Design for business continuity requirements. Challenges and advantages of base isolation above ground, a case study.

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ABSTRACT: Post-earthquake business continuity of building tenancies is becoming a more frequent requirement of tenants and subsequently building owners. Base isolation, by limiting acceleration and displacement demands imposed on the building superstructure, is one means of achieving this in case of a severe earthquake and associated aftershocks. This paper illustrates a case study building with the isolation plane located between the habitable ground floor and the first storey. This layout helps minimise additional costs associated with base isolation where often a crawl space below ground floor level would be constructed purely to accommodate the isolation plane at this level but it can also present challenges in the detailing phase of the project. The tenant/client brief for the case study building was for reoccupation within 3-5 days following a severe seismic event. In order to achieve this, the building has been isolated by 21 triple friction pendulum bearings installed on the top of reinforced concrete cantilever columns supported on a raft foundation. The superstructure above the isolators is braced laterally by concentrically braced frames and precast concrete shear walls designed to remain elastic with minimal inter-storey drift to reduce likelihood of damage to the structure in case of a significant earthquake. At the underside of level 1, where isolator displacements of up to 575mm are accommodated, architectural items and mechanical services runs are detailed to sustain this movement and minimise losses and downtime associated to earthquake damage.

1 INTRODUCTION

The building considered in this paper is located at 93 Cambridge Terrace, in Christchurch and it is one of the buildings part of the Ngai Tahu Property development on King Edward Barracks (KEB) site comprising two commercial office buildings, a multi-story carpark and landscaped area. The site is served by a District Energy System (DES) for the distribution of heating and chilled water.

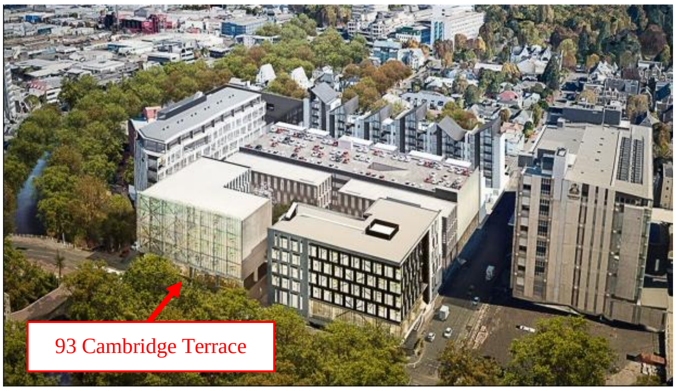

Figure 1. An aerial impression of Ngai Tahu's King Edward barracks redevelopment and, impression of the office building at 93 Cambridge Terrace. Renders by Warren and Mahoney Christchurch.

The tenant/client brief for the case study building was for reoccupation within 3-5 days following a severe seismic event. This corresponds to a Platinum resilient objective in accordance with the REDi Rating System (Almufti & Willford, 2013).

The cause of most business disruption and downtime is generally associated to damage to fit-out, partitions, and non-structural elements which are often classed as either acceleration sensitive or displacement sensitive.

In order to achieve this requirement, the building has been isolated between the habitable ground level and level 1 through the means of Triple Friction Pendulum (TFP) bearings (manufactured by Earthquake Protection System, San Francisco, California).

The decision of installing the isolators at level 1 was partly driven by the geotechnical conditions at the site.

A holistic design approach has been followed in order to limit the likelihood of severe earthquake damage to structural and non-structural elements. To achieve this, innovative architectural and engineering solutions have been developed and applied to this building as it is described in more detail below.

2 BASE ISOLATION AND BUSINESS CONTINUITY REQUIREMENTS.

As mentioned in the previous section, building reoccupation within a maximum of 5 days following a severe earthquake was a specific tenant/client requirement.

The REDi guidelines (Almufti & Willford, 2013) highlight that the time to achieve functional recovery of a damaged building is not only related to the time required to complete the repair works but other impeding factors (e.g. loss assessment) can cause additional delay to recovery time (Figure 2).

Reliable damage-controlling systems such as base isolation coupled with robust design of non-structural elements within a building can lead to the design of economically viable buildings that are likely to suffer far less damage in strong earthquakes than conventional code-design building.

