REPORT

Head of Lake Wakatipu Natural Hazards Adaption

Engineering Approaches for Managing Liquefaction-Related Risk

Prepared for
Otago Regional Council

Prepared by
Tonkin & Taylor Ltd

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1 What is this report about?

Otago Regional Council (ORC) has engaged Tonkin & Taylor Ltd. (T+T) to provide engineering advice regarding the susceptibility of the Glenorchy area to liquefaction and lateral spreading hazards.

The first stage of this assessment was to undertake ground investigations and analysis to help understand the current susceptibility of the land. The results were presented in the T+T report "Glenorchy Liquefaction Vulnerability Assessment" (v1, issued May 2022), including the liquefaction vulnerability map shown in Figure 1.1 below. The assessment concluded that significant damage due to liquefaction and lateral spreading could be expected at a "50 to 100 year" level of earthquake shaking (a 40 – 60% chance of occurring over the next 50 years). The key areas identified are:

- Areas where both liquefaction and lateral spreading damage could occur. This area is subdivided into Major and Severe lateral spreading.
- Areas where only liquefaction damage is expected. This area is subdivided into Medium and High liquefaction vulnerability.

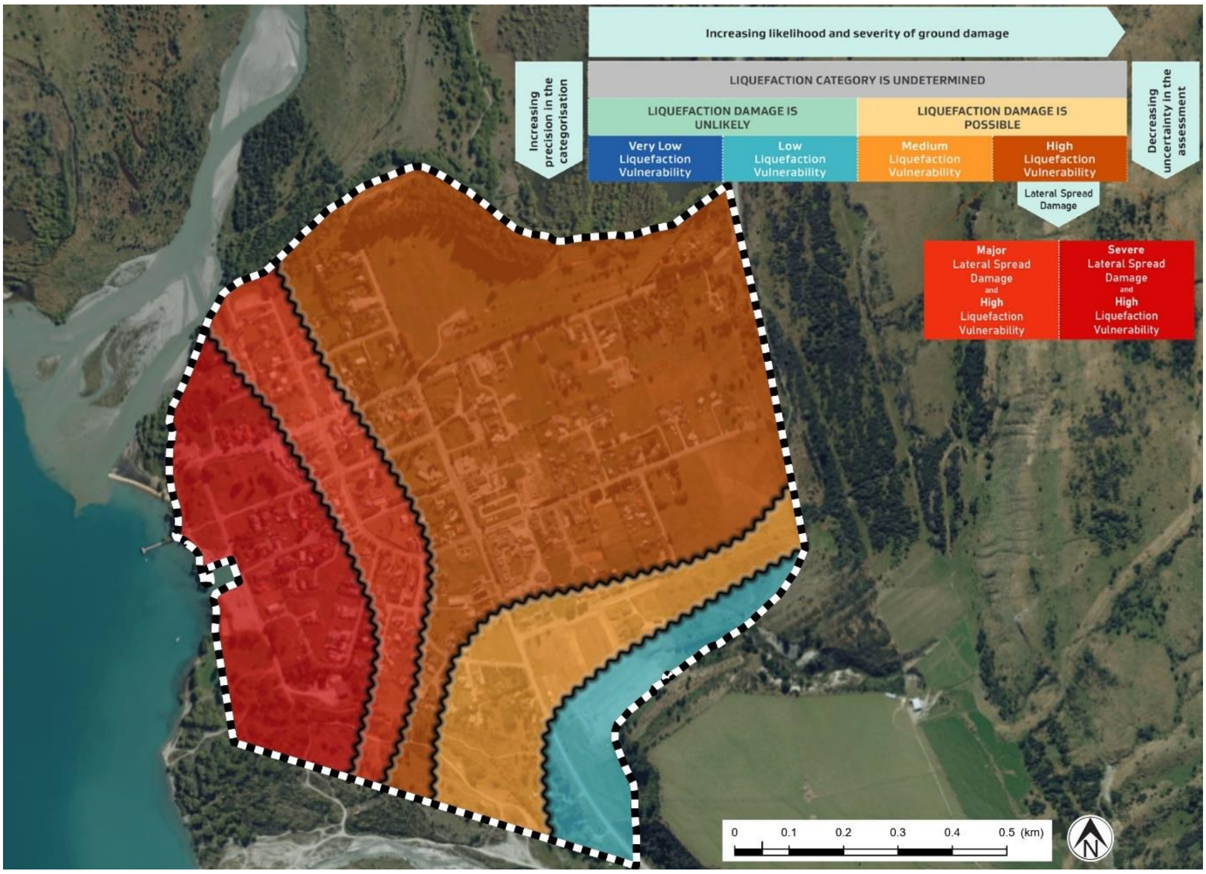


Figure 1.1: The liquefaction vulnerability map from the T+T May 2022 report. Note that boundaries between the various categories are not precise, so more or less damage could occur on either side of the boundaries.

This current report presents the second stage of the liquefaction assessment – aiming to help ORC and the local community understand potential engineering approaches for managing the liquefaction and lateral spreading hazards. Other non-engineering approaches also exist (e.g. land use planning and emergency preparedness), however ORC will be considering these separately so they are not covered here. This report identifies a range of mitigation techniques that could be considered for land, buildings and infrastructure, and how these techniques could be applied across the Glenorchy township. It then provides a preliminary high-level assessment of how effective these mitigation works could be in reducing damage, and an indicative relative cost comparison.

2 What damage could be caused by liquefaction?

Liquefaction is a natural process where earthquake shaking increases the water pressure in the ground in some types of soil, resulting in temporary loss of soil strength. The following three key elements are all required for liquefaction to occur:

- Sufficient ground shaking (a combination of the duration and intensity of shaking).
- A loose to medium-dense soil (typically sands and silts, or in some cases gravel).
- That these soils are saturated (i.e., below the groundwater table).

The severity of the liquefaction hazard therefore depends on the strength and duration of earthquake shaking, the thickness, depth, density and type of soils and the depth of the groundwater table.

Liquefaction can cause significant damage to land, buildings and infrastructure. It can cause highly variable settlement of the ground due to ejection of liquefied soil and consolidation of loose ground. It can also trigger lateral spreading, which is where the ground cracks and drops sideways towards a "free face" such as a river, lake or terrace edge. Lateral spreading is often the cause of the most severe liquefaction-related damage to land, buildings and infrastructure, particularly in areas closest to the free face.

Some of the effects of liquefaction and lateral spreading are illustrated in Figure 2.1, Figure 2.2 and Figure 2.3 below, with examples from the 2010 – 2011 Canterbury Earthquakes and the 2016 Kaikoura Earthquake.

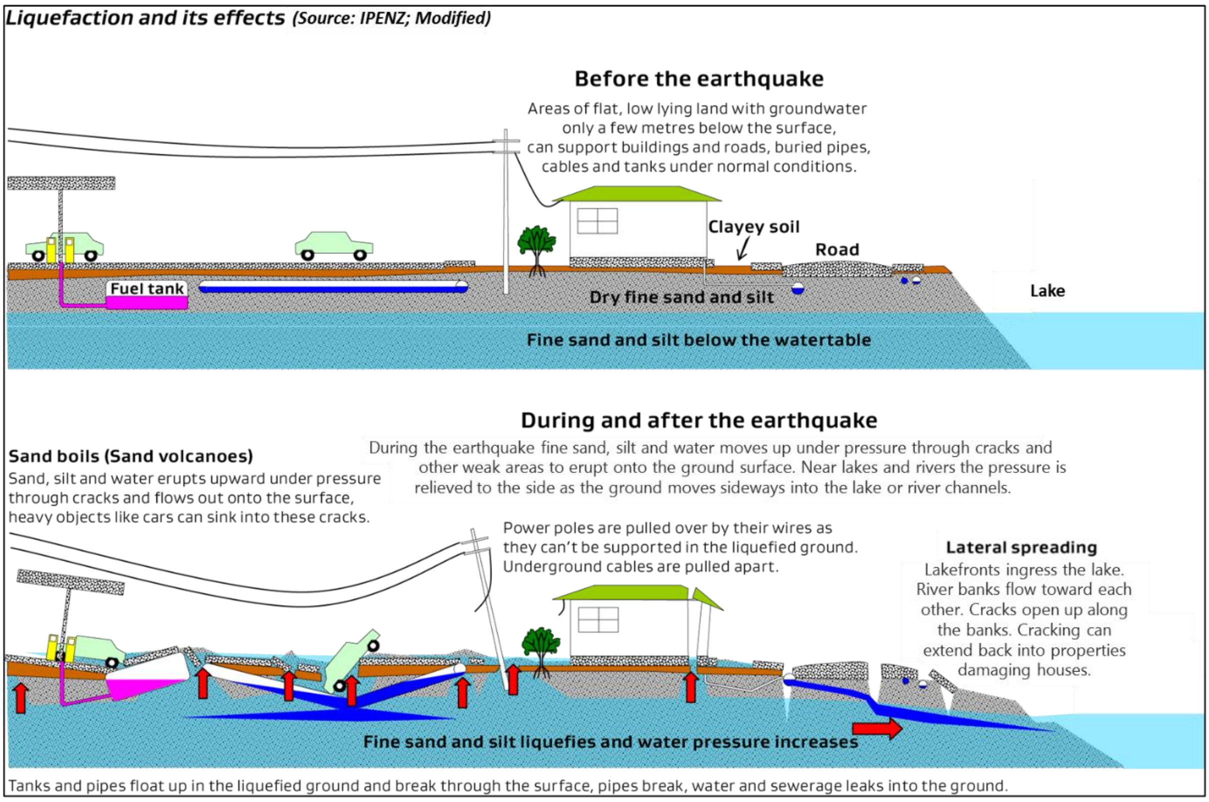


Figure 2.1: Visual schematic of the consequences of liquefaction.

Liquefied sand ejected from underneath a house.

Liquefied sand on the street, with piles of sand shovelled out from under and around houses.

Foundation and brickwork damage.

Liquefied sand that has broken through the floor slab and filled up inside the house.

Power transformer that has sunk into the liquefied ground.

Stormwater manholes that have floated up out of the liquefied ground.

Figure 2.2: Example photographs of the types of damage to land, buildings and infrastructure that could be expected in a large earthquake in the parts of Glenorchy categorised as Medium and High liquefaction vulnerability (without lateral spread).

Lateral spreading pulled this foundation beam out from underneath the house.

A 1m wide ground crack ran through the middle of this house, pulling the garage walls apart.

The cracks running under this house caused the front part to pull away and drop 0.5m.

Lateral spreading buckled this bridge and damaged the approaches, cutting the main trunk water supply and fibre optic cable running across the bridge.

Lateral spreading caused a series of 0.5m cracks and drops in this road.

Liquefaction and lateral spreading pushed these power poles over, and flooded the streets.

Figure 2.3: Example photographs of the types of damage to land, buildings and infrastructure that could be expected in a large earthquake in the parts of Glenorchy categorised as Major and Severe lateral spreading. For these examples the free face was about 4m high. In Glenorchy the free face is much higher (about 25m below lake level), so lateral spreading could be more severe and extend further inland.

3 How much risk is tolerable?

Before discussing potential options for managing liquefaction hazard, it is useful to ask the question "how much risk is tolerable". This helps to set a benchmark level of performance that the various different options can be compared against.

When it comes to natural hazards risk management and adaptation planning, there are no fixed rules about exactly how much risk is tolerable. Rather than being a purely technical engineering or legal question, this becomes a balance between costs and benefits, recognising that communities have many other objectives in addition to managing natural hazards. Finding the balance that best suits a particular situation requires a collaborative approach including the community, stakeholders, technical experts and decision-makers. To help with these discussions, Table 3.1 includes various factors that may be relevant when deciding how much liquefaction-related risk is tolerable.

