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RE-LEVELLING & BASE ISOLATION RETROFIT OF THE CHRISTCHURCH ART GALLERY

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Abstract

In the aftermath of the 2011 Canterbury Earthquakes, higher building performances were demanded by building owners in order to protect non-structural components and building contents, which many times can be valued more than the building itself. In the case of the Christchurch Art Gallery, the building structurally performed well and was used as the emergency operations center for the New Zealand Civil Defense and the Canterbury Earthquake Recovery Authority (CERA) after the 22 Feb 2011 earthquake. However, damage did occur, in the terms of deep liquefaction which caused the Gallery to experience differential settlement and damage to some of the art collection due the high acceleration experienced inside the building.

This paper presents the drivers, benefits and methods of an in-ground solution of re-levelling the Art Gallery and subsequent retrofitting base isolation to the Gallery’s super-structure. This solution was desired by the Christchurch City Council in order to ensure the future safety of the valuable art collection and the Art Gallery’s ability to continue to serve as the center of art and culture in Christchurch and the wider Canterbury. When completed in December 2015, this will be the first base isolation retrofit on South Island.

Keywords: Christchurch Art Gallery; in-ground re-levelling; base isolation retrofit; Christchurch Rebuild

1. Introduction

1.1. Description of the Art Gallery Building

In May 2003 Christchurch Art Gallery Te Puna o Waiwhetu opened on its new central city site, on the edge of Christchurch's historic cultural precinct. It quickly became a well-known icon and jewel in the Christchurch City Council crown. It is recognized as a key public facility in Christchurch, an integral part of the city's identity and key to its brand. The gallery is an important part of the cultural life of the city and New Zealand as a whole. It is a place to where local, national and international visitors return again and again.

The building houses nine exhibition areas, a reference and study library, multi-purpose auditorium, education workrooms, an underground car park, a restaurant, retail outlets and extensive collection storage spaces. Along the building frontage on the west elevation is the iconic large-scale sculptural glazed façade (see Figure 1) enclosing a large full height foyer space and looking out onto a forecourt area which incorporates permanent sculptures and landscaped areas.

Figure 1 - Seismic trench construction adjacent to the iconic western sculptural façade

(Image Courtesy of Christchurch Art Gallery Te Puna o Waiwhetu. Photographer: John Collie)

1.2. Canterbury Earthquake Sequence

The Art Gallery was subjected to a number of earthquakes and aftershocks during the 2010-2012 Canterbury Earthquake Sequence. In general the building withstood the earthquakes much better than many other buildings in the city and was commandeered as the earthquake operations center for Civil Defense following the February 22nd 2011 aftershock that caused devastating damage to the Christchurch CBD.

The Christchurch Art Gallery welcomed 4,381,034 visitors between its opening and the 22nd February 2011 aftershock. It was then closed to the public until it was retrofitted, repaired and reopened in December 2015. During this period, essential services were maintained within the building and the gallery's collection of art was put into storage in order to allow repair and strengthening works to be carried out.

The building suffered moderate widespread damage as a result of the earthquakes. Differential foundation settlement reduced the buildings capacity to tolerate further settlement, the glass façade sustained extreme face loading forces with significant displacements and vertical accelerations causing the façade to lose some of the vertical hanger supports. Building services were damaged and precast panel parapet cladding connections and support structure was severely damaged.

1.3. Why Re-level the Building?

The Christchurch Art Gallery suffered differential settlement due to deep liquefaction which 'bent' the basement level parking garage structure. This bending induced stresses in the elevated ground floor slab. The greatest settlement occurred on the backside (east) of the Gallery structure with a displacement of 150mm (See Figure 2). A secondary low point was located on the Montreal Street (west) side of the basement with a displacement of 50mm. This created a relative high point in the middle of the gallery's forecourt. All viewing galleries in the building subsequently also had a slope to the floors.

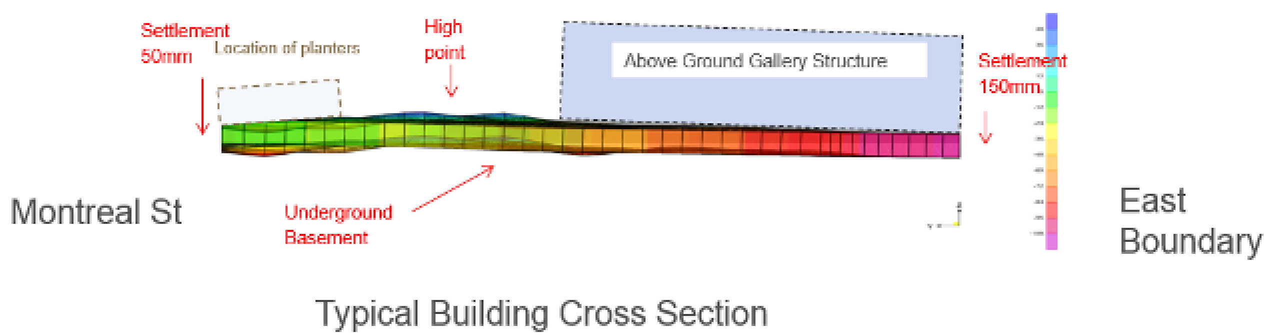


Figure 2 - Profile of the basement parking garage with differential settlement. (Figure Courtesy of Aurecon)

