EARTHQUAKES AND PAVEMENT RESILIENCE

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ABSTRACT

In September 2010, the Canterbury region of New Zealand was shaken by a 7.1 (ML) magnitude earthquake which caused significant liquefaction and slope failures, followed by over 10,000 aftershocks and major earthquakes during the next 18 months. An investigation was carried out to assess the performance of various pavement structures used in Christchurch and surrounding districts, to identify what were the most resilient pavements for the reconstruction of roads in the region. The most common pavement type in Christchurch and surrounding districts consists of chip seals over unbound granular bases and subbases.

Following site inspections and analysis of data and photographs, five main failure mechanisms caused by the seismic events were identified; these are explained in this paper. A pavement treatment selection procedure for post-earthquake repairs was developed and was implemented.

Significant conclusions are:

- The most resilient pavements in seismic events, considering factors such as level of service after the event(s), survivability of the pavement and economics of repair, are thin-surfaced unbound granular and foamed bitumen stabilised pavements.
- Aggregate in unbound granular pavements could be contaminated with up to 30% liquefaction material without adversely affecting its performance.
- The liquefaction was often trapped in lenses under pavement layers and surfacings of lower permeability and created bulges, leaving the surfacing intact. The only means of repairing these bulges is to remove layers overlying the lenses of liquefaction material and replace with new construction.

Key Words: Liquefaction, road rebuild, earthquake damage, pavement resilience, seismic
INTRODUCTION

In September 2010, a 7.1 (ML) magnitude earthquake struck the Canterbury region of New Zealand and caused significant liquefaction and slope stability issues; this earthquake and its aftershocks caused widespread damage to buildings and infrastructure but resulted in no loss of life. Six months later, the February 2011 Christchurch earthquake severely damaged New Zealand's second-largest city, killing 185 people in one of the nation's deadliest peacetime disasters. The magnitude 6.3 (ML) earthquake was centred 10 kilometres (6 miles) south-east of the centre of Christchurch, which is in the Canterbury region. Even though it was only a 6.3 (ML) event, the massive intensity of the shaking concentrated on a populated centre was unprecedented in New Zealand; the Peak Ground Acceleration recorded during the earthquake in Christchurch was 2.2g. This makes it one of the most severe peak ground accelerations ever recorded, and possibly even the most severe ground acceleration recorded in a modern city.

The earthquake caused widespread damage across Christchurch, especially in the central city and eastern suburbs, with damage exacerbated by buildings and infrastructure, including pavements and subsurface pipes already affected by the September 2010 earthquake and its aftershocks. Significant liquefaction occurred in the eastern suburbs, producing over 400,000 tonnes of silt and sand. The liquefaction material consisted primarily of very fine, uniformly-sized, loosely deposited river sand, typically containing 85% 0.1 mm sized particles. When saturated, this material liquefied easily under short duration seismic events. Some of the larger aftershocks, that had epicenters located closer to liquefaction-susceptible areas in the city, caused more damage in the ensuing 15 months.

An investigation was requested by the Stronger Canterbury Infrastructure Rebuild Team (SCIERT) to assess the performance of various pavement structures. SCIERT is an alliance of the three government organisations (Christchurch City Council, New Zealand Transport Agency and the Canterbury Earthquake Recovery Agency) leading the infrastructure recovery and five major contractors. Further details about SCIRT can be found elsewhere (1).

New Zealand Geology

New Zealand straddles the boundary zone between the Pacific and Australasian tectonic plates. These plates are colliding directly under the South Island of New Zealand, causing significant up thrust and therefore the formation of the Southern Alps; off the east coast of the North Island, the plates are colliding at an angle, resulting in the lower hilly terrain on the east coast. The Alpine Fault, which spans the length of the South Island (from the southwest to the northeast), is moving north-east at approximately 25 mm per annum, and the Southern Alps are the fastest-rising mountain range in the world (2).

Most of the South Islands’ landmass is comprised of sedimentary rocks formed on ocean floors, which formed greywackes. Greywackes contain significant quantities of quartz and feldspar, the main minerals found in granite. In the west and south of the South Island of New Zealand, heat and pressure from the Alpine Fault has converted greywacke into schist. Banks Peninsula, which forms the southern area of Christchurch, was formed by a series of massive volcanoes during the uplift of New Zealand around 10 million years ago.

The glaciers that carved out the valleys amongst the Southern Alps also created large stockpiles of scree, which was gradually transported to the coast by various rivers and deposited. Gradually the rivers deposited their alluvial gravels further and further from the Alps, thereby filling in what was formerly ocean between the Southern Alps and the Banks Peninsula volcanoes, creating the Canterbury plains.

During the last glacier era, sea level dropped by more than 100m, eventually rising again when the huge ice caps in the northern hemisphere melted. When the sea level was
lower, rivers deposited porous sediment; when the sea levels were high, the oceans deposited
finer impermeable sediment. This alternating structure is the reason the Canterbury Plains has
extremely large aquifers throughout it.