Table 3.1: Relevant factors when deciding how much risk is tolerable

Factor	Comments
Life safety during an earthquake	Lateral spreading damage to buildings is the main life safety concern related to liquefaction. While there were no deaths caused by lateral spreading in the 2010 – 2011 Canterbury Earthquakes, this was more a matter of good luck rather than good design – if the shaking had been stronger or longer then building collapse could have occurred.
Habitability in the days and weeks after an earthquake	If buildings are severely damaged, it may not be possible to use them after the earthquake so people would need alternative accommodation. Damage to electricity, water supply, stormwater and sewer networks would also impact on habitability, potentially for many months (or longer) after the earthquake. These issues could be worsened if earthquake damage cuts off the only road in and out of the town.
Long term recovery after an earthquake	While it is the most severe damage which often attracts most attention immediately after an earthquake, a more significant issue for long term recovery can sometimes be the minor and moderate damage (as it can be much more extensive). While it may be possible to continue living with this damage until it is eventually repaired, there can be far-reaching economic, social and environmental consequences.
Other hazards	Some locations may also be exposed to other hazards (e.g. flood) and cascading hazards (e.g. liquefaction settlement leaves building more flood-prone).
Building Act	All building work must comply with the Building Code regardless of whether a building consent is required, and irrespective of whether it is to construct a new building or to repair or alter an existing building. In the case of alterations or repairs it is only the new work that must comply with the current Building Code. If existing parts of the building do not comply, then the main requirement (with some exceptions) is that the alterations or repairs do not result in the building complying with the Building Code to a lesser extent than before. The Building Act requires councils to refuse building consent if the land is likely to be subject to natural hazards, unless adequate steps are taken to protect against the hazard. However, the Act provides a specific list of hazards that this applies to, and it is unclear whether this includes earthquakes and liquefaction. Nonetheless, it is useful to note that the test of whether a hazard is considered "likely" has been defined as a "100 year" event (which has a 40% chance of occurring over the next 50 years).

Table 3.1 (continued): Relevant factors when deciding how much risk is tolerable

Factor	Comments
Building Code minimum requirements	For most "normal" buildings (and other structures) the Building Code mandates minimum acceptable performance for two earthquake scenarios: The Serviceability Limit State (SLS) is assessed for "25 year" earthquake shaking levels (a 90% chance of occurring over the next 50 years). The building should suffer little or no structural damage and remain accessible and safe to occupy. There may be minor damage to building fabric that is readily repairable. The Ultimate Limit State (ULS) is assessed for "500 year" earthquake shaking levels (a 10% chance of occurring over the next 50 years). The building is expected to suffer moderate to significant structural damage (which might not be repairable), but not to collapse.
Resource Management Act (RMA)	The RMA identifies management of significant risks from natural hazards as a matter of national importance, which means it needs to be considered at all levels of planning and decision-making. The RMA also gives councils power to refuse or place conditions on subdivision consents where there is a significant natural hazard risk.
Insurance and mortgages	Insurers each make their own decisions about natural disaster risk, often balancing many different factors. The availability and cost of insurance is subject to these decisions. In New Zealand there is an increasing trend of insurers moving toward more "risk-based" pricing where specific attributes (such as location and presence of hazards) are taken into account in both deciding whether to offer cover, and in determining the cost of providing that cover. Following the Christchurch earthquakes, most insurers adopted an approach where new dwellings would be provided insurance cover on the basis that compliance with the Resource Management Act and Building Act/Code largely provided mitigation of the hazards potentially affecting the dwelling. In general, insurers were more concerned with existing dwellings on land that was revealed to be both liquefaction and flood prone, as there was little opportunity to mitigate the hazards for existing buildings. In the past banks have typically provided mortgage lending as long as insurance was in place, however in future banks may also undertake their own independent assessment of natural hazard risk before offering lending.
Chance of an earthquake occurring	The T+T May 2022 liquefaction assessment report concluded that significant damage due to liquefaction and lateral spreading could be expected at a "50 to 100 year" level of earthquake shaking (a 40 – 60% chance of occurring over the next 50 years). The Alpine Fault is particularly relevant, as it passes relatively close to Glenorchy (55km at its nearest point). There is a 75% chance of a large earthquake occurring on the Alpine Fault within the next 50 years. It is likely that a large Alpine Fault earthquake would cause significant liquefaction and lateral spreading damage in Glenorchy, however there is some uncertainty in the severity and extent of damage that could occur.
Type of land use activity	There are many different ways that land can be used, such as for housing, commercial activity, infrastructure, recreation, environmental purposes etc. Because each of these different land uses has different consequences if damaged in an earthquake, they each have different risk profiles. This means that a particular degree of liquefaction-induced damage might be tolerable for some types of land uses but not for others.

4 What can be done to manage the risk?

There is a wide range of possible approaches for managing the risks from natural hazards, as illustrated in Figure 4.1 below. It is not necessary to select just a single approach, in fact it is often best to combine multiple approaches to find the best balance for the particular situation faced by each individual community.

This report discusses only engineering approaches for managing liquefaction-related risk, as ORC will be considering other types of approaches and other hazards separately. The primary focus of this report is on mitigation which reduces the potential impact of liquefaction. This can be achieved by reducing how often damage occurs (so a larger earthquake is needed to trigger damage), by decreasing the severity of that damage when it occurs and making it easier to repair afterwards. However, this report also provides information about the potential impacts after mitigation is undertaken (or with no mitigation), to help ORC and the community make informed decisions about what residual risks[1] it might be appropriate to accept.

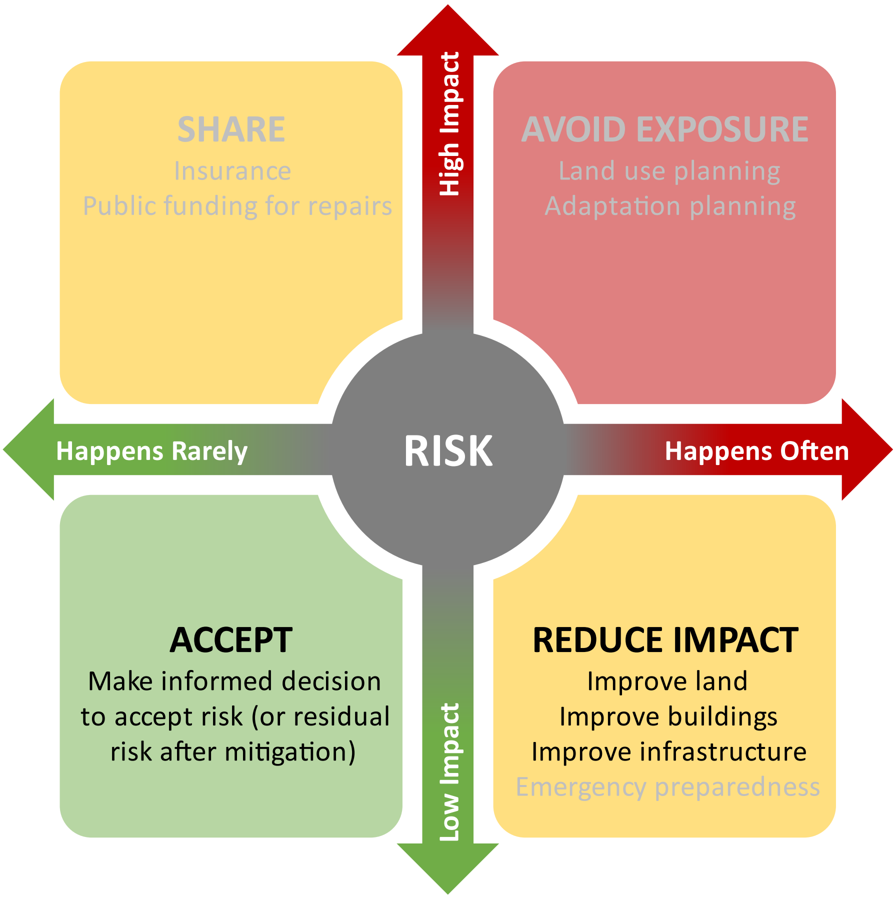


Figure 4.1: Example aproaches for managing the risks from natural hazards, depending on the frequency of the event and severity of the impacts. This report focusses only on engineering approaches only (black text above). Other approaches also exist (grey text above), however Otago Regional Council will be considering these separately.

[1] "Residual risk" is the risk that remains even after all adopted risk management measures are implemented. It is usually not practical or affordable to completely eliminate all risks. One of the goals of risk management is to find the point where the residual risk is reduced to a level which is acceptable, or the point of "diminishing returns" where further investment in risk management measures does not give a worthwhile reduction in the overall level of residual risk.

5 What engineering mitigation techniques are available?

There are various mitigation techniques available for protecting land, buildings and infrastructure from the effects of liquefaction. The techniques considered for this assessment are summarised in Table 5.1, Table 5.2 and Table 5.3 table below. The options are listed in order from the most robust (and also the most expensive, disruptive and time-consuming) at the top, through to the least robust (and least expensive, disruptive and time-consuming) at the bottom.

We have considered a wide range of options, spanning from very robust options through to a "do nothing" option. At the more robust end of the range, there could be many cases where undertaking the work would be impractical or unaffordable. At the less robust end of the range, there could be many cases where new buildings might not meet minimum the Building Code requirements for building consent, or where it may become more difficult to obtain insurance because of the high residual risk. However, rather than pre-judge any outcomes and rule out any options immediately we have included them in this report to provide context for discussion about a wide range of approaches that exist.

In New Zealand it is rare for ground improvement for mitigation of liquefaction hazards (as presented in Table 5.1 below) to be undertaken at a township or suburb scale, however over the past two decades there have been some examples of large-scale ground improvement (tens of hectares in area) as part of new subdivision construction.

Similarly, while residential buildings in New Zealand have historically not been designed to accommodate the effects of liquefaction, this is now becoming standard practice where liquefaction-prone soils are present. The MBIE Canterbury rebuild guidance[2] provides a range of foundation concepts which offer improved robustness and ability to tolerate the effects of liquefaction, as summarised in Table 5.2 below. While initially intended for the Canterbury rebuild, it has proven to be useful more widely across the country to help guide resilient foundation design. These foundations are grouped into three "Technical Categories" (TC's) depending on the potential consequences of liquefaction and the level of geotechnical investigation and specific engineering design required:

TC1: Future land damage from liquefaction is unlikely, and ground settlements from liquefaction effects are expected to be within normally accepted tolerances. Shallow geotechnical investigations are required, and if a 'good ground' test is met then conventional NZS 3604 foundations (simple concrete slabs or suspended timber floors) can be used.

TC2: Liquefaction damage is possible in future large earthquakes. Shallow geotechnical investigations are required and if this proves that the ground has sufficient strength then "off the shelf" suspended timber floor or enhanced slab foundation options can be used.

TC3: Liquefaction damage is possible in future large earthquakes. Deep geotechnical investigation (or assessment of existing information) and depending on the geotechnical assessment, might require specific engineering design for foundations.