Due to the possibility of a future earthquake, which could cause further settlement, it was determined the basement structure could not handle any more differential settlement without risking fracturing the raft foundation and ground level slab. Re-leveling was required to restore the resiliency of the basement and foundation.

1.4. Why Base Isolate?

The Christchurch Art Gallery is crucial within New Zealand's network of galleries and museums. With well over 6,400 works of art having been acquired since its foundation in 1932 and now valued at NZ$86M, the collection is important and varied. In addition to the local collection, the Art Gallery sources and displays art collections on loan from international lenders. This is a core business activity, and the value of these collections is typically in excess of NZ$15M. For the three years prior to February 2011, the Christchurch Art Gallery borrowed around 650 works of art.

Following the Canterbury Earthquakes, Christchurch found itself in a 'New Seismic Normal' that puts it alongside California, Japan and parts of Asia. In these regions, seismic risks are mitigated for key public buildings, including galleries and museums, by building high performance buildings or by retrofitting seismic resilience, both of which target preservation of the building contents. These 'special' buildings are specifically designed to cope with higher seismic risk environments and enable valuable art collections to be publicly displayed.

The Christchurch earthquakes severely damaged the Christchurch Art Gallery's reputation to provide adequate protection to valuable collections on loan from international lenders. Prior to the 2011 earthquakes, the Christchurch Art Gallery, being a modern building designed to withstand significant seismic forces, did not feature as a high risk environment for lenders. Following the 2011 earthquakes, the seismic risk profile changed significantly. The new seismic environment has deterred risk adverse international lenders. This significantly compromises the Christchurch Art Gallery's ability to source and borrow international reputable collections for display. The Christchurch Art Gallery found itself in an untenable position of losing its ability to function as an international reputable art gallery and provide its service to the City of Christchurch as it previously did.

Seismic risk is considered as a matter of course when valuable works of art are borrowed from, and lent to, national and international lenders. Internationally, galleries and museums in higher risk seismic areas provide detail about how they manage seismic risk through the GFR they supply to prospective lenders. Internationally, it is accepted that the most robust method of seismic risk mitigation for a building and its contents is by base isolating the entire building.

The most significant benefit of base isolation is the reduction in building floor accelerations induced by ground shaking. It is not only the structure that is protected but also the building contents. In the case of the Christchurch Art Gallery, the building accelerations are reduced from approximately 0.9g to 0.17g (See Figure 3). This is a significant reduction in transmitted seismic forces and enables the building structure, contents and fitout to ride out a major seismic event without significant risk to the building or its valuable contents.

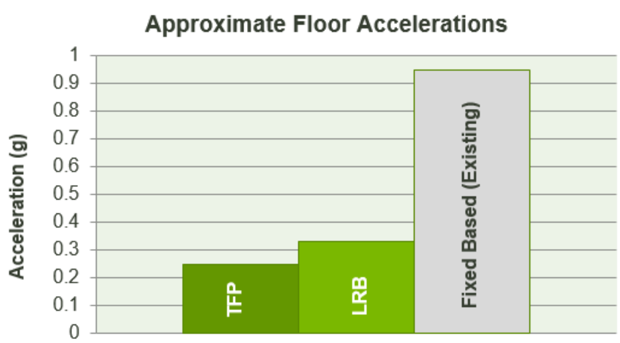


Figure 3 - The graph depicts the preliminary floor accelerations the superstructure will experience with Triple Friction-Pendulum (TFP) isolators, Lead-Rubber Bearings (LRB) isolators and without any base isolation (fixed based). Later refinements in the design lowered the TFP to 0.17g.

1.5. Project Team Roles

The project was split into three clear phases. The first phase involved Aurecon developing and overseeing a method of relevelling of the art gallery on behalf of the building owner, Christchurch City Council (CCC) to its pre-earthquake levels using an in-ground solution. Design and methodology was a joint effect between Aurecon, the general contractor, Mainmark (formerly Uretek) and the specialist re-levelling contractor, the Chemical Grouting Company of Japan.