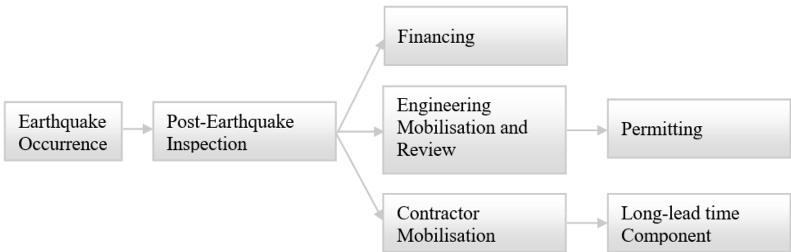

Figure 2. Sequence of delay due to impeding factors (Almufti, I. & Willford, M. 2013)

The use of isolation devices reduces horizontal acceleration demands and associated racking displacement demands imposed on the superstructure by an earthquake when compared to an equivalent building with a more conventional structural system.

In general, for base isolated structures the structural displacement is concentrated at the isolation plane, limiting the demand in the superstructure and minimizing the inter-storey drift.

In the case of 93 Cambridge Terrace, the bearings have a displacement capacity of 575mm and limit the inter-storey drift to approximately 0.8% during an earthquake with a return period of 1/2500 years (i.e. Maximum Considered Earthquake (MCE)).

As a result, the non-structural items within the building are subjected to a smaller displacement and acceleration demands than if more conventional structural systems were used (e.g. up to 2.5% inter-storey drift is allowed by NZS1170 for an Ultimate Limit State event – in this case corresponding to a 1/500 years event) leading to a reduced likelihood of severe damage as a consequence of an earthquake.

Moreover, a building on friction pendulum isolators has self-centring properties and in case of a severe seismic event causing differential settlements the building can be relevelled relatively simply at the isolation plane avoiding more complex foundation relevelling procedures and reducing the consequent downtime.

On the downside, the use of the isolators might present a higher level of design complexity (e.g. building services and architectural items) than a standard building. In fact, most of the building services cross the isolation plane to supply the building with water and power and architectural details have to deal with the movement interface to achieve compliance and make the building a dry, and comfortable environment. More details are provided in the following sections.

3 THE CASE STUDY: 93 CAMBRIDGE TERRACE, CHRISTCHURCH

The Ngai Tahu Property building at 93 Cambridge Terrace is characterized by a 10.8m by 10.8m structural grid and it has 4 suspended storeys with isolators installed at the top of the columns within the habitable ground floor space as shown in Figure 3.The suspended floors accommodate office space whilst the ground floor contains retail spaces and an entrance lobby.

Figure 3. 93 Cambridge Terrace building and detail of isolators installed on top of ground floor columns.

3.1 Geotechnical conditions and foundations

The site ground conditions are characterized by a thin layer of gravel of variable thickness on top of a sand, silt, and silty sand. Moreover, the level of the water-table is approximately 1.5-3m below ground level. For these reasons, an excavation as shallow as possible engaging the good soil and avoiding dewatering of the site during construction was deemed the most economical option. This ruled out a partial basement that would be required to isolate the building below the ground floor and the isolators have been located at the underside of level 1.

The foundation is a 1.1m reinforced concrete raft supporting 21 square reinforced concrete cantilever columns. The thick raft has the dual purpose of mitigating differential settlements due to possible liquefaction of the underlying soils, and resisting the cantilever action imposed by load eccentricity due to the large movements of the building on top the isolation bearings possible in case of a seismic event.

On top of the raft, a separate concrete slab has been installed with the dual purpose of future proofing of the building ensuring flexibility for location of services and, in the unlikely case of severe differential settlement, to enable relevelling of the floor without any major intervention to the foundations.

3.2 **The superstructure**

The first floor above the isolators is characterized by precast reinforced concrete beams of section depths varying between 750-1200mm, in situ concrete capitals and composite steel beams supporting a 150mm thick Comflor80 slab. The reinforced concrete beams support the gravity loads and resist, in conjunction with the ground floor columns, the seismic P-Delta moments induced by the eccentricity trigged by movement at the isolation plane.

The typical floors (i.e. above level 1) are also 150mm thick Comflor80 slabs supported by steel welded primary beams and steel UB secondary beams working compositely with the floor slab.

The roof is a light-weight steel structure of steel beams and D.H.S purlins with diagonal tension only rod bracing. Due to the DES operating on the site, no heavy equipment is required on the roof.

The structure is restrained laterally by steel concentrically braced frames and reinforced concrete load bearing shear walls that also act as the building façade on the northern and western sides of the building. The superstructure is design to remain elastic under a Design Based Event with a return period of 1/500 years and it has been verified for stability for an MCE event with a return period of 1/2500 years.

3.3 **The isolation plane**

As previously mentioned, the isolators are TFP bearings. They are characterized by four concave sliding surfaces, one pair within an outer pair that are able to accommodate a maximum displacement of 575mm. These devices are fabricated with a ductile retaining ring around the bearings which prevent the building from losing the support in case the displacement demand is in excess of the capacity of the isolators.