[2] https://www.building.govt.nz/building-code-compliance/canterbury-rebuild/repairing-and-rebuilding-houses-affected-by-the-canterbury-earthquakes/

Table 5.1: Liquefaction mitigation techniques for reducing damage to land

Mitigation works	Description
15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	A long vibrating probe is used to compact the ground and inject gravel to form columns about 1m in diameter, in a grid pattern at about 2m spacings. This strip of very deep improvement along the lake edge acts like an “underground dam” of solid ground which helps to hold back the liquefied ground and reduce lateral spreading ground displacements. Perimeter treatment can help reduce the lateral spreading hazard for areas further inland (but the inland ground could still experience settlement damage if the underlying ground liquefies).
12m deep ground improvement, all land	Ground compaction and gravel columns as above, covering all land in an area (e.g. under buildings, roads and the land in between). Only 12m deep so there is still potential for the ground deeper than this to liquefy. This means that liquefaction settlement and lateral spreading could still occur, but the magnitude of displacement should be less.
12m deep ground improvement, land under buildings & infrastructure only	Ground compaction and gravel columns as above, but only covering land under buildings & infrastructure (no improvement of land in between). This will form individual “islands” of ground improvement which can help to reduce settlement and lateral spreading (but less effective at controlling lateral spreading that the options above).
12m deep ground improvement, land around buildings & infrastructure where accessible	This ground improvement approach could be considered where there are existing buildings & infrastructure, to avoid the need relocate them to improve underneath. The main benefit of this is reducing lateral spreading by improving a block of surrounding ground. Significant ground settlement could still occur due to liquefaction of the unimproved ground beneath.
4m deep ground improvement, land under buildings & infrastructure only	There are various shallow ground improvement methods which could be used to compact the upper 4m of the soil profile, including gravel columns (as above), dynamic compaction (a crane drops a weight on the ground) and impact compaction (a square roller or hammer hits the ground). This will have little effect on lateral spreading displacements, but can help reduce the severity of differential ground settlement due to liquefaction and ejected soil. Therefore this option is more applicable in areas further inland where less lateral spreading is expected, or in conjunction with perimeter treatment to reduce lateral spreading displacements.
1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only	This method provides a stiff platform of well compacted and reinforced gravel beneath buildings & infrastructure. The main benefit of this is to help reduce the severity of differential ground settlement due to liquefaction and ejected soil. The geogrid can help reduce the magnitude of lateral ground stretching to some degree (encouraging cracks to instead form on either side), but is less effective than deep ground improvement for controlling lateral spread. Therefore this option is more applicable further inland where less lateral spread is expected, or in conjunction with perimeter treatment which reduces lateral spreading.
No improvement	Ground remains in its current state within an area. However, in some mitigation scenarios ground improvement in a neighbouring area may help to provide some reduction in lateral spreading ground displacement, so we have made allowance for this in our damage estimates where appropriate.
NOTE: The details quoted in this table (such as depth and extent of treatment) are intended to be indicative only, to provide a general picture of the relative scale of the various options. Actual details would need to be determined as part of the design process, to meet agreed target performance requirements.	

Table 5.2: Liquefaction mitigation techniques for reducing damage to buildings

Mitigation works	Description
New TC3 surface structure foundations	The MBIE Canterbury rebuild guidance provides five concepts for raised platform foundations designed to accommodate significant ground settlement and lateral spreading while limiting deformation of the overlying structure. Settlement and damage is still expected to occur, but the aim is for this to be readily repairable. Existing buildings would need to be temporarily lifted, and possibly relocated, for the new foundation to be constructed underneath. This foundation type also has the added benefit of raising floor levels higher above flood levels.
New TC2 waffle slab foundation or enhanced lightweight platform on timber piles	The MBIE Canterbury rebuild guidance provides numerous TC2-type foundation options, however the most commonly adopted are waffle slab foundations (for concrete slabs) and enhanced lightweight platforms (for timber floors). Existing buildings would need to be temporarily lifted, and possibly relocated, for the new foundation to be constructed underneath. Enhanced lightweight platforms also have the added benefit of raising floor levels higher above flood levels.
Retrofit to strengthen existing foundations and buildings	While the primary focus of the MBIE Canterbury rebuild guidance is on robust design of new buildings and repair of damaged buildings, some of the same concepts could be applied for proactive retrofit strengthening of existing buildings. This would avoid the need to lift/relocate existing buildings, but might not provide the same performance as a new TC2 or TC3 foundation. For timber floor foundations this could include subfloor sheet bracing, bolt-spliced bearers, and enhanced connections between piles and bearers. Retrofit strengthening may be more difficult for concrete slab foundations, but could include internal and perimeter tie beams and edge stiffening. There may also be opportunities to enhance the superstructure, such as sheet claddings/linings, lightweight roof/cladding, stiffening walls, and enhanced connections between walls and roof framing.
No improvement	Foundation and building remain in their current state.
NOTE: The foundation concepts in this table are for simple lightweight timber-frame buildings (such as typical houses, or small commercial buildings of similar construction). It might be possible to apply similar concepts to other types of building, but this would need specific engineering assessment. For all buildings, actual details would need to be determined as part design, to meet Building Code performance requirements for building consent.	

Table 5.3: Liquefaction mitigation techniques for reducing damage to infrastructure

Mitigation works	Description
New infrastructure with resilient detailing	New infrastructure should incorporate resilient detailing to better accommodate displacement. This includes avoiding higher hazard areas, providing redundancy within a system, adopting appropriate technology (e.g. pressure sewer), careful selection of pipe/cable materials, robust/flexible connections, utilising details that resist uplift, and granular/cemented trench backfill.
Retrofit to strengthen existing infrastructure	For existing infrastructure, opportunities to enhance the entire network can be more limited (short of complete replacement). However, detailed assessment of the system may identify critical "weak links" where targeted upgrades can improve the overall resilience of the wider network.
No improvement	Infrastructure remains in its current state.

6 How could these mitigation techniques be applied across Glenorchy?

Two of the important factors when deciding what type of mitigation (if any) is undertaken at particular locations across the town are:

- The current vulnerability of the ground to liquefaction and lateral spreading at the location. This is shown on the map in Figure 1.1.
- Whether there are existing buildings and infrastructure at the location, or whether new development is proposed.

Table 6.1 and Table 6.2 below summarise a range of potential layouts for how liquefaction mitigation could be undertaken across Glenorchy. The options are listed in order from the most robust (and also the most expensive and disruptive) at the top, through to the least robust (and least expensive and disruptive) at the bottom. The options towards the top of the table might prove to be impractical or unaffordable, while the options towards the bottom of the list might not meet building consent requirements or be difficult to obtain insurance for. However, rather than rule any options out immediately we have included them in this report to provide context for discussion.

At this stage it is uncertain whether it would be feasible to undertake ground improvement underneath existing buildings and infrastructure, and this may vary depending on the specific details of each situation. Therefore our assessment has considered both potential outcomes to help understand the implications either way:

- For Table 6.1, we have assumed that it would be feasible to undertake ground improvement beneath existing buildings and infrastructure (Options A1 to C1). This would help to provide protection against both liquefaction settlement and lateral spreading. Existing buildings would need to be temporarily lifted, and probably relocated, for the ground improvement to be constructed underneath. For some types of existing infrastructure it may be possible to undertake ground improvement on either side to protect the infrastructure. For other types of existing infrastructure it may be more practical to install new robust infrastructure after the ground improvement, rather than attempting to improve underneath the existing.
- For Table 6.2, we have assumed that it would not be feasible to undertake ground improvement beneath existing buildings and infrastructure (Options A2 to C2). For these options, we have instead assumed ground improvement is undertaken in the clear space around buildings and infrastructure. This would help to provide some degree of protection against lateral spreading, but not liquefaction settlement.

Further consideration of these options is provided in Appendix A, including the degree to which they might reduce the liquefaction hazard and the level of damage.

Table 6.1: Mitigation options - ground improvement under existing buildings & infrastructure