The second phase also involved Aurecon providing a developed structural design for the base-isolation of the art gallery on behalf of the building owner, CCC. Along with the developed structural scheme, Aurecon carried out a detailed non-linear time history analysis of the triple friction pendulum base isolation system to provide a performance based specification for the supply of the base isolator devices. The detailed analysis carried out to completion by Aurecon was peer reviewed by Forell/Elsesser Engineers (out of their San Francisco office), who have extensive experience with the analysis and retrofit of base isolation devices into existing structures.

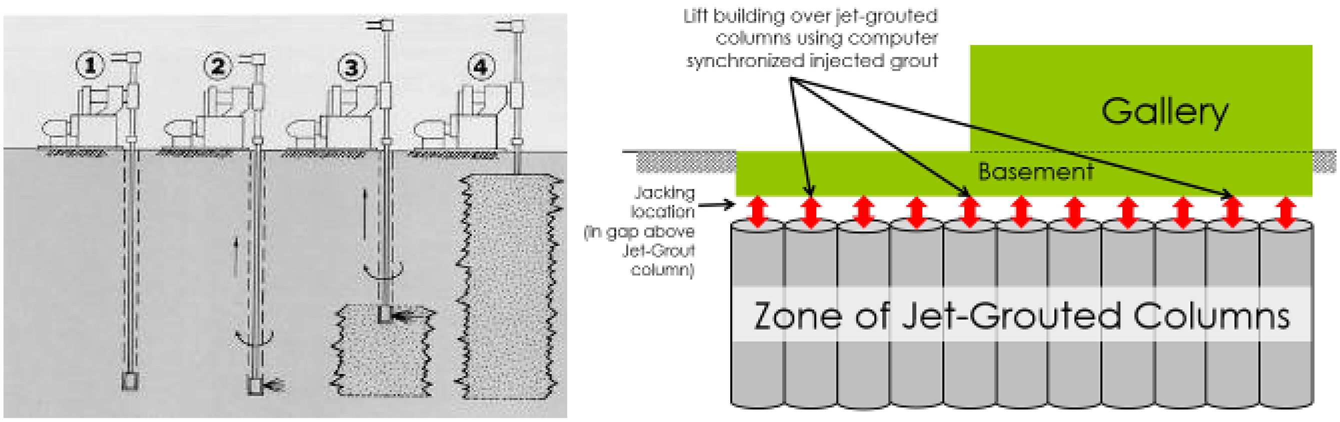
The third phase involved a design-build contract for the retrofit project. This process was chosen to provide financial certainty for Christchurch City Council where the design development risk would be taken on by the design-build contractor. Fulton Hogan, the design build contractor who won the tender process, teamed up with Ruamoko Solutions to provide the detailed structural engineering design for the retrofit project. There was a large degree of collaboration between Ruamoko Solutions and Aurecon relating to the structural engineering design, with Aurecon providing a peer review of the detailed strengthening design carried out by Ruamoko Solutions.

2. The Re-levelling Process

The re-leveling was a three-step process. Step one required locating the 72 ground anchors that were installed during the original construction. It was assumed the ground anchors were installed to counteract buoyancy forces before the superstructure was constructed. The ground anchors needed to be released before any re-leveling could be done, since they could resist against any lifting process.

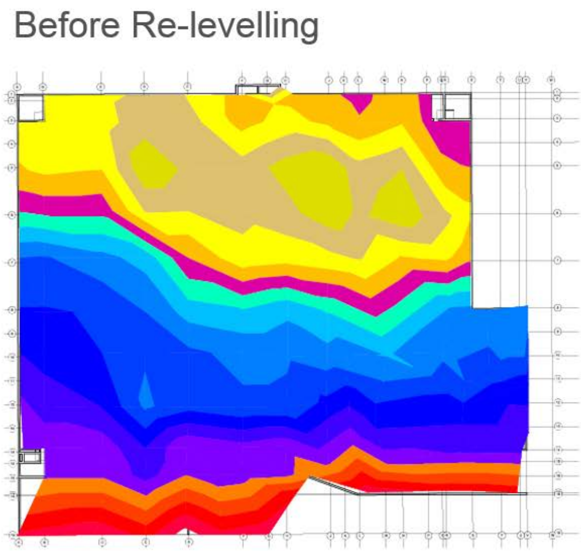
Step two was the installation of grouted columns under the raft foundation. These grouted columns would serve as a surface to jack the building up off of. The grouted columns started at a depth of 7m below the foundation up to just below the bottom face of the raft foundation, leaving a narrow void between the top of the grouted columns and the bottom of the raft foundation.

Grouted columns were constructed by drilling a 4cm hole through the raft foundation inserting a high pressure grout jet. The jet would start at 7m below the foundation and shoot horizontally high pressure grout, displacing the soil. The jet would spin and slowly pulled up shooting grout in a helictical path creating a 5m wide grouted column (see Figure 4a). 125 grouted columns were created in a grid pattern under the raft foundation.

