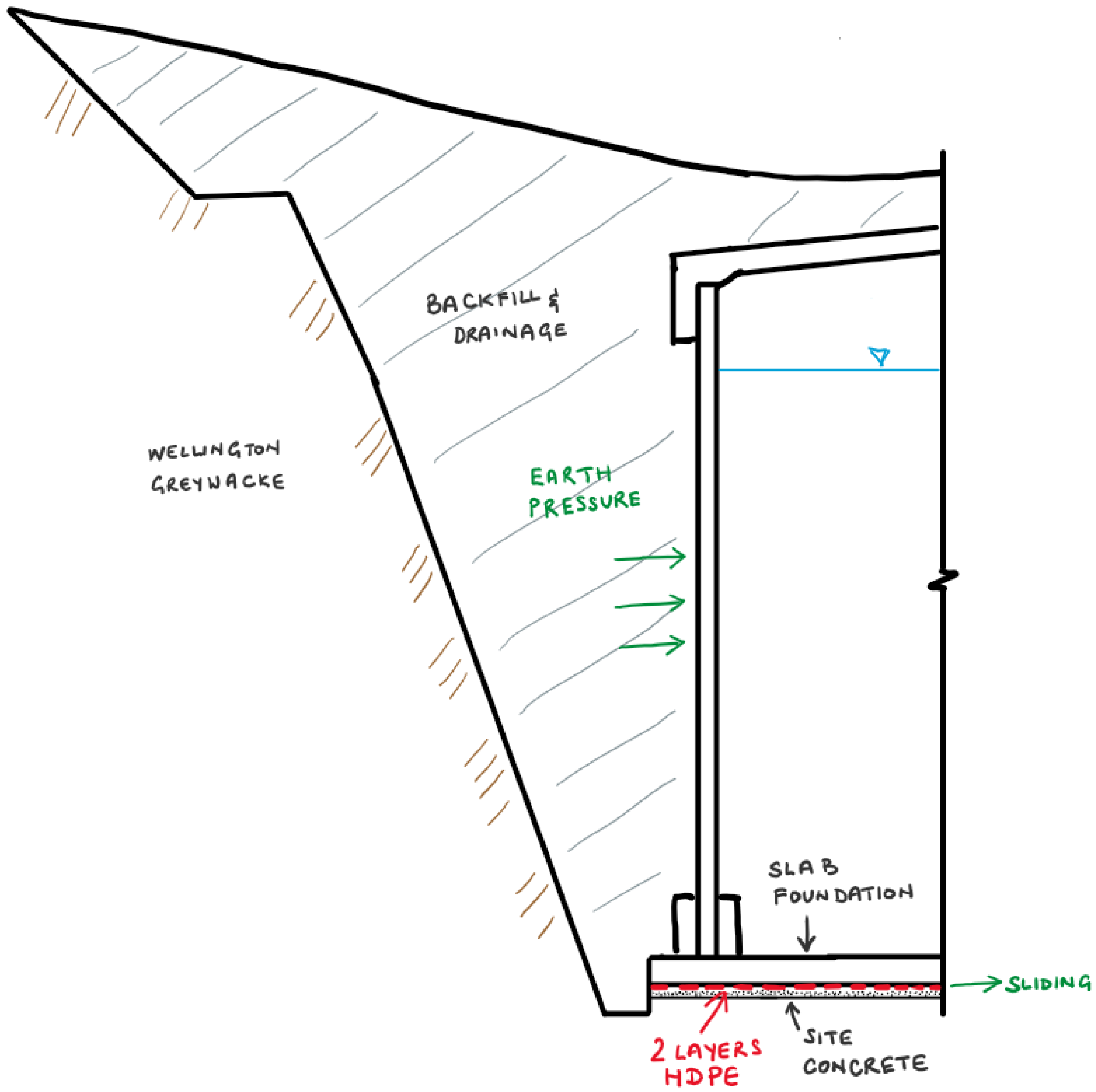

Figure 3: Holmes' Seismic Design Philosophy

2.1 Analyses and Results

To determine the lateral earth pressures on the tank wall and predicted displacements during the various design seismic events, we carried out dynamic time history finite element analyses using the program RS2 by Rocscience. The model used is shown in Figure 4. Sensitivity analyses of the model were carried out on the joint normal stiffness, friction angle, shear stiffness, rock UCS, rock GSI, rock Young's Modulus, rock Poisson's Ratio, Filtering Frequency and the base material friction angle. Out of those listed, the Young's Modulus of the Moderately Weathered Rock had the biggest impact on the resulting earth pressures and sliding displacements. For design, we used the Young's Modulus based on the Shear Wave Velocity Testing.