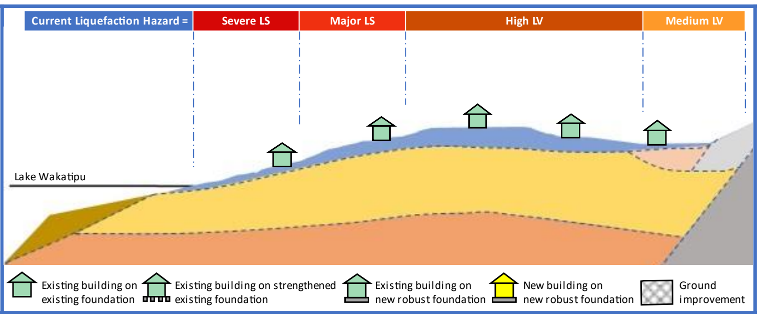
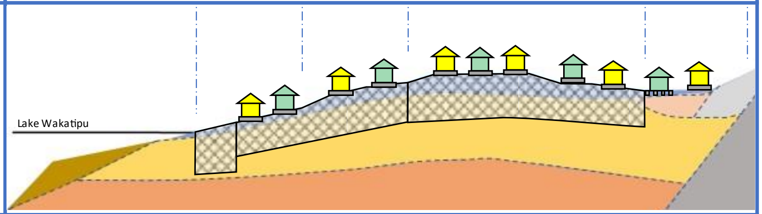
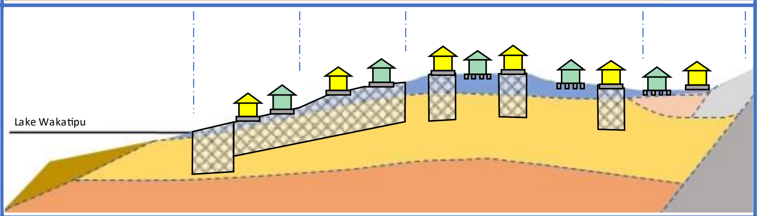
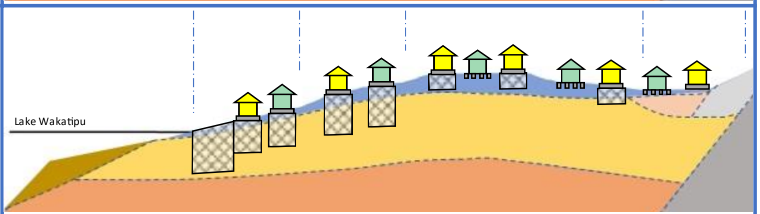
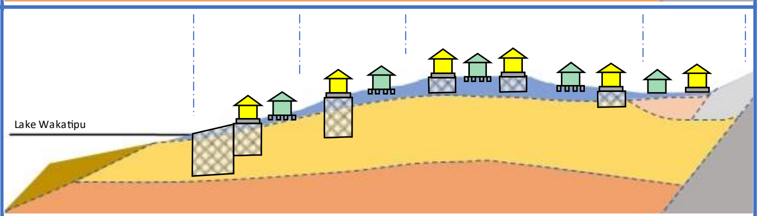
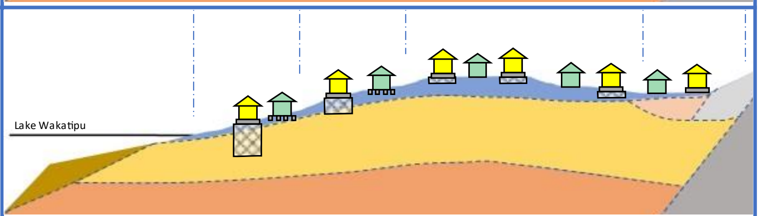
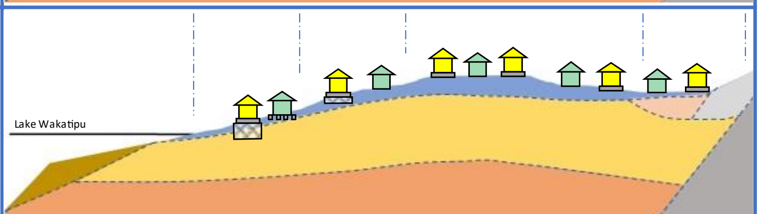
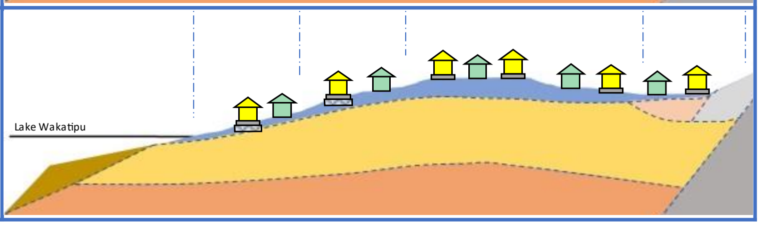
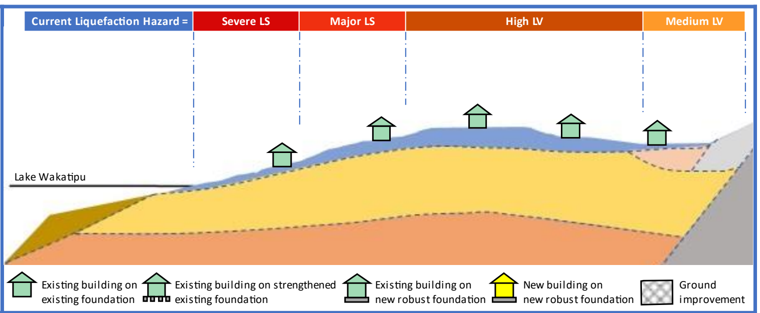
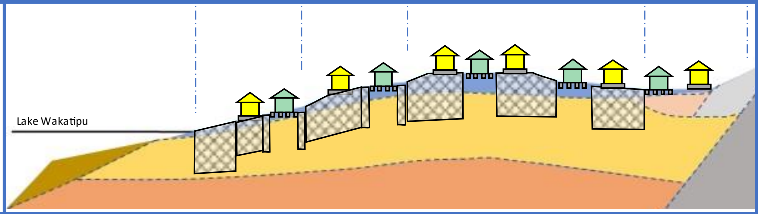
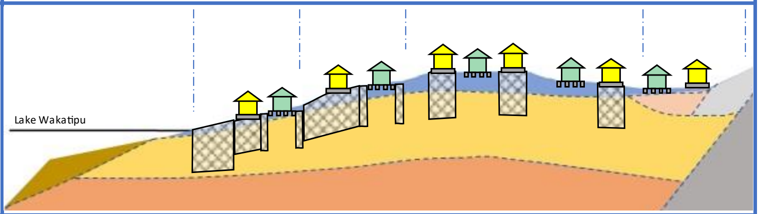
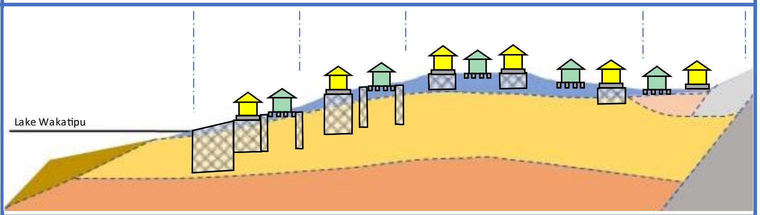
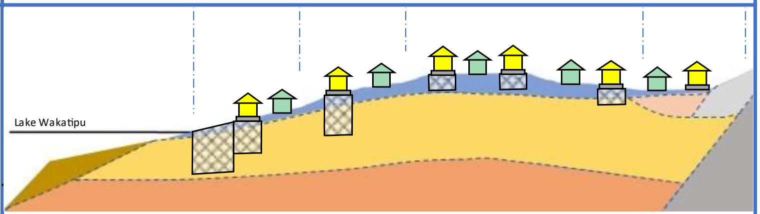
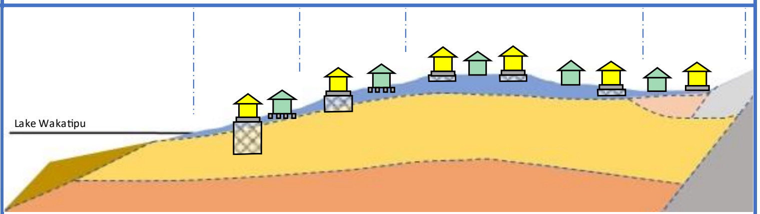
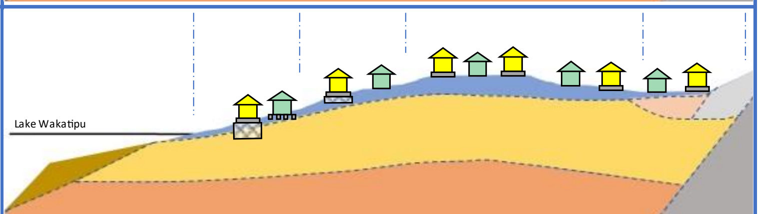
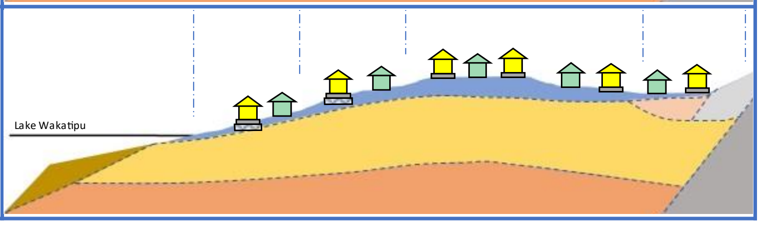
Current situation	
Option A1 Perimeter treatment beside lake. Deep ground improvement and robust foundations & infrastructure for all of lateral spread and High LV area. Elsewhere, robust new buildings and infrastructure, and retrofit strengthening for existing.	
Option B1 Perimeter treatment beside lake. Deep ground improvement and robust foundations & infrastructure for all of lateral spread area, and under new robust buildings and infrastructure for High LV area. Elsewhere, robust new buildings and infrastructure, and retrofit strengthening for existing.	
Option C1 Perimeter treatment beside lake. In lateral spread area deep ground improvement under robust buildings & infrastructure. In High LV area shallow ground improvement under robust new buildings & infrastructure. Elsewhere, robust new buildings & infrastructure, and retrofit strengthening for existing.	
Option D1 Perimeter treatment beside lake. In lateral spread area deep ground improvement under robust new buildings & infrastructure. In High LV area shallow ground improvement under robust new buildings & infrastructure. Elsewhere, robust new buildings & infrastructure, and retrofit strengthening for existing (except Medium LV).	
Option E In Severe LS area deep ground improvement under new robust buildings & infrastructure, reducing to shallow improvement for Major LS area. In High LV area gravel rafts under robust new buildings & infrastructure. Elsewhere, robust new buildings & infrastructure. Retrofit strengthen existing buildings & infrastructure in lateral spread area.	
Option F In Severe LS area shallow ground improvement under new robust buildings & infrastructure, reducing to gravel rafts for Major LS area. Elsewhere, robust new buildings & infrastructure. Retrofit strengthening for existing buildings & infrastructure in Severe LS area.	
Option G In lateral spread area gravel rafts under robust new buildings & infrastructure. Elsewhere, robust new buildings & infrastructure. No retrofit strengthening for existing buildings & infrastructure.	

Table 6.2: Mitigation options - no ground improvement under existing buildings & infrastructure

Current situation	
Option A2 Perimeter treatment beside lake. Deep ground improvement and robust foundations & infrastructure for all accessible parts of lateral spread and High LV area. Elsewhere, robust new buildings and infrastructure, and retrofit strengthening for existing.	
Option B2 Perimeter treatment beside lake. Deep ground improvement and robust foundations & infrastructure for all accessible parts of lateral spread area, and under new robust buildings and infrastructure for High LV area. Elsewhere, robust new buildings and infrastructure, and retrofit strengthening for existing.	
Option C2 Perimeter treatment beside lake. In lateral spread area deep ground improvement under new robust buildings & infrastructure, or around existing where accessible. In High LV area shallow ground improvement under robust new buildings & infrastructure. Elsewhere, robust new buildings & infrastructure, and retrofit strengthen existing.	
Option D2 Perimeter treatment beside lake. In lateral spread area deep ground improvement under robust new buildings & infrastructure. In High LV area shallow ground improvement under robust new buildings & infrastructure. Elsewhere, robust new buildings & infrastructure. No retrofit strengthening of existing buildings & infrastructure	
Option E In Severe LS area deep ground improvement under new robust buildings & infrastructure, reducing to shallow improvement for Major LS area. In High LV area gravel rafts under robust new buildings & infrastructure. Elsewhere, robust new buildings & infrastructure. Retrofit strengthen existing buildings & infrastructure in lateral spread area.	
Option F In Severe LS area shallow ground improvement under new robust buildings & infrastructure, reducing to gravel rafts for Major LS area. Elsewhere, robust new buildings & infrastructure. Retrofit strengthening for existing buildings & infrastructure in Severe LS area.	
Option G In lateral spread area gravel rafts under robust new buildings & infrastructure. Elsewhere, robust new buildings & infrastructure. No retrofit strengthening for existing buildings & infrastructure.	

7 How well do these mitigation options work?

The very thick deposits of liquefiable soil under Glenorchy, and the very high free face at the lake edge, mean that it will be challenging to improve the performance of the land in an earthquake. Even with very extensive ground improvement to reduce the liquefaction and lateral spreading hazard, it is unlikely that the hazard could be eliminated. This means that it is important to understand the level of “residual risk” that would remain even after mitigation works were undertaken.

An understanding of residual risk can help to guide discussion about mitigation options, and comparison against other non-engineering risk management approaches (e.g. land use planning and emergency preparedness). This can be useful to help to find the point of “diminishing returns” where the additional benefits of undertaking more robust mitigation do not justify the additional costs. This should consider not just financial benefits, but also social and environmental measures.

Table 7.1 below provides a general picture of the residual liquefaction hazard that would remain after each mitigation option was implemented. Table 7.2 presents a similar summary, looking at the approximate proportion of buildings and infrastructure expected to experience severe liquefaction-induced damage for each option[3]. As explained above, even for the most robust mitigation options listed, there remains significant liquefaction hazard and potential for damage.

When considering the cost and benefits of mitigation works, it can be useful to ask the question “who benefits from the mitigation work?”, which runs in parallel with a similar question of “who bears the costs?”. For mitigation options which include deep ground improvement over a large area, there can be benefits for other properties further inland if these works help to reduce the severity of lateral spreading towards the lake. Similarly, ground improvement which helps to protect infrastructure at locations of highest hazard or “weak links” can have benefits to many users across the wider network.

[3] This damage analysis is based on generalised damage trends observed from the 2010-2011 Canterbury Earthquakes. The analysis uses damage data for ground conditions and types of buildings which are generally similar to those in Glenorchy, but it is not based on a specific analysis of the individual buildings in Glenorchy. For this analysis, severe damage to buildings and infrastructure is taken to mean that it would likely be impractical or uneconomic to repair. There will also be additional buildings and infrastructure which are damaged, but not as severely. As the proportion of severe damage increases, the general scale and nature of this other damage will also worsen.

Table 7.1: Indicative liquefaction hazard, after mitigation works are undertaken

	EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:	Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Option A1	High LV	High LV	Medium LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Option B1	High LV	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Option C1	High LV	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Option D1	Severe LS	Major LS	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Option E	Severe LS	Major LS	High LV	Medium LV	Major LS	Major LS	High LV	Medium LV
Option F	Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Option G	Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Option A2	Major LS	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Option B2	Major LS	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Option C2	Major LS	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Option D2	Severe LS	Major LS	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV

Table 7.2: Indicative proportion of buildings & infrastructure with severe liquefaction damage in a large earthquake, after mitigation works are undertaken

	EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:	Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Expected damage for current ground conditions:	90%	75%	50%	25%	-	-	-	-
Option A1	30%	25%	15%	15%	25%	20%	10%	10%
Option B1	30%	25%	40%	15%	25%	20%	15%	10%
Option C1	35%	30%	40%	15%	30%	25%	20%	10%
Option D1	55%	50%	40%	25%	35%	30%	20%	10%
Option E	75%	65%	50%	25%	40%	40%	25%	10%
Option F	80%	75%	50%	25%	50%	50%	30%	10%
Option G	90%	75%	50%	25%	60%	50%	30%	10%
Option A2	45%	40%	40%	15%	30%	25%	10%	10%
Option B2	45%	40%	40%	15%	30%	25%	15%	10%
Option C2	45%	40%	40%	15%	30%	25%	20%	10%
Option D2	65%	60%	50%	25%	35%	30%	20%	10%

NOTE: These table are intended to be indicative only, to provide a general picture of the relative effectiveness of the various options. Actual performance in an earthquake is expected to be variable, with some locations experiencing more damage than listed above, and some locations experiencing less.