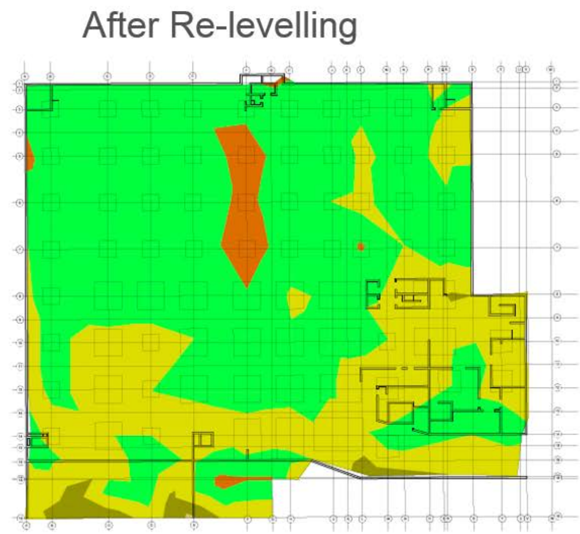


Figures 4 – The left figure (a) depicts the method of creating the grouted columns under the raft foundation which later served as a base to lift off from. The right figure (b) depicts the area where the lifting grout was injected which provided the actual lifting of the whole building. (Images courtesy of Aurecon)

Step three was the lifting of the building. The Mainmark / Chemical Grouting Company of Japan team used a computer-controlled grouting system to re-level the gallery by injecting grout over 44 days, which required 22 staff on an average day. The grout was pumped into the void between the top of the previously grouted columns and the bottom face of the raft foundation which pushed the foundation upward (see Figure 4b). There was no excavation or vibration. The system used high pressure, low volume grout pumps that delivered cementitious grout through 12mm lines to a number of grout monitors in a 'daisy chain' formation. Controlled to the millimeter, the gallery was lifted an average of 2mm per day, with lifts of up to 182mm required in some areas over the course of the job (see Figure 5).



Min Elevation	Max Elevation	Color
0.090	0.100	
0.100	0.110	
0.110	0.120	
0.120	0.130	
0.130	0.140	
0.140	0.150	
0.150	0.160	



Min Elevation	Max Elevation	Color
-0.010	0.000	
0.000	0.010	
0.010	0.020	

Figure 5 - Floor levels before and after the re-levelling process. (Figure courtesy of Aurecon)

3. Benefits of the Base Isolation Retrofit Solution

3.1. Suitability of the Christchurch Art Gallery for Base isolation

The retrofit of base isolation devices under the art gallery not only has the benefit of requiring no additional intervention or strengthening works above the ground floor, but critically provides the level of protection to the building contents that is now required for the Christchurch Art Gallery to host some of the most prestigious international exhibitions in the current high seismic risk environment.

There are many aspects of the original building design that were favorable for the retrofit of the building with base isolators. In order to retrofit an existing structure with base isolator devices a single isolation plane at which the building is free to move horizontally must be provided. Base isolation generally have a high vertical stiffness to transmit gravity loads to a substructure below the isolation plane, and a very low horizontal stiffness to minimize the accelerations and seismic forces that can be transferred to the structure above the isolation plane during seismic events.

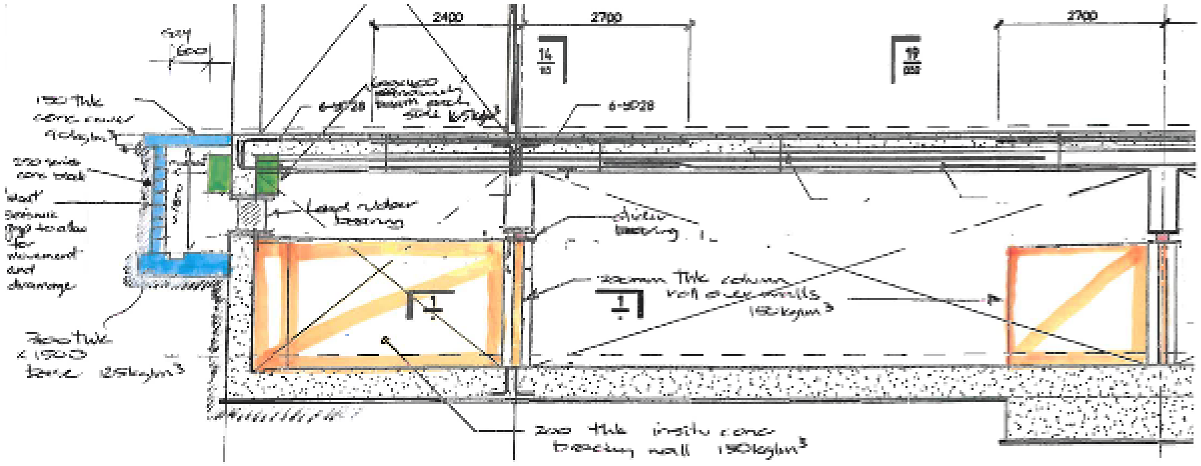


Figure 6 - Early feasibility and conceptual drawing of retrofitting base isolation in the basement which originally was calling out for lead-rubber isolators.