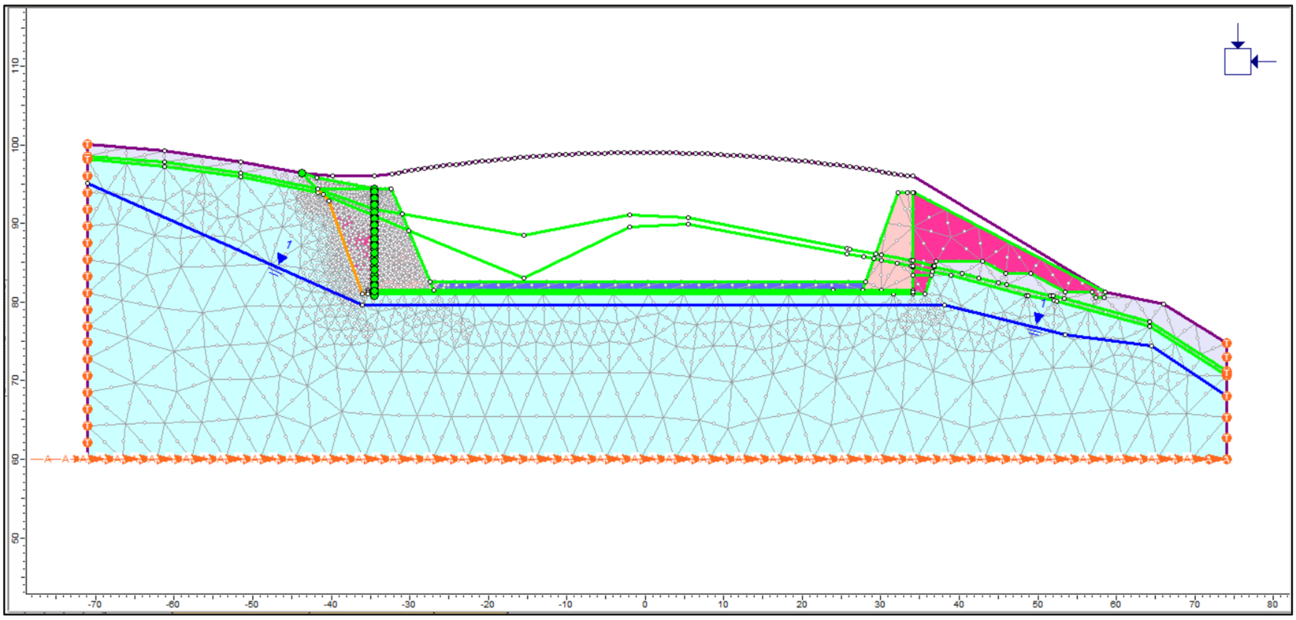

Figure 4: Finite Element Model (FEM) used to assess earth pressures and displacements.

The results of the analyses showed that the earth pressures on the tank significantly reduced with even modest levels of displacement (<10mm).

3 SAVINGS AND EMBEDDED CARBON

By all accounts, the seismic design philosophy described above was not revolutionary nor convoluted; on the contrary, the change in design was simple and uncomplicated. It allowed the structure to move with the forces, attract less load into the various elements, allowing for smaller structural elements. The reduction in member sizes resulted in a reduced need for steel and concrete for the project. The reduction in the volume of concrete required was 2500 cubic metres, equivalent to almost 1,000 tonnes of CO2 emissions of cement and 680 tonnes of steel, equivalent to almost 1,300 tonnes of CO2. (*See Table 1**Error! Reference source not found.**)*. Added to the material savings, reducing the need to cut shear keys into the rock resulted in a reduction of 9000 cubic metres of cut and 6000 cubic metres of fill required at the site.

Moving from shear keys cut into the rock, to a slab foundation, also eliminated the need to cut circular strips into the rock which would have been time consuming and tricky to construct. The reduction in materials and labour required, equated to about a 3.5 month saving on the construction program.

The total CO_2 emissions was calculated to be approximately 2,400 CO_2. To offset emissions of this magnitude, this would require planting about 25,000 trees over 25 years (https://treesthatcount.co.nz).

Table 1: Summary of the significant test properties.

Item	Reduction in quantities and programme	Comments
Concrete	Reduction in concrete volume = 2500 cubic metres	Manufacture of 1 tonne of cement is equivalent to ~1 tonne of CO_2 emissions* Every cubic metre of concrete includes circa 400 kg of cement.
Reinforcing steel	Reduction in steel tonnage = 680 tonnes	Manufacture of 1 tonne of steel is equivalent to ~2 tonnes of CO_2 emissions**
Excavations	Reduction in cut volumes = 9000 cubic metres	Significant savings in CO_2 emissions
Fill	Reduction in fill volume = 6000 cubic metres	Significant savings in CO_2 emissions
Programme	3.5 months	Shorter construction related disturbance to local community and environment
Total		Approx. 2,400 tonnes CO_2.

*Fayomi et al., 2019.

**World Steel, 2020.

4 DISCUSSION

The instinct to design structures to resist loads was born out of decades of engineering based on the principle of limit equilibrium, i.e. Factor of Safety must be greater than or equal to 1. It is also common for engineers to teach other engineers how to carry out calculations using the same method they learned; engineering methods get passed down through generations. However, the seismic environment that we're operating in is very different than it was 20, 10 and even 5 years ago. The seismic loads that we engineers are being asked to design for, are some of the largest in the world. Designing with the same thinking that we used, will lead to bigger structures, more concrete and steel, but to what end?

With seismic loads having more than doubled in some regions of Aotearoa, we need to change our thinking from trying to hold things in place, to allowing them to move and embracing a displacement-based approach, possibly in areas that we haven't done before. Working with nature, and working with loads, instead of against them, may allow us to reduce the size of structure required, as was shown in the case study presented in this paper.

4.1 A note on resilience

The definition of resilience, according to the Merriam – Webster dictionary is: *an ability to recover from or adjust easily to misfortune or change*. This case study challenges the reader to question what 'resilience' looks like for their project. Does it necessarily mean stricter performance requirements resulting in a bigger, stronger, but more expensive structure? Or is there room for another interpretation of resilience? One where movement and limited damage is accepted and incorporated into the design generally resulting in smaller, lighter and more flexible structures.

5 CONCLUSIONS

Given the seismic environment that we're in, where we're routinely having to design for >0.6g, it requires us to think about resilience and failure in a different way.

In this case study we see the benefits of working with nature and allowing structures to move. This paper encourages the reader to question: (1) question if FoS < 1 actually means 'failure', (2) understand if allowing movement would be tolerable for the structure and (3) discussing what resilience actually means for the project.

6 REFERECES

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