8 How much do these mitigation options cost?

As this is an initial concept report only, we have not undertaken any analysis or design for the various mitigation options presented. However, we have developed assumed mitigation concepts based on our experience assessing area-wide remediation options for the “Red Zone” following the Canterbury Earthquakes. Similarly, we have not undertaken project-specific cost estimation, instead relying on indicative cost information from ground improvement trials undertaken by the Earthquake Commission following the Canterbury Earthquakes. Based on these preliminary assumptions, we have prepared, in relative terms, an approximate comparison of potential estimates for the various mitigation options, as summarised in Table 8.1.

When considering the cost and benefits of mitigation works, it can be useful to ask the questions “when are the costs incurred?” and “when are the benefits received”. One of the challenging aspects of liquefaction mitigation works is that there can be a significant up-front cost to undertake the work, but most of the benefit is not received until some uncertain time in the future when an earthquake occurs. This means that a very long-term view is required when evaluating options for managing liquefaction-related risk. It also means that the engineering analysis and design needs to strike a careful balance to avoid being overly pessimistic or optimistic. There can be significant current-day costs for construction if the mitigation design is more robust than is actually needed, but also significant future costs from damage if the mitigation design is not robust enough.

The same as when assessing benefits, the viability assessment should consider not just financial costs, but also social and environmental measures, and the opportunity cost of investing in mitigation works instead of other things. Given the current economic environment, careful consideration of cost inflation would also be prudent.

Table 8.1: Indicative relative comparison of estimates for mitigation works

		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	$$$$	$$$$	N/A	N/A	$$$$	$$$$	N/A	N/A
LAND	12m deep ground improvement, all land	$$$$$	$$$$$	$$$$$	N/A	$$$$$	$$$$$	$$$$$	N/A
LAND	12m deep ground improvement, land under buildings & infrastructure only	$$$$	$$$$	$$$$	N/A	$$$$	$$$$	$$$$	N/A
LAND	12m deep ground improvement, land around buildings & infrastructure where accessible	$$$$	$$$$	N/A	N/A	N/A	N/A	N/A	N/A
LAND	4m deep ground improvement, land under buildings & infrastructure only	$$$	$$$	$$$	N/A	$$$	$$$	$$$	N/A
LAND	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only	$$$	$$$	$$$	N/A	$$$	$$$	$$$	N/A
LAND	No land improvement	-	-	-	-	-	-	-	-
BUILDINGS	New TC3 surface structure foundations	$$$$	$$$$	$$$$	N/A	$$$	$$$	$$$	N/A
BUILDINGS	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles	N/A	N/A	N/A	$$$	N/A	N/A	N/A	$
BUILDINGS	Retrofit to strengthen existing foundations and buildings	$$	$$	$	$	N/A	N/A	N/A	N/A
BUILDINGS	No foundation or building improvement	-	-	-	-	-	-	-	-
INFRASTRUCTURE	New infrastructure with resilient detailing	$	$	$	$	$	$	$	$
INFRASTRUCTURE	Retrofit to strengthen existing infrastructure	$	$	$	$	N/A	N/A	N/A	N/A
INFRASTRUCTURE	No infrastructure improvement	-	-	-	-	-	-	-	-

INDICATIVE RELATIVE COST SCALE

-	No mitigation works, so no construction cost
$	Estimate in the order of $25,000
$$	Estimate in the order of $50,000
$$$	Estimate in the order of $100,000
$$$$	Estimate in the order of $200,000
$$$$$	Estimate more than $300,000
N/A	Mitigation option is not applicable for this scenario

Notes:
1) These indicative estimates are based on the results of the EQC residential ground improvement trials and ground improvement pilot projects undertaken in 2015, uplifted by 50% for construction cost inflation between 2015 and 2022.
2) All estimates are per property, assuming an average building footprint of 150m^2 on a lot size of 800m^2.
3) For perimeter treatment & infrastructure, the total estimate for mitigation is divided between the properties which benefit.
4) For existing development, TC2 and TC3 foundation estimates include the foundation construction as well as the enabling and reinstatement works required (e.g. lifting the existing building, repairing damage and reinstating services). These estimates relate to the direct construction work only, and do not include indirect costs such as overall community-wide programme management or temporary accommodation.
5) For new development, TC2 and TC3 foundation estimates are calculated as the additional over and above a NZS3604 foundation (the standard foundation typically used for ground that is not liquefaction-prone).
6) Infrastructure mitigation works relate to underground services only. Estimates are calculated as the additional over and above standard infrastructure construction on ground that is not liquefaction-prone.
7) The estimates presented in this report are indicative only, to illustrate the potential order of magnitude and relativity between options. These estimates are based on assumed concepts – no analysis or design has been undertaken. Consequently, a significant margin of uncertainty exists on the estimates. If decision-making is found to be sensitive to these estimates, then we recommend further, more location-specific engineering design and construction cost advice is sought.

9 Applicability

This report has been prepared for the exclusive use of our client Otago Regional Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

The cost estimates presented in this report are indicative only, to illustrate the potential order of magnitude and relativity between options. These estimates are based on assumed concepts – no analysis or design has been undertaken. In particular, we have not made any attempt to allow for the potential impact of COVID-19 in this estimate. Also, supply chain disruptions are currently having quickly-changing effects on construction costs and schedules. Consequently, a significant margin of uncertainty exists on the estimates. If decision-making is found to be sensitive to these estimates, then we recommend further, more location-specific engineering design and construction cost advice is sought.

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Document control

Title: Head of Lake Wakatipu Natural Hazards Adaption – Engineering Approaches for Managing Liquefaction-Related Risk					
Date	**Version**	**Description**	**Prepared by:**	**Reviewed by:**	**Authorised by:**
8-Feb-2023	1	Client issue	M. Jacka	S. van Ballegooy	T. Morris

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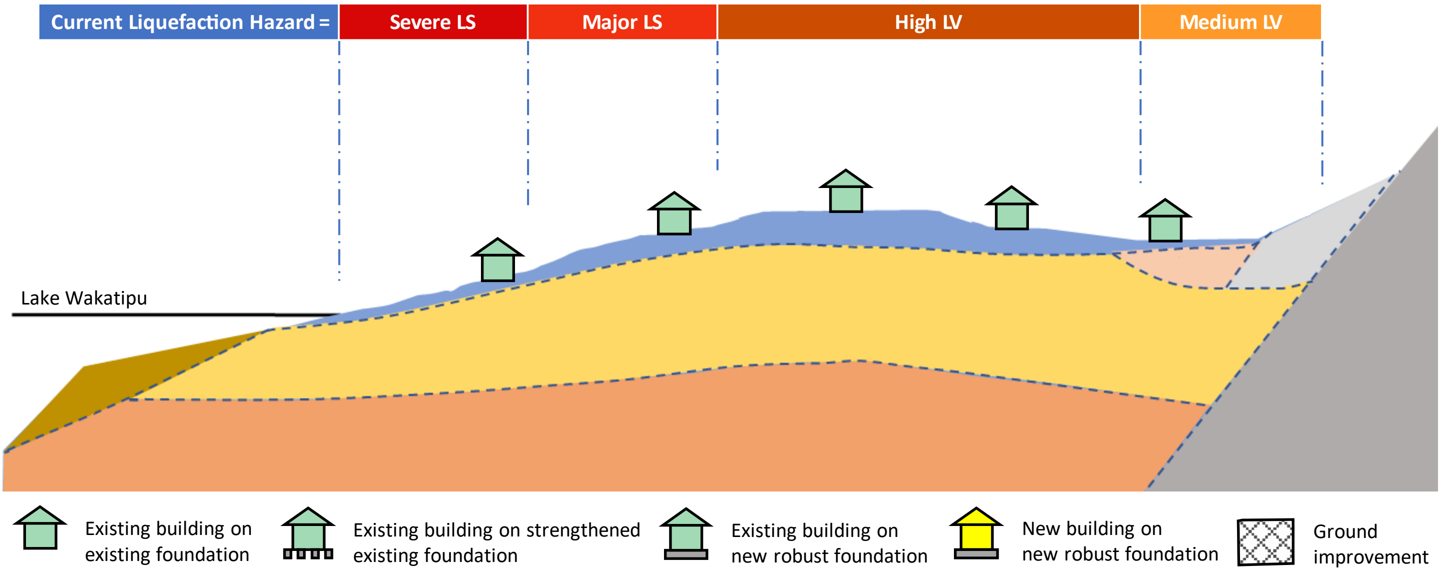
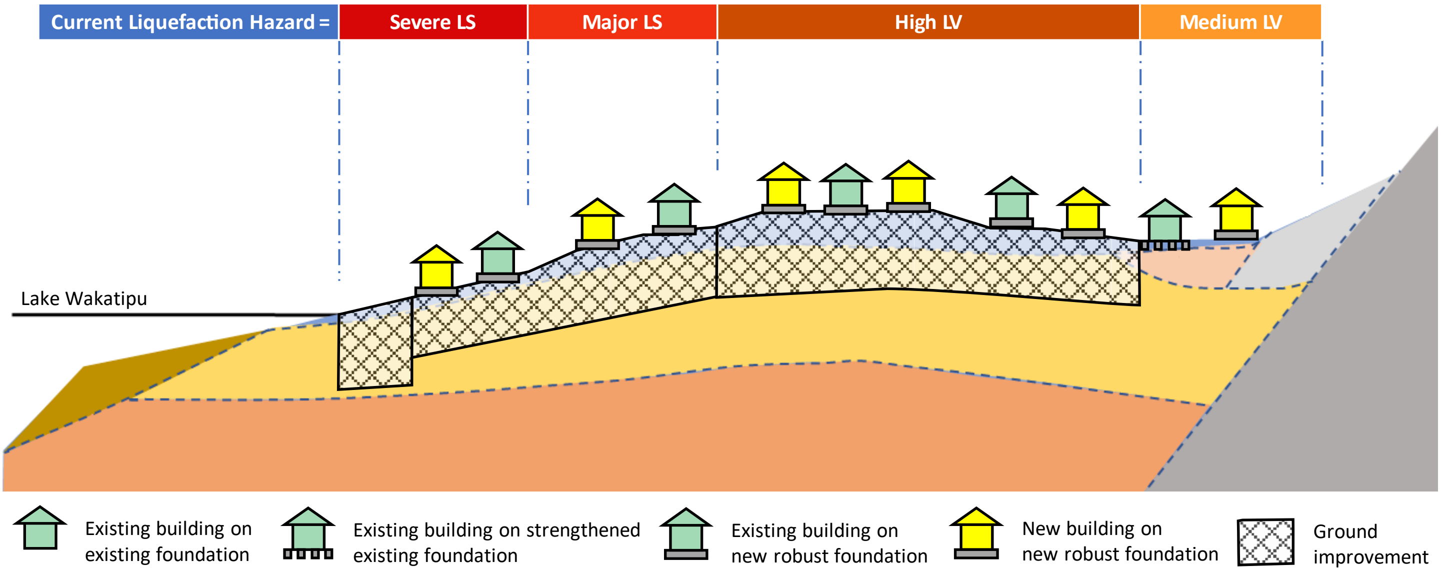
Appendix A Mitigation concept layouts