(Image courtesy of Aurecon)

As the art gallery had an existing basement carpark below approximately 90% of the art gallery, there was already a substructure below capable of supporting loads from above the isolation plane. This meant that most of the retrofit works were limited to the basement, allowing repair and fit out works to the art gallery above to occur simultaneously, significantly reducing the project programme. Having the works limited to the basement also reduced the number of services and architectural finishes that would be affected during the strengthening works (see Figure 6).

The building already had space on all four sides of the site that could accommodate a ‘rattle space’ for the building to move into during earthquake shaking. Due to the relatively high water level at the site, the original designers of the structure allowed for a relatively heavy and strong ground floor to provide sufficient weight to hold the building down. This is ideal for the retrofit of the structure using base isolation as the strength of the existing ground floor structure is better equipped to deal with the new forces from the retrofitted base isolation devices than that of a more conventional ground floor construction.

One of the more significant issues with isolating the art gallery was the asymmetric nature of the gravity and seismic load distribution of the structure. With some isolators supporting three storeys of heavy concrete structure and other isolators supporting only courtyard loads, the loads were highly variable. Traditional base isolation devices which provide a fixed level of horizontal resistance were not suitable as the amount of resistance required at each isolator location was highly variable. Triple friction pendulum devices (see Figure 7) rely on friction between an internal puck and curved stainless steel surfaces to provide horizontal resistance. The amount of resistance provided at each isolator location is directly proportional to the weight applied and the friction coefficient of the sliding surfaces, providing a uniform response across the entire site regardless of the loading eccentricity. The curvature of the sliding surfaces provides some restoring force to re-centre the isolators following an earthquake event. For MCE earthquakes, the pucks themselves have internal sliding surfaces which provide an increased level of resistance near the displacement limit of the isolators to prevent the maximum displacement from being exceeded.

3.2. Environmental Sustainability

A conventional strengthening approach that would convince the local and international art lending community that the Art Gallery was no longer a high seismic risk would require invasive and substantial strengthening to the building superstructure. Many of the exterior and interior structural walls and slabs would need to be thickened to provide more strength to the building. In turn, substantial amounts of external and internal cladding, flooring and partition walls would require replacement. This would also include replacement of electrical and mechanical systems in many areas.

With this strengthening option, the NZ$86M art collection would be required to be removed off site and relocated into a purpose built and environmentally regulated environment. The cost of this was estimated at approximately NZ$5.0M and would have delayed the building re-opening by six months. Overall this would create a tremendous volume of waste and necessitate large volumes of new materials. This, and the energy required to build a temporary storage facility presents a clear and substantial environmental impact.

Conversely, retrofitting of base isolators has only required significant intervention within the basement. The noisy, dusty and intrusive work has been almost entirely confined to the car park and workshop areas. While this work was intense in many locations, it has required the replacement of only a relatively small amount of architectural finishes and mechanical and electrical systems. During the base isolation retrofit, the art collection has remained on site in a monitored gallery storage area with continuous humidity, temperature and dust control. By undertaking the structural upgrade in this way, the art collection has remained fully insured throughout the base isolation retrofit process. The methodology of the base isolation retrofit has significantly minimized environmental impacts in multiple areas.

3.3. Economical Sustainability

The retrofit of base isolators to the building was completed for approximately 50% of the estimated cost of conventional strengthening. The cost benefits of the base isolation option are further supported by the fact that conventional strengthening would have necessitated thicker walls and other structural elements in the upper floors inhibiting the openness of the galleries and impeding the functionality of the back of house spaces.

Furthermore, a conventional strengthening scheme utilizing wall thickening has a direct effect on the calculated strength capacity of the building but has no positive effect in protecting the Art Gallery contents which are susceptible to the damaging effects of earthquake shaking. Strengthening by wall thickening does not reduce the seismic risk to the collections, and has a knock-on effect in compromising the Art Galleries economic sustainability for remaining open and functioning as normal.