3.3.1 *Piped and cabled building services*

The piped and cabled building services, including the heating and chilled water which is provided from the District Energy System (DES), cross the isolation plane. These services need to be designed to accommodate the displacement at the isolators with no significant damage. Typical solutions involve large flexible/moving offsets and require significant space to accommodate multiple services. Drainage is often treated as sacrificial for base-isolated buildings. A simpler vertical solution was developed by the services team for this building, reducing the space requirements and allowing multiple services to be easily coordinated. A non-sacrificial solution was also trialled for the drainage systems. By arranging the flexible movement in a vertical plane and extending the active section over the floor height, the flex and extension requirement of the joints are significantly reduced and multiple service lines will remain parallel. For this building, and a 600mm movement allowance, this arrangement required a deflection of less than 12^{o} and an elongation of less than 40mm in each joint. The new arrangement for pressure and drainage pipework is illustrated in Figure 4.

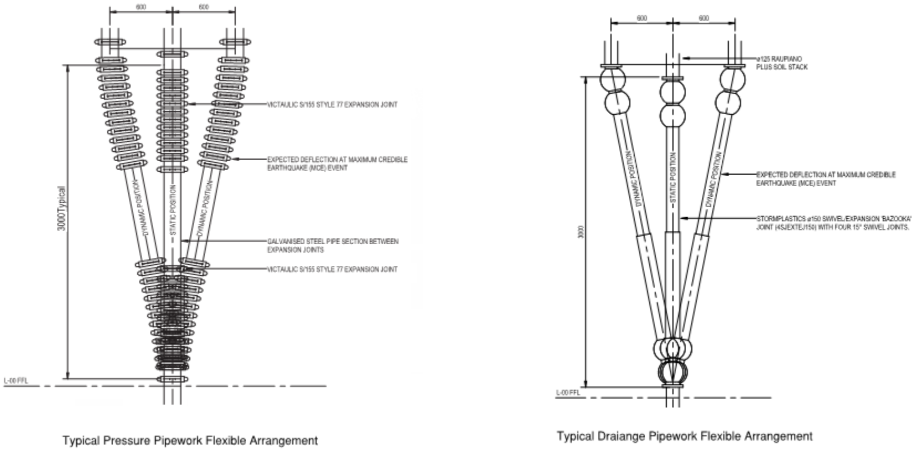

Figure 4. Drainage pipework with flexible joints to accommodate displacement at the isolation plane. Schematic.

Cabled services were arranged in a similar manner. The pressure pipe solution developed (using a thermal expansion joint) is now being marketed as a large seismic movement solution by the component manufacturer and has been installed on a number of buildings.

3.3.2 *Architectural features*

The envelope of the building is a light-weight glazed and terracotta façade curtain wall system designed with a discontinuity between level 1 and the ground floor at location of the isolation plane to avoid damage to the façade in case of a seismic event.

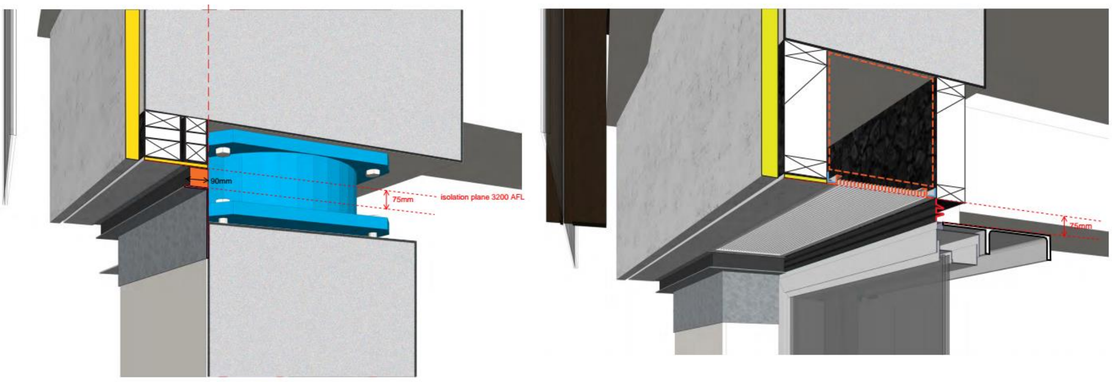

Figure 5. Schematic architectural solution at the perimeter of the building. Weather protection and installation of mechanical ventilation plenum.