Existing situation



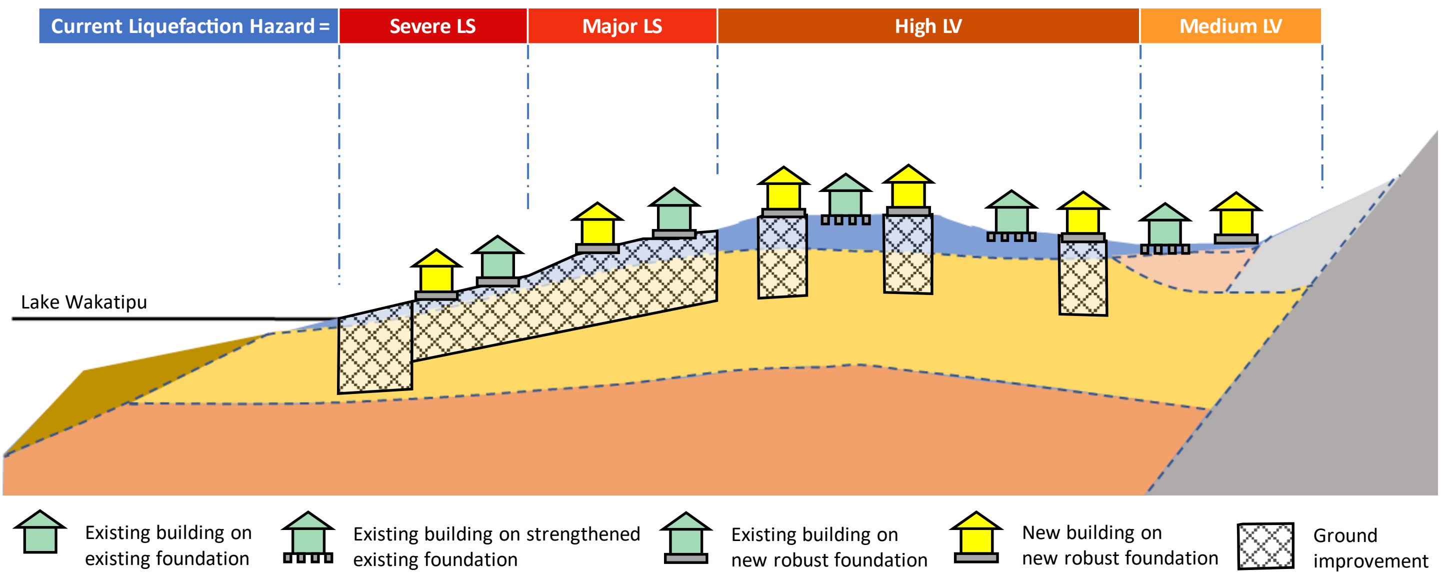
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	-	-	-	-
Post-mitigation liquefaction hazard:		-	-	-	-	-	-	-	-
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		-	-	-	-	-	-	-	-
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake								
	12m deep ground improvement, all land								
	12m deep ground improvement, land under buildings & infrastructure only								
	12m deep ground improvement, land around buildings & infrastructure where accessible								
	4m deep ground improvement, land under buildings & infrastructure only								
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only								
	No land improvement	X	X	X	X				
BUILDINGS	New TC3 surface structure foundations								
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles								
	Retrofit to strengthen existing foundations and buildings								
	No foundation or building improvement	X	X	X	X				
INFRASTRUCTURE	New infrastructure with resilient detailing								
	Retrofit to strengthen existing infrastructure								
	No infrastructure improvement	X	X	X	X				

Option A1



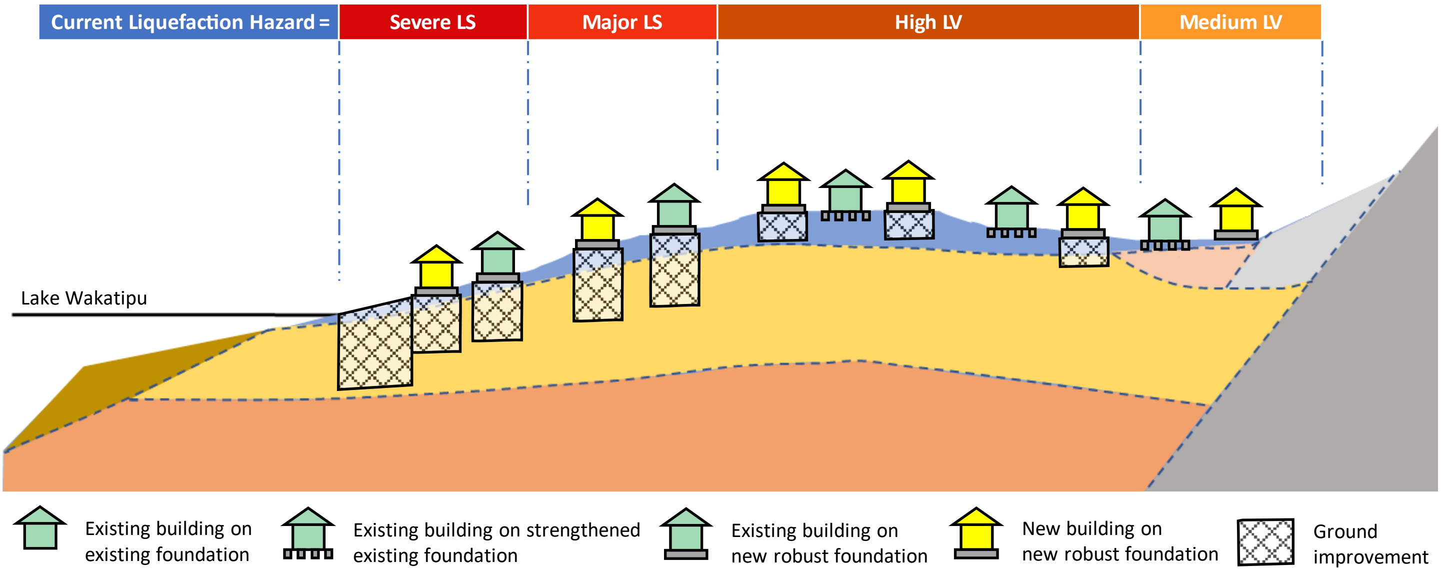
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		High LV	High LV	Medium LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		30%	25%	15%	15%	25%	20%	10%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	X				X			
	12m deep ground improvement, all land	X	X	X		X	X	X	
	12m deep ground improvement, land under buildings & infrastructure only								
	12m deep ground improvement, land around buildings & infrastructure where accessible								
	4m deep ground improvement, land under buildings & infrastructure only								
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only								
	No land improvement				X				X
BUILDINGS	New TC3 surface structure foundations	X	X			X	X		
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles			X				X	X
	Retrofit to strengthen existing foundations and buildings				X				
	No foundation or building improvement								
INFRASTRUCTURE	New infrastructure with resilient detailing	X	X	X		X	X	X	X
	Retrofit to strengthen existing infrastructure				X				
	No infrastructure improvement								

Option B1



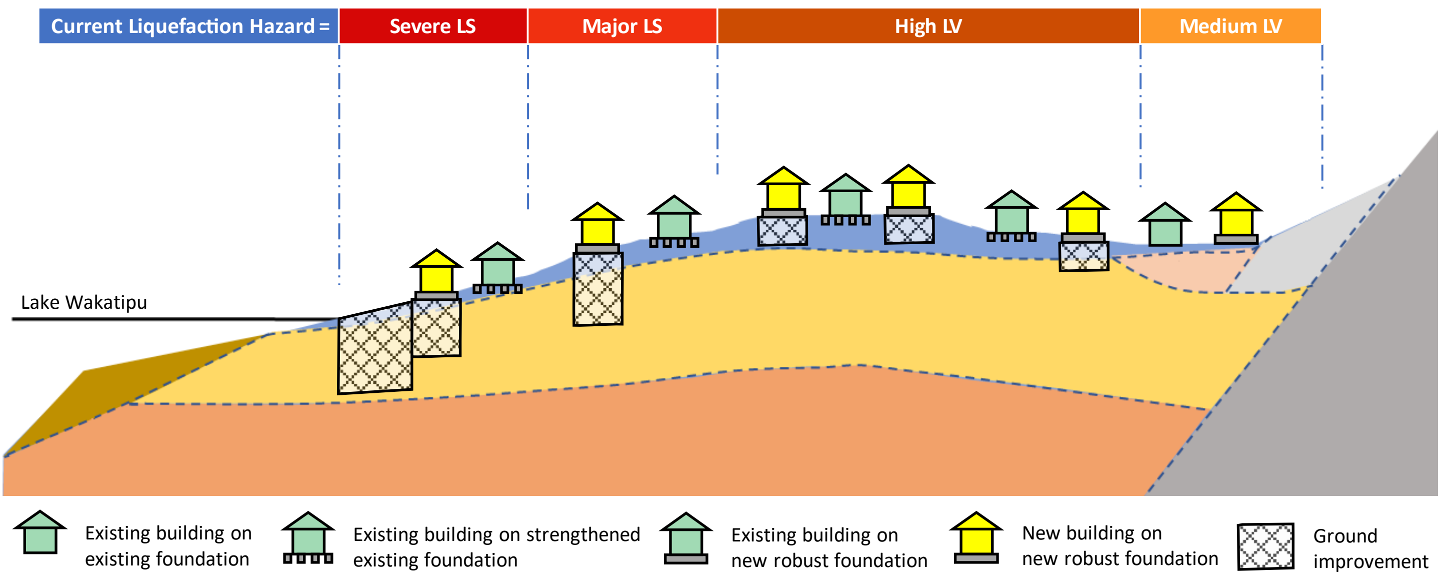
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		High LV	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		30%	25%	40%	15%	25%	20%	15%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	X				X			
	12m deep ground improvement, all land	X	X			X	X		
	12m deep ground improvement, land under buildings & infrastructure only							X	
	12m deep ground improvement, land around buildings & infrastructure where accessible								
	4m deep ground improvement, land under buildings & infrastructure only								
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only								
	No land improvement			X	X				X
BUILDINGS	New TC3 surface structure foundations	X	X			X	X		
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles							X	X
	Retrofit to strengthen existing foundations and buildings			X	X				
	No foundation or building improvement								
INFRASTRUCTURE	New infrastructure with resilient detailing	X	X			X	X	X	X
	Retrofit to strengthen existing infrastructure			X	X				
	No infrastructure improvement								

Option C1



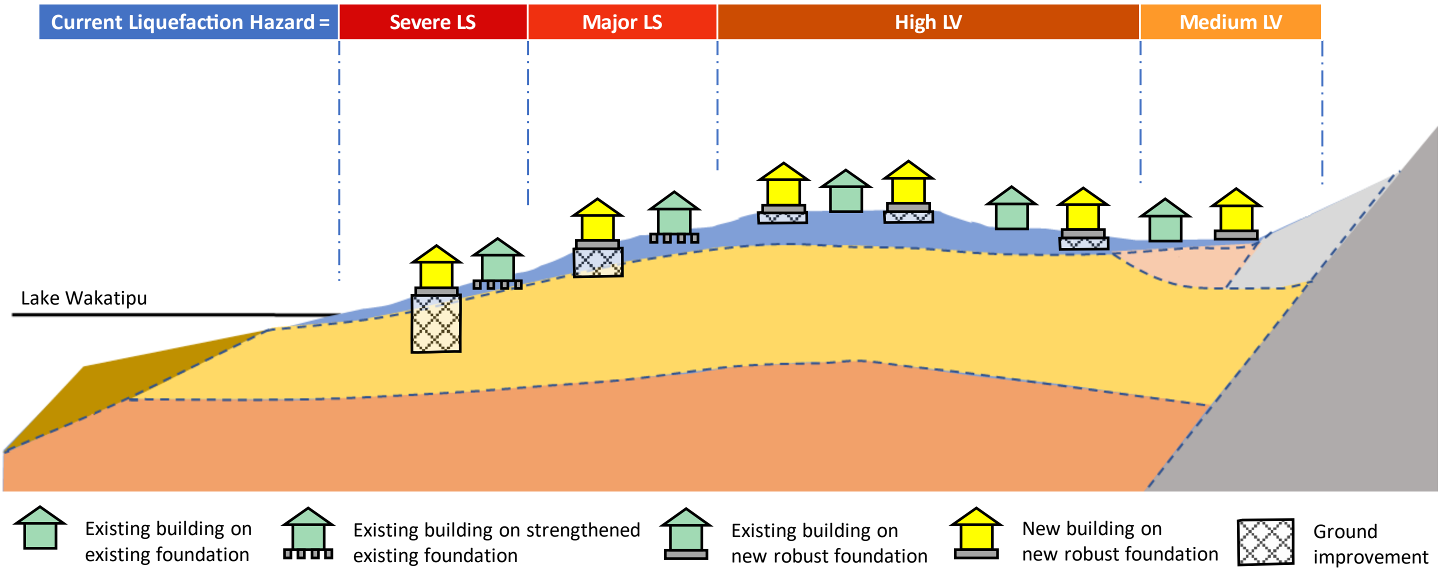
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		High LV	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		35%	30%	40%	15%	30%	25%	20%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	X				X			
	12m deep ground improvement, all land								
	12m deep ground improvement, land under buildings & infrastructure only	X	X			X	X		
	12m deep ground improvement, land around buildings & infrastructure where accessible								
	4m deep ground improvement, land under buildings & infrastructure only							X	
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only								
	No land improvement			X	X				X
BUILDINGS	New TC3 surface structure foundations	X	X			X	X		
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles							X	X
	Retrofit to strengthen existing foundations and buildings			X	X				
	No foundation or building improvement								
INFRASTRUCTURE	New infrastructure with resilient detailing	X	X			X	X	X	X
	Retrofit to strengthen existing infrastructure			X	X				
	No infrastructure improvement								