Figure 7: Triple curvature base isolation devices delivered to the Art Gallery basement for installation

(Image Courtesy of Art Gallery Te Puna o Waiwhetu. Photographer: John Collie)

An important aspect of the choice to base isolate is to secure the Christchurch Art Gallery's economic sustainability. The gallery prides itself on being a modern facility, its curatorial staff, and the collections the gallery has been able to attract to Christchurch. The most recent example of this prior to the 2011 February earthquake was the 'Ron Mueck' exhibition. This exceptional exhibition had door takings which totaled NZ$1.5M and provided a substantial operating surplus. The Christchurch Art Gallery was the sole New Zealand venue for this exhibition with this success the result of active engagement with international peers, good planning, the strong reputation of the gallery curatorial and technical staff, and the location in a purpose-built central-city public art gallery. The direct economic benefit to the Canterbury area was NZ$2.98M. The economic sustainability of the Christchurch Art Gallery's business operations relies on its ability to borrow art collections from international lenders. The choice to base isolate the building ahead of intrusive wall thickening has a direct effect in securing the Art Galleries ability to source international collections for display and remain economically sustainable into the future.

It is also anticipated that insurance benefits will be recognized in the form of reduced premiums, albeit in an insurance market which shifted dramatically in the intervening period. While experience in California suggests that insurance companies tend to under value the risk reduction provided by base isolation, there are still potential cost savings.

4. Design and Construction of the Base Isolation System

4.1. Foundation and Column Strengthening

The original design of the basement foundations allowed for large reinforced pad footings to support columns and walls with heavy structural loads, while columns and walls with lighter loads were founded directly on the 400-500mm thick basement floor. For the retrofitted columns, which are subjected to vertical and horizontal loads from the base isolators, a structural assessment using the revised punching shear provisions introduced in the 2008 amendment of the reinforced concrete design standard NZS3101:2006(A2), indicated that the foundations would fail under retrofitted punching shear actions. Figure 8 conceptually shows where the building was split between the seismically isolated superstructure and fixed substructure/basement.

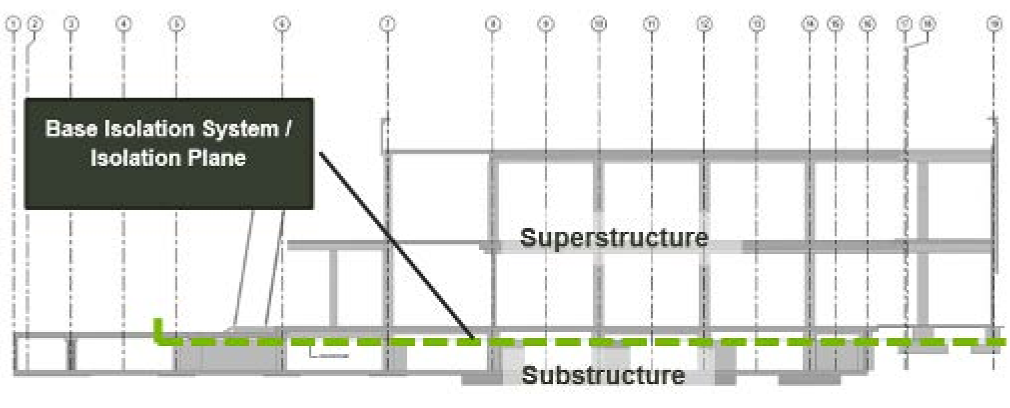


Figure 8 - Concept of the separation between the fixed basement and the isolated superstructure.

(Image courtesy of Aurecon)

As the basement floor is subject to hydrostatic uplift from the relatively high water table at the site, strengthening of the existing foundations was considered risky, difficult and invasive. Instead, the punching shear demand was reduced by increasing the size of the column base and spreading the punching shear demand over a larger area of the basement slab. The detailed design was initially carried out using conservative assumptions for the behavior of the floor slab and the reaction of the soils underneath. Using subgrade stiffness values provided by the geotechnical engineer, including an assessment of the post-grout re-levelling stiffness's, a finite element analysis study was able to refine the punching shear capacity and confirm that the bearing capacity of the soil under the slab was not likely to be exceeded in an ULS earthquake event.

4.2. Overhead Concrete, Concrete Cutting and Temporary Propping Works

In a seismic event, the lateral movement of the building on the isolators creates eccentric vertical loading, inducing a 'rollover' moment in the beams and slab above the isolator as well as the columns below. The amount of rollover moment is dependent on the lateral offset (P-Δ effect) and the friction coefficient of the isolator. Although not required everywhere, a significant number of beams and floor slabs had to be strengthened to cope with these new demands.

Figure 9 - A basement column being cut at the top after the mid and lower sections were jacketed and retrofitted. Propping is placed on either side of the column to allow load transfer before cutting.

(Image courtesy of Aurecon. Photographer: Forrest Lanning)

The 'rollover' beams and intervention work involved casting new concrete beams or under-slab thickenings at the underside of the ground floor. To ensure their structural efficacy, bond to the structure above was essential. Ruamoko Solutions worked with Fulton Hogan to develop a concrete mix design and sound methodology suitable for the overhead concrete work. Successful trial pours were carried out to refine the methodology and ensure the poured concrete would not shrink away and separate from the existing concrete.