Weather protection around the perimeter of the building is provided through the means of a proprietary seismic cover supplied by a specialist sub-contractor (Construction Specialties). The system is a two-part system that has a more visually pleasing outer rubber gasket than other alternatives and can cope with smaller movements and can be easily clipped back into place after larger displacements. The second part is a folded rubber element sitting behind the front cover that can cope with larger movements and retain weatherproofing after a large shake. This element runs the entire perimeter of the building above all the glazed ground floor shopfronts (Figure 5).

At the ground floor (i.e. below the isolators) the ceiling is hung from level 1. The partitions at ground floor are timber framed walls that are broken at the isolation plane. The lower portion of the walls are designed to be self-supporting during a seismic event. The upper portion of the walls is designed to hang from the suspended structure above. The back of house area on the ground floor including the staff toilets and showers, are built as a standalone lightweight timber 'box' where the ceilings and walls are all built off the ground floor slab and sit under the isolation plane – including services to these areas which sit on top of this timber box.

Figure 6. Hanging ceiling and detail of the walls at ground floor and "hanging" stair.

The discontinuity between the top and bottom portions of the partitions represents a challenge in regard of fire rating/protection. This detail needed to be able to accommodate the displacement without losing fire protection performance. At 93 Cambridge Terrace a fire-rated '*Firefly*' blanket has been used where the seismic gap is not exposed. Where a gap is visible, this has been packed with fire-rated insulation and proprietary seismic covers with rubberised covers that are designed to allow some movement before they 'pop out' and can be easily reinstalled following a large seismic event.

Acoustic separation is retained at the isolation joint in the walls using a similar method to above with the isolation gap filled with acoustic insulation and proprietary seismic covers with rubberised covers to the face of the walls in locations where a gap would otherwise be visible.

3.3.3 *Means of escape*

The means of escape from throughout the building is provided by precast concrete stairs between level 4 and level 1, and steel stairs that hung from the level 1 structure to ground level. In a similar manner, the structure supporting the lift rail hangs from the level 1 structure. A 600mm rattle space around the hanging structure has been provided for both the lift and steel stairs to allow the structure to move with the building above in case of a seismic event (Figure 6). The rattle space is covered using a horizontal cover plate which will slide with the isolated structure.

3.4 **Holistic design strategy for 93 Cambridge Terrace**

As explained above many design items across the different design disciplines are affected by the presence of the isolation plane and by the movement that might occur in this location. The matrix below in Table 1 summarises the aforementioned items and the design strategy that has been adopted to avoid damage and achieve business continuity for 93 Cambridge Terrace. This matrix has been developed by the design team and is representative of the holist approach adopted for this building.

Table 1. Design Strategy for elements crossing or in proximity of the isolation plane.

		LIMIT STATE EVENTS				
		<SLS	**SLS**	**ULS**$^{(1)(2)}$	**MCE**$^{(2)}$	Notes/Comments
		0-70mm	70mm	300mm	600mm	Design Displacements
Discipline	Item	Approx. 1/10year to 1/43year	1/43years	1/500years	1/2500year	Likelihood of Occurrence
FIRE	Sprinklers	✓	✓	✓	✓	
	Alarm Cabling	✓	✓	✓	✓	
	Hydrants	✓	✓	✓	✓	
	Ground floor walls separations	✓	✓	×	×	Ground walls separations are to be inspected after any isolators displacement for any damage to seal.
ELECTRICAL	Power Cables	✓	✓	✓	✓	
	Data Cables	✓	✓	✓	✓	
HYDRAULIC	Domestic Water	✓	✓	✓	✓	
	Plumbing and Drainage	✓	✓	✓	✓	
	Storm Water	✓	✓	✓	✓	
	Tenants Stacks	✓	✓	TBC	TBC	To architectural details
MECHANICAL	Hot and Cold Water	✓	✓	✓	✓	
	Kitchen Extract	✓	✓	TBC	TBC	Dependant on kitchen layout.
STRUCTURAL	Isolators	✓	✓	✓	✓	
	Cover plates	✓	✓	✓	×	Requirements discussed with Client.
	Cover plates – main means of escape	✓	✓	✓	✓	
FACADE		✓	✓	✓	✓	The façade is hanging

		LIMIT STATE EVENTS				
		<SLS	**SLS**	**ULS**(1)(2)	**MCE**(2)	Notes/Comments
		0-70mm	70mm	300mm	600mm	Design Displacements
Discipline	Item	Approx. 1/10year to 1/43year	1/43years	1/500years	1/2500year	Likelihood of Occurrence
						above the isolation plane.
OTHER ARCHITECTURAL	Weather protection on perimeter of the building	✓	✓	✓	×	Proprietary seismic cover. Easily repaired after larger event.
	Acoustic separation	✓	×	×	×	Proprietary seismic cover. Easily repaired after seismic event.