Option D1



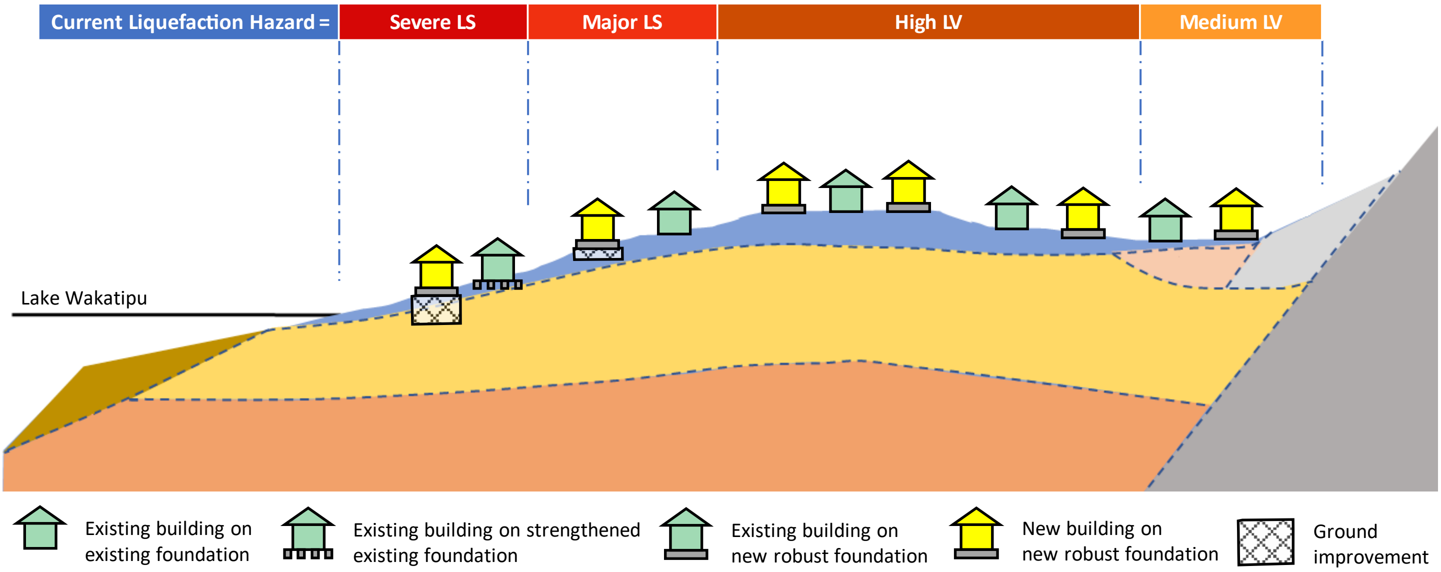
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		55%	50%	40%	25%	35%	30%	20%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	X				X			
	12m deep ground improvement, all land								
	12m deep ground improvement, land under buildings & infrastructure only					X	X		
	12m deep ground improvement, land around buildings & infrastructure where accessible								
	4m deep ground improvement, land under buildings & infrastructure only							X	
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only								
	No land improvement	X	X	X	X				X
BUILDINGS	New TC3 surface structure foundations					X	X		
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles							X	X
	Retrofit to strengthen existing foundations and buildings	X	X	X					
	No foundation or building improvement				X				
INFRASTRUCTURE	New infrastructure with resilient detailing					X	X	X	X
	Retrofit to strengthen existing infrastructure	X	X	X					
	No infrastructure improvement				X				

Option E



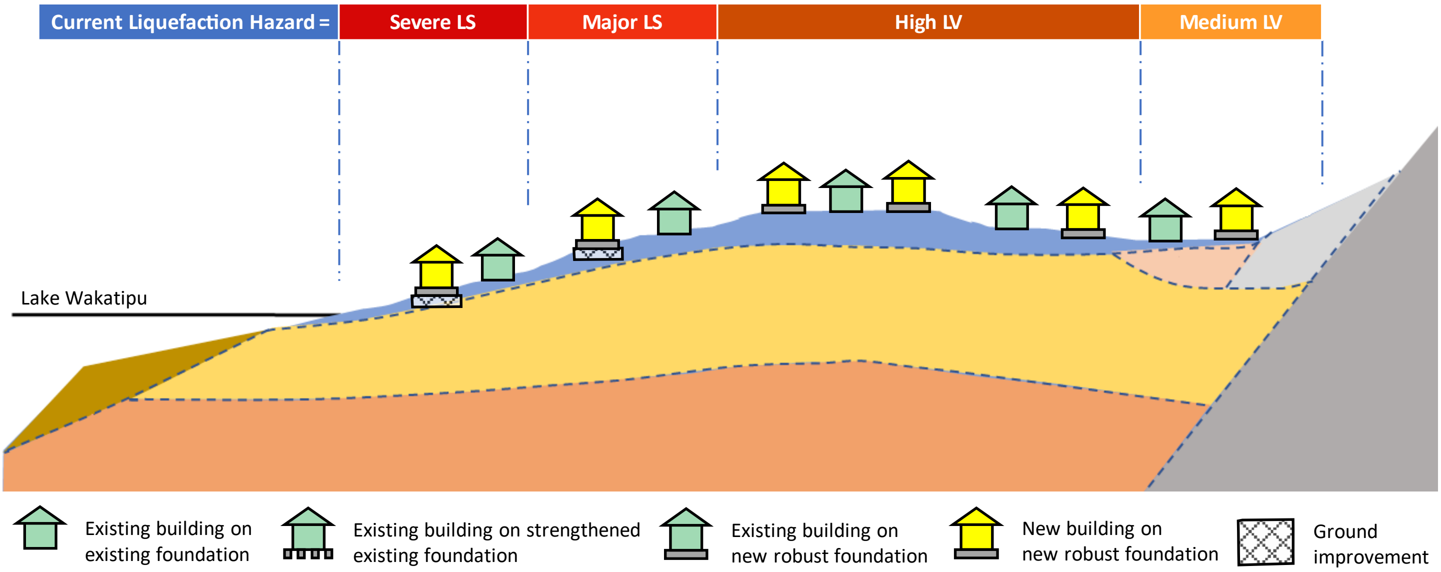
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Major LS	Major LS	High LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		75%	65%	50%	25%	40%	40%	25%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake								
	12m deep ground improvement, all land								
	12m deep ground improvement, land under buildings & infrastructure only					X			
	12m deep ground improvement, land around buildings & infrastructure where accessible								
	4m deep ground improvement, land under buildings & infrastructure only						X		
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only							X	
	No land improvement	X	X	X	X				X
BUILDINGS	New TC3 surface structure foundations					X	X	X	
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles								X
	Retrofit to strengthen existing foundations and buildings	X	X						
	No foundation or building improvement			X	X				
INFRASTRUCTURE	New infrastructure with resilient detailing					X	X	X	X
	Retrofit to strengthen existing infrastructure	X	X						
	No infrastructure improvement			X	X				

Option F



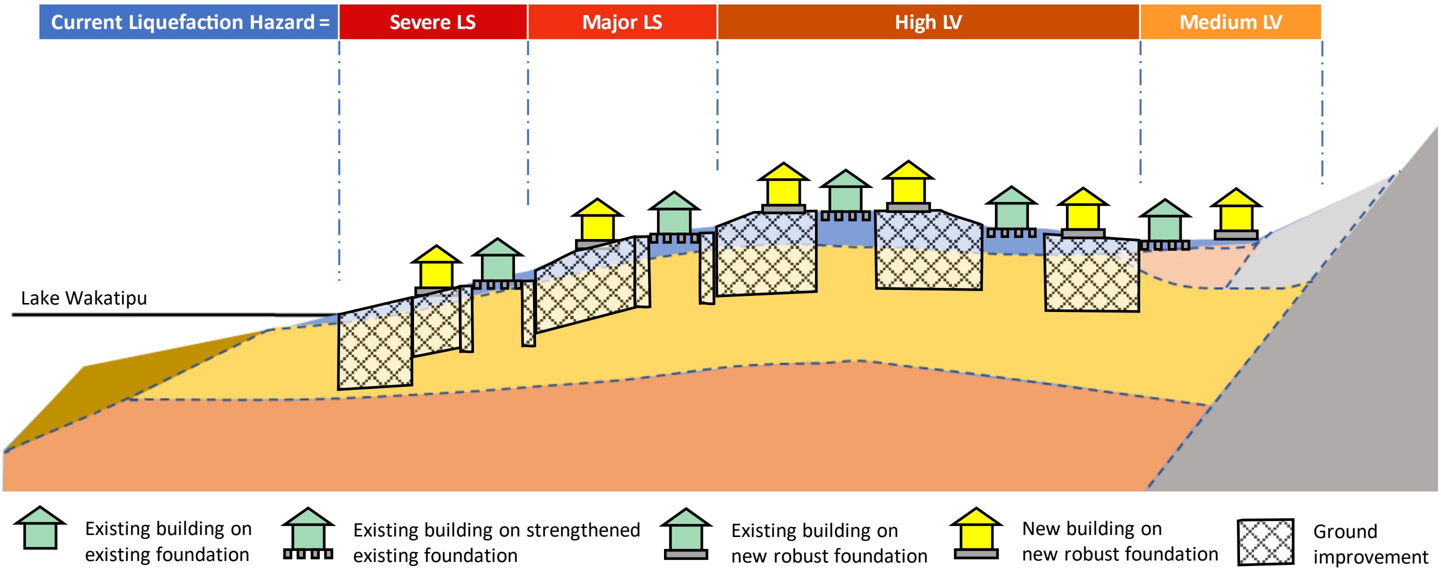
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		80%	75%	50%	25%	50%	50%	30%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake								
	12m deep ground improvement, all land								
	12m deep ground improvement, land under buildings & infrastructure only								
	12m deep ground improvement, land around buildings & infrastructure where accessible								
	4m deep ground improvement, land under buildings & infrastructure only					X			
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only						X		
	No land improvement	X	X	X	X			X	X
BUILDINGS	New TC3 surface structure foundations					X	X	X	
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles								X
	Retrofit to strengthen existing foundations and buildings	X							
	No foundation or building improvement		X	X	X				
INFRASTRUCTURE	New infrastructure with resilient detailing					X	X	X	X
	Retrofit to strengthen existing infrastructure	X							
	No infrastructure improvement		X	X	X				