Along with the specialized overhead casting of concrete, there was a large amount of specialised cutting and propping works required for the job. Propping was required in most isolator locations where the structure between the basement and ground floor was cut to allow the placement of the base isolators (see Figure 9). Ruamoko Solutions worked closely with Fulton Hogan to accommodate the propping requirements, integrating items such as cast-in steel plinth armouring or widened reinforced pads into the final structure. Precise monitoring was required during construction to ensure deflections under propping and transferring the loads to the isolators weren't inducing adverse stresses in the existing superstructure.

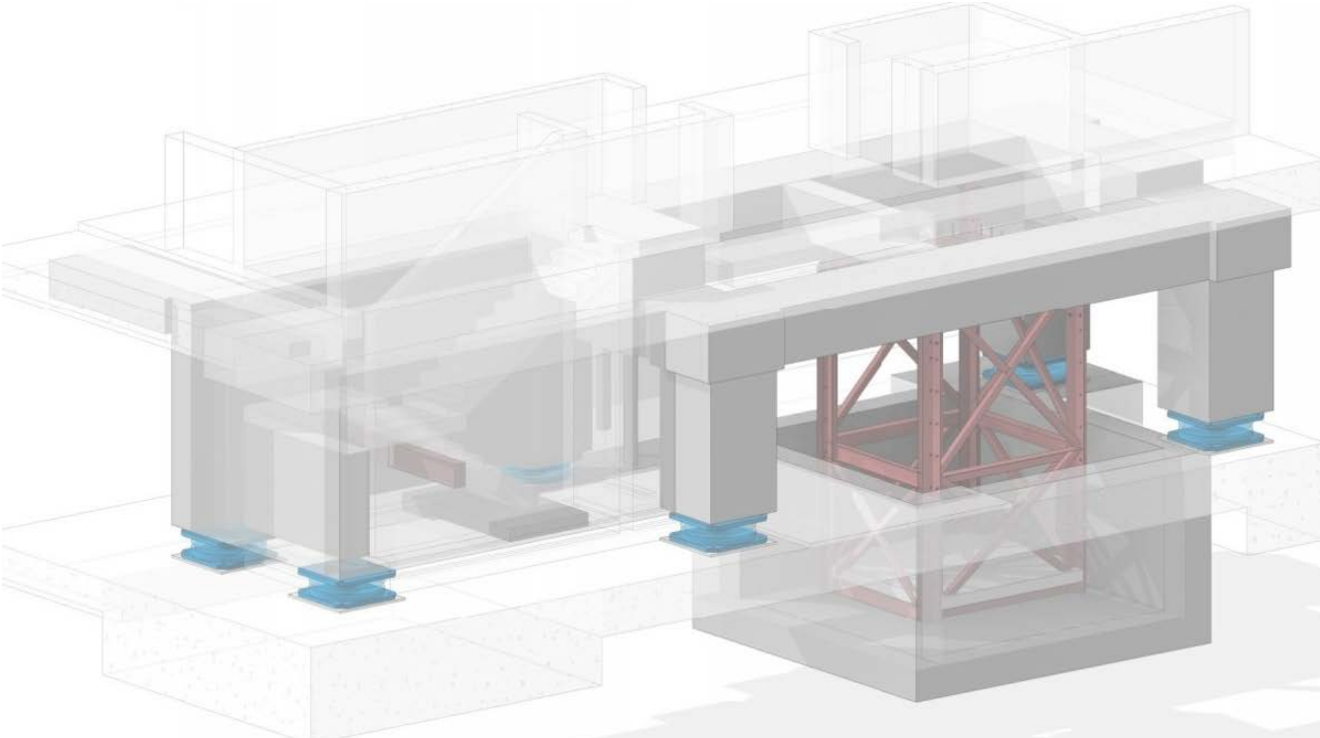


Figure 10 –Lifts and stairwells servicing the basement were designed and constructed to laterally move along with the ground floor above during an earthquake.

(Image courtesy of Ruamoko Solutions)

4.3. Maintaining Building Integrity during Retrofit Works

An essential aspect of the retrofit design was the ongoing seismic support of the structure during the conversion of the structure from fixed base to base-isolated. A minimum seismic strength of 34% of the New Building Standard (NBS) with an Importance Level 3 (IL3) was maintained during construction. Specific basement walls remained fully intact and temporary diaphragm continuity across the western courtyard seismic slot was used to provide the minimum seismic strength. During the final conversion to the building's isolated state, these remaining walls and floor slabs were cut over a period of 18 hours to minimize the amount of time the building would have less than 33%NBS strength.

4.4. Vehicle Ramps, Suspended Lifts, Stairs and Mechanical Platforms

In several areas, the building structure was required to connect the ground floor to the basement floor including the main vehicle ramp, lifts and stairs. A wide range of solutions were required to ensure these elements were able to move independently and without obstruction above the basement floor.