GENERAL NOTES
(1) ULS limit state (Return Period 1/500 years) correspond to 100%NBS Level
(2) ULS and MCE events are likely to be followed by a sequence of earthquakes (aftershocks) characterized by varying intensity.

LEGEND
✓ Provision for displacement has been achieved
× Provision for displacement has not been achieved

4 ISOLATION ABOVE A HABITABLE FLOOR: CHALLENGES AND ADVANTAGES

The building at 93 Cambridge Terrace is base isolated at the underside of level 1, on top of the columns of the ground floor which is a habitable space.

The decision to install the isolators above ground has been govern by geotechnical and economic considerations. This configuration helps minimise additional costs associated with base isolation where often a crawl space below ground floor level would be constructed purely to accommodate the isolation plane. However, the isolators located above ground level can also present challenges in the detailing phase of the project.

In Table 2, 93 Cambridge Terrace is compared with a hypothetical building with isolation plane at ground level (no basement) to highlight the challenges, advantages, and the lessons that the team have learned the design and construction of this building.

Table 2. Challenges and advantages of isolation plane above a habitable floor.

	93 Cambridge Terrace	**Building with isolation plane and crawl space**
1	80% of the habitable area of the building is based isolated.	100% of the area of the building is based isolated.
2	Architectural details require attention at the isolation plane.	No particular attention is required from an architectural point of view in location of the isolation plane other than create a “moat” and allow for the presence of services.
3	Specific details required for fire separation crossing the isolation plane since the ground floor is habitable	No fire separation details are required in location of the half basement.
4	Specific details required for weather protection in location of the isolation plane.	The façade can be design “as usual”.
5	Ground level partitions need additional structure to ensure seismic bracing for the walls with no structure crossing the isolation plane.	Partitions can be seismically restrained as per standard construction with diagonal braces in the ceiling or deflection head details.
6	Flexible joint/alternative solutions for service pipes able to accommodate displacement at the isolation plane.	Flexible joint/alternative solutions for service pipes able to accommodate displacement at the isolation plane.
7	Hanging structure for lifts and elevators.	No hanging structure required within the building.
8	Rattle space inside the habitable space, around the perimeter	Rattle space and cover plate required all around the perimeter

	93 Cambridge Terrace	Building with isolation plane and crawl space
	of the hanging structure. Cover plate required only in certain areas around the perimeter of the hanging structure, such as lift and stairs entry.	of the building.
9	Layout minimises additional costs associated with base isolation where often a crawl space below ground floor level is constructed purely to accommodate the isolation plane	Crawl space required to accommodate the isolators.
10	Isolators mostly within the building envelope/protected environment and easy to access in unlikely case relevelling is required. Easy post-earthquake inspection of the bearings.	Isolators are below the building and difficult to access. Additional cost associated to construction of suspended ground floor.
11	Less excavation and no dewatering of the site during construction. No need for sheet piling. Approximate excavation depth 1100mm.	Increased excavation, dewatering, and sheet piling required during construction. Approximate excavation required 2100mm.
12	Ground floor tenants do not receive full benefit business continuity that base isolation offers.	All tenants covered by advantages of base isolation.
13	'Rattle-space' required for lift/fire stairs and 'rattle-rooms' for services crossing the isolation plane can use up valuable floor area on the ground level.	No need for rattle-zones at ground floor.
14	Significant concrete columns to ground level need to be factored into overall architecture.	Steel columns can be built to ground level – visually only one structural system.

5 CONCLUSIONS

The building at 93 Cambridge Terrace is base isolated at the underside of level 1 above habitable ground floor space. The design team followed a holistic design philosophy in order to ensure the business continuity requirements that the tenants/owner have requested for this building. Particular attention has been payed to the items crossing the isolation plane where displacements of up to 575mm can occurs in the case of a severe seismic event. Several original solutions have been developed during the design phase to limit damage in such a scenario. This process has underlined advantages and challenges of base isolation above a habitable ground floor space from both architectural and engineering perspectives. Each of these should be carefully considered in the early phases of the design.

6 ACKNOLEDGEMENTS

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Any opinion, findings and conclusion or recommendations express in this paper are those of the Authors and do not necessarily reflect those of Aurecon New Zealand Limited, Warren and Mahoney, and Ngai Tahu Property Limited.

7 REFERENCES

Almufti, I. & Willford, M. (2013). REDi^{TM} Rating System. Resilience-based Earthquake Design Initiative for the Next Generation of Buildings. Arup, 2013.