Option G



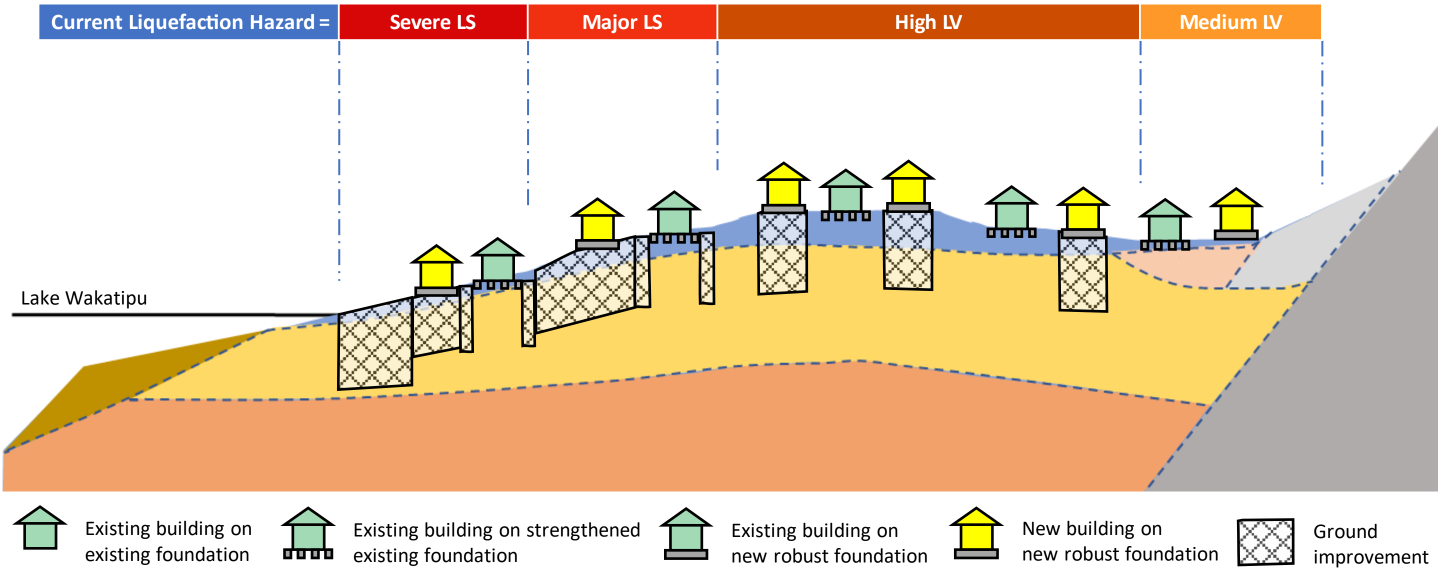
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	60%	50%	30%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake								
	12m deep ground improvement, all land								
	12m deep ground improvement, land under buildings & infrastructure only								
	12m deep ground improvement, land around buildings & infrastructure where accessible								
	4m deep ground improvement, land under buildings & infrastructure only								
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only					X	X		
	No land improvement	X	X	X	X			X	X
BUILDINGS	New TC3 surface structure foundations					X	X	X	
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles								X
	Retrofit to strengthen existing foundations and buildings								
	No foundation or building improvement	X	X	X	X				
INFRASTRUCTURE	New infrastructure with resilient detailing					X	X	X	X
	Retrofit to strengthen existing infrastructure								
	No infrastructure improvement	X	X	X	X				

Option A2



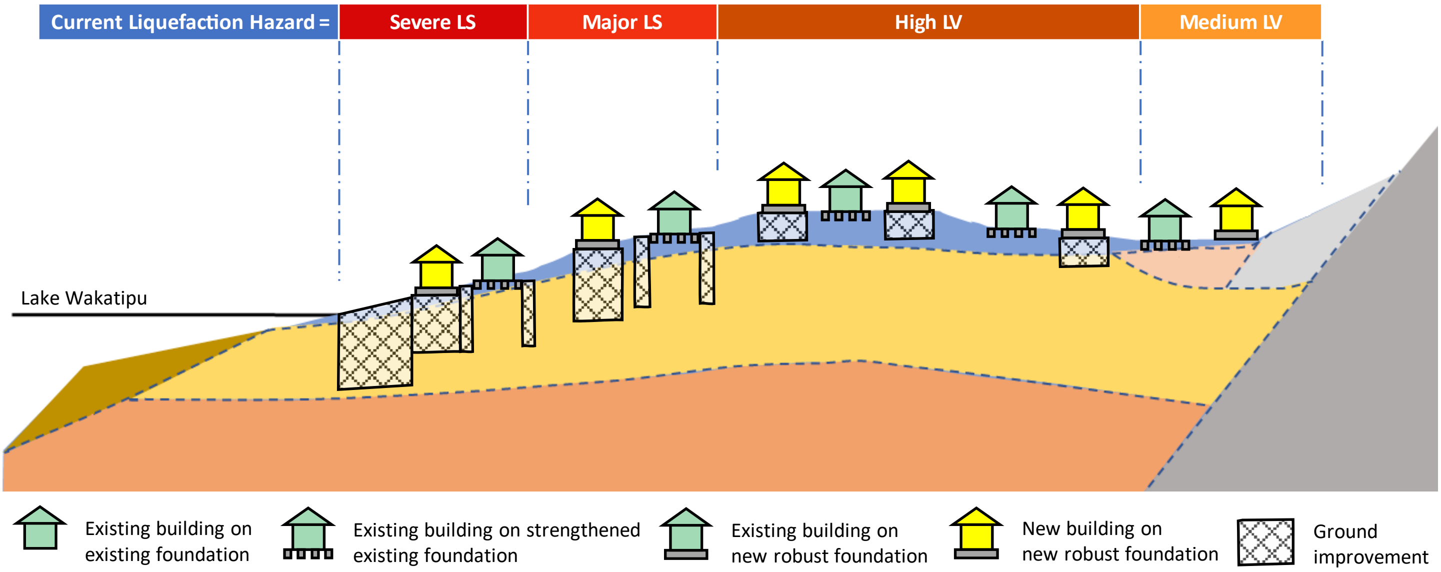
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		Major LS	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		45%	40%	40%	15%	30%	25%	10%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	X				X			
	12m deep ground improvement, all land					X	X	X	
	12m deep ground improvement, land under buildings & infrastructure only								
	12m deep ground improvement, land around buildings & infrastructure where accessible	X	X						
	4m deep ground improvement, land under buildings & infrastructure only								
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only								
	No land improvement			X	X				X
BUILDINGS	New TC3 surface structure foundations					X	X		
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles							X	X
	Retrofit to strengthen existing foundations and buildings	X	X	X	X				
	No foundation or building improvement								
INFRASTRUCTURE	New infrastructure with resilient detailing					X	X	X	X
	Retrofit to strengthen existing infrastructure	X	X	X	X				
	No infrastructure improvement								

Option B2



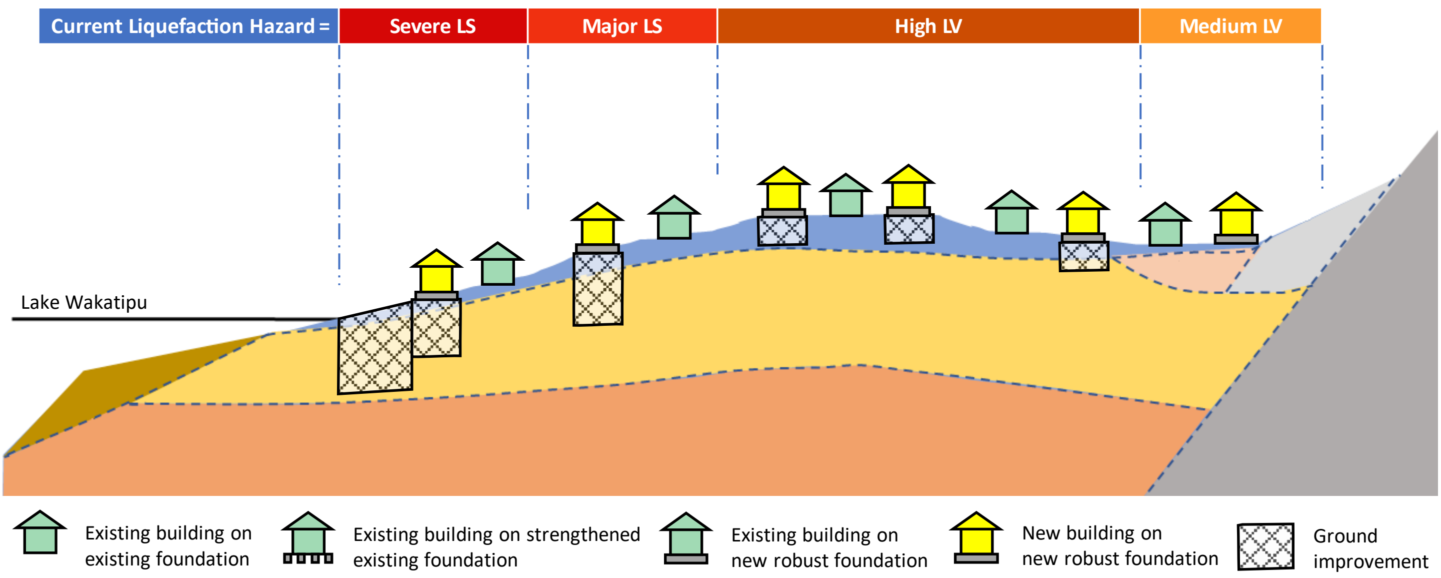
		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		Major LS	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		45%	40%	40%	15%	30%	25%	15%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	X				X			
	12m deep ground improvement, all land					X	X		
	12m deep ground improvement, land under buildings & infrastructure only							X	
	12m deep ground improvement, land around buildings & infrastructure where accessible	X	X						
	4m deep ground improvement, land under buildings & infrastructure only								
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only								
	No land improvement			X	X				X
BUILDINGS	New TC3 surface structure foundations					X	X		
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles							X	X
	Retrofit to strengthen existing foundations and buildings	X	X	X	X				
	No foundation or building improvement								
INFRASTRUCTURE	New infrastructure with resilient detailing					X	X	X	X
	Retrofit to strengthen existing infrastructure	X	X	X	X				
	No infrastructure improvement								

Option C2



		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		Major LS	High LV	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		45%	40%	40%	15%	30%	25%	20%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	X				X			
	12m deep ground improvement, all land								
	12m deep ground improvement, land under buildings & infrastructure only					X	X		
	12m deep ground improvement, land around buildings & infrastructure where accessible	X	X						
	4m deep ground improvement, land under buildings & infrastructure only							X	
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only								
	No land improvement			X	X				X
BUILDINGS	New TC3 surface structure foundations					X	X		
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles							X	X
	Retrofit to strengthen existing foundations and buildings	X	X	X	X				
	No foundation or building improvement								
INFRASTRUCTURE	New infrastructure with resilient detailing					X	X	X	X
	Retrofit to strengthen existing infrastructure	X	X	X	X				
	No infrastructure improvement								

Option D2



		EXISTING DEVELOPMENT				NEW DEVELOPMENT			
Current liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	Severe LS	Major LS	High LV	Medium LV
Post-mitigation liquefaction hazard:		Severe LS	Major LS	High LV	Medium LV	High LV	High LV	Medium LV	Medium LV
Current % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		90%	75%	50%	25%	-	-	-	-
Post-mitigation % of buildings & infrastructure with severe liquefaction damage in a major earthquake:		65%	60%	50%	25%	35%	30%	20%	10%
MITIGATION WORKS									
LAND	15 – 20m deep by 30 – 40m wide perimeter treatment ground improvement alongside lake	X				X			
	12m deep ground improvement, all land								
	12m deep ground improvement, land under buildings & infrastructure only					X	X		
	12m deep ground improvement, land around buildings & infrastructure where accessible								
	4m deep ground improvement, land under buildings & infrastructure only							X	
	1.2m deep geogrid-reinforced crushed gravel raft, under buildings & infrastructure only								
	No land improvement	X	X	X	X				X
BUILDINGS	New TC3 surface structure foundations					X	X		
	New TC2 waffle slab foundation or enhanced lightweight platform on timber piles							X	X
	Retrofit to strengthen existing foundations and buildings								
	No foundation or building improvement	X	X	X	X				
INFRASTRUCTURE	New infrastructure with resilient detailing					X	X	X	X
	Retrofit to strengthen existing infrastructure								
	No infrastructure improvement	X	X	X	X				