As illustrated in Figure 10, the stairs and lifts are generally suspended and braced below ground floor level to move within or above the basement level. Lift pits not servicing the basement have been designed to slide on plinths in the basement while the lift servicing the basement received a widened lift pit to accommodate the seismic movement of the suspended structure. Stairs generally slide at basement slab level or at mid-height landings. The mechanical platform was similarly suspended below the ground floor to significantly minimize the number of services that need to function whilst crossing the isolation plane. The isolation plane changed heights in many areas around the stairs, lifts and mechanical plant room which required careful design consideration and design of seismic jointing around the stepped isolation planes.

The ramp presented complex challenges due to the intersection of the horizontal isolation plane and inclined ramp. Along the length of the ramp, pairs of new insitu and precast concrete 'staple' shaped portal frames extend above and below the isolation plane. The portal frames resist the existing gravity loads as well as the new seismic loads from the movement at the isolation joint. Maintaining head height and width for the 'staple' frames around the ramps were major constraining factors. Figure 11 shows some examples of the retrofitting works.

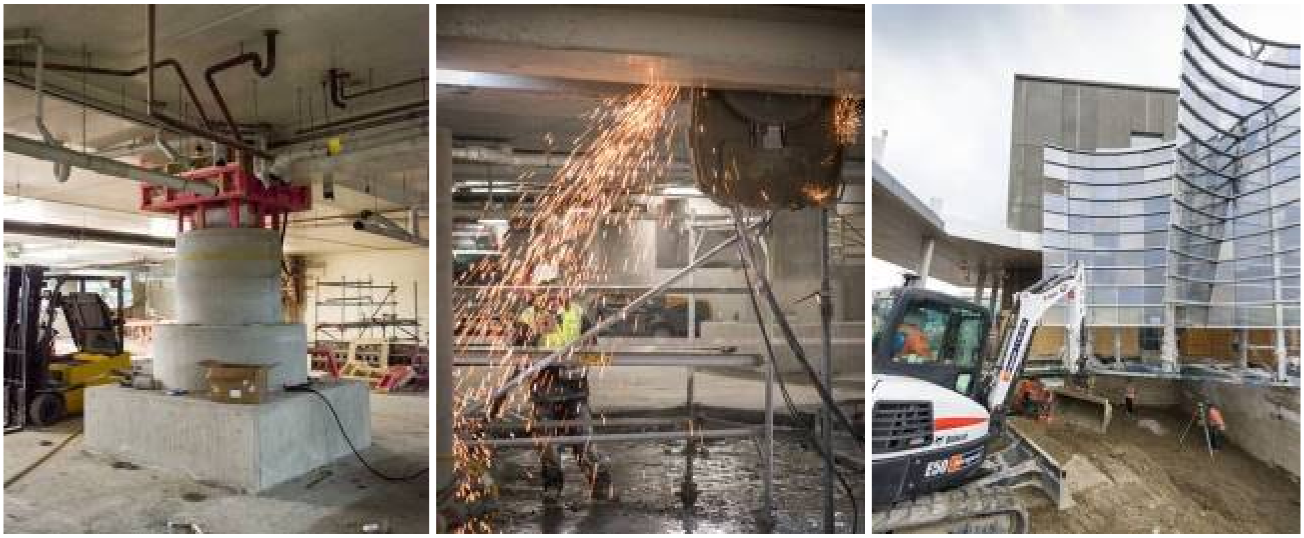


Figure 11 – a) Overhead work around columns (left), b) precision cutting works (centre) and c) temporary support works to the glazed sculptural façade (right)

(Images courtesy of Christchurch Art Gallery Te Puna o Waiwhetu. Photographer: John Collie)

5. Conclusion

The retrofit of the Christchurch Art Gallery Te Puna O Waiwhetu was the first use of triple friction pendulum devices for the retrofit of an existing building in New Zealand. The base isolation retrofit project was complex, and required extensive depth of technical knowledge. The structural analysis and specification of the base isolators involved a full non-linear study of the building requiring in-depth knowledge of local seismicity, seismic design and the intricacies of triple friction pendulum isolators, and the dynamic performance of the building.

The overall success of the project was its ability to meet the clients brief in a timely and cost-effective manner. The positive comments from the client are testament to the success of the design team. Done under budget and to a tight programme, the base isolation retrofit not only has the benefit of requiring no additional intervention or strengthening works above the ground floor, but critically provides the level of protection to the building and its contents. The facility has been restored to the highest international standards which has secured its position in Australasia as a premier Art Gallery capable of hosting prestigious international exhibitions. In doing so, the project has made the Art Gallery socially and economically sustainable and allows art and culture to continue to flourish in Christchurch.