The extremely high stresses caused by two tectonic plates moving together under the
Southern Alps have created many stress failures throughout the New Zealand landmass.
Pressure built up by the movement of the two plates is dissipated through these fault lines,
causing localised geological movement and earthquakes. The proximity of Canterbury to the
main Southern Alps fault line is the reason why there is such an extensive network of minor
fault lines in the bedrock under the plains, compounded by the influence of the dormant
Banks Peninsula volcanoes (2). Unfortunately, as these minor Canterbury fault lines were
covered over by alluvial gravels thousands of years ago, and there hadn’t been any major
seismic activity near Christchurch since human settlement, the extent of the fault lines under
Canterbury were unknown until 2010.

Scope of Study
The objective was to identify the best performing/most resilient pavement structure designs to
adopt for the rebuild of Canterbury roads affected by the recent earthquakes. The
investigation included a comprehensive review of international literature, site inspections,
laboratory testing, and canvassing maintenance contractors, Christchurch City Council, New
Zealand Transport Agency and consultant engineers to ensure that the investigation included
all relevant issues.

The initial scope of this investigation was to review the performance of the various
pavement structures during and after the earthquakes and subsequent aftershocks. The aim
was to assess the resilience and performance of different pavement structures and to identify
which pavement types would provide optimum performance in future seismic events,
including economic considerations.

INTERNATIONAL LITERATURE REVIEW
A search of international literature about post-earthquake transportation rebuild
methodologies found that the main focus in the road rebuild strategies after major
earthquakes overseas was to design resilience and redundancy into the new structures
(bridges, etc.), and retrofit resilience and redundancy into the surviving structures. A separate
research project was commissioned by the New Zealand Transport Agency to develop design
guidance for bridges in New Zealand for liquefaction and lateral spreading effects (3), but the
scope of this project excluded pavements. The international literature review yielded no
definitive information to help develop seismic resistant pavements as most pavements can be
made trafficable with relative ease at relatively low cost compared with other road structures
such as bridges etc.

Also, the majority of urban streets, local roads and state highways in New Zealand,
including the Christchurch area, consist of chip seal surface treatments or thin (less than 40
mm) asphalt surfacings over unbound granular pavements. The unbound granular aggregate
complies with New Zealand’s material specification for basecourse aggregate (4) that has
been proven over time to provide adequate performance in the road.

A common theme found in the research was to prevent liquefaction from occurring by
identifying susceptibility in the ground beneath road corridors. This would require either that
the road be built elsewhere or by using ground improvement techniques to prevent
liquefaction damage in future seismic events.
CAUSES OF PAVEMENT FAILURES INDUCED BY SEISMIC ACTIVITY

One of the key objectives of this research was to identify pavement structures that performed well in the recent seismic events. These should then be the pavement structure of choice when rebuilding so that pavement resilience would be built into the pavements.

Inspection showed that most pavements had performed well and that the damage to the pavements was caused by failures beneath the pavement.

The five main failure mechanisms caused by the seismic events include:

1. Slope stability issues at the top and toe of slips in the hill suburbs (Figure 1).

2. Horizontal and/or vertical displacement of the pavement caused by physical shortening, lengthening or shearing of the land in global and localised areas.

3. Subsidence and lateral slips caused by liquefaction of underlying materials during an earthquake event, which may be in small localised areas or larger more global areas.

4. Liquefaction eruptions breaking through the pavement surface causing pavement roughness and holes in the pavement (Figure 2).

5. Liquefaction contaminating the pavement materials contributing to early failure of the pavement.

Can slope stability issues be prevented by pavement design?

Slope stability issues were outside the scope of this investigation but no pavement construction methodology will prevent failures caused by ground movement as the result of slope instability; even pavements supported by structures cantilevered off solid rock would not necessarily preclude the effects of slope stability on the pavement.
Can horizontal and vertical displacement be prevented by pavement design?
Apart from not building roads across known fault lines and over areas of liquefaction susceptible material, no pavement design can prevent failures of this type. However paving stones/slabs might be used as a reusable surface treatment.

Can subsidence and lateral sliding be prevented by pavement design?
Preventing liquefaction is the only solution that would guarantee no liquefaction failures. However, as liquefaction originates from beneath the pavement, there is no pavement design that will prevent liquefaction. Ground improvement methods that modify the liquefaction susceptible material so that it will not liquefy are the only method of preventing liquefaction. This is unlikely to be cost effective for large scale areas but may be a solution for isolated areas that are critical to remain serviceable.

Can pavements be designed that will prevent liquefaction breaking through to the surface?
The pavement could be designed with a continuous cap of reinforced concrete, with wicks or sand drains to divert the liquefied material to the edges of the pavement.

In some pavement structures inspected, the liquefaction was contained below seals or asphalt layers; however, the liquefaction still broke through discontinuities and the loss of the bulk material from beneath the pavement resulted in settlement, often unevenly. Even if thick concrete or structural asphalt pavements were constructed over liquefaction susceptible ground, they would have to be designed to bridge large voids where liquefaction occurred to avoid subsidence caused by the loss of bulk material from underneath. If sand or wick drains were used to relieve the pressure, liquefaction would not break through the cap; however if liquefaction is expelled through the sand drains or wicks, then there will still be subsidence issues. But, a seismic event may cause the concrete slabs to break due to shortening, lengthening, vertical uplift, or horizontal shear, and then liquefaction would be able to flow through.

This option is very expensive to build and very expensive to repair, and thus was not considered a viable option.

Can resilience be built into pavements to prevent liquefaction contamination of the materials?
Most pavement failures inspected were caused by liquefaction where liquefaction silt/sand and water was expelled to the surface. The liquefaction erupted through weak spots in the pavement, eroding and undercutting the surrounding pavement, resulting in sink holes and differential subsidence of the pavement. The weak spots were generally discontinuities located at service trenches, service covers, and along the pavement edges and through construction joints sometimes finding soft spots in the previous construction layers.

As high moisture content is a key factor in liquefaction-susceptible soils, the moisture content in the subgrade under the pavement can be reduced using stone columns and wick drains, which can be installed at the time of new construction or rehabilitation. For example, the Christchurch Southern Motorway was being constructed at the time of the earthquakes and where stone columns had been installed under bridge approaches and piers prior to the earthquakes, those structures suffered no or minimal damage during the seismic events.

In existing road pavements, the liquefaction was often trapped in lenses under pavement layers and/or surfacings of lower permeability and created bulges, leaving the overlying pavement and surfacing layers intact (Figure 3). The only means of repairing these bulges is to remove the asphalt and the pavement layers over the liquefaction lense(s), and replace with new construction.
It was concluded that the primary form of resilience that could be built into the pavement would be to prevent pavement materials from getting contaminated so that they could be recycled in situ if required after a seismic event. Inspections of pavements affected by liquefaction concluded that modifying the materials and installing a geotextile fabric beneath the pavement helped to minimize the contamination of the pavement materials. Whilst this would not prevent damage to the pavement with liquefaction breaking through any discontinuities, it would mean that significant portions of the pavement materials would be reusable when rebuilding the pavement.

**PAVEMENT PERFORMANCE OBSERVATIONS**

After examining the performance of the different pavement types, the authors recommended that the best approach to providing some pavement resilience is to prevent or minimise the liquefaction contamination of the pavement materials so that the materials can be utilised in the next pavement.

Christchurch has many different pavement structures due to age, ground conditions and traffic loadings, including unreinforced concrete pavements constructed in the 1930’s. All pavement types were severely tested by the seismic events since September 2010, providing a proving ground for each pavement type.

In most cases the actual pavement performed well. Despite liquefaction rupturing pavement and forming holes and large cracks, the pavement layers more or less remained intact between the breakage points. In localised areas, the liquefaction flow eroded the subbase and basecourse materials, forming large holes where large amounts of liquefaction discharged. The overriding issue for all pavements performance is that if the pavement was built over liquefaction susceptible ground and liquefaction occurred then, regardless of the pavement structure, the liquefaction found its way to the surface.

In general, most of the better performing pavements are recently constructed pavements; however, some of the worst performing pavements are those constructed in subdivision works in the eastern suburbs in relatively recent times, which were built over some of the most liquefaction susceptible ground in Christchurch.

The authors did observe a trend for thicker bound pavements to have less liquefaction than thinner unbound pavements, but Christchurch has very small lengths of the former. Older pavements tended to have more discontinuities, such as trenches and repairs, that are release points for liquefaction through pavements.
Overall, the relative performance of different pavement structures corresponded to the amount of liquefaction that occurred, which was related to the liquefaction susceptible materials in the 20m to 30m beneath the pavement and not the pavement structure itself.

Any observations of better performance in preventing liquefaction contamination?
The investigation was restricted to visual observations so conclusions regarding contamination prevention are based on expected performance. Contamination of pavement materials was reported but so far has not been measured.

Since 2005, foamed bitumen stabilization (FBS) has been used to recycle and rehabilitate unbound granular pavements in Christchurch, and these generally performed well; however, the only direct comparison of FBS vs. an unbound granular pavement was on Blighs Road where the granular pavement was affected by liquefaction and the FBS section exhibited negligible effects from liquefaction.

Some unbound granular pavements performed well while others failed. Care needs to be taken to ensure that when comparing the performance of pavement construction techniques, it is likely that where unbound granular pavement was constructed, the subgrade structure is likely to be better than where other construction techniques were used.

In pavement sections where geofabric was used in the pavement construction, there was less liquefaction identified through the pavement than on adjacent sites without fabric. Unfortunately the records of locations and details of pavements containing geotextile fabrics are not complete. The only issue identified with fabric performance was the leakage of liquefaction through the fabric joints, both transversely and longitudinally, and around underground services.

The main conclusion from above is that the use of bound materials and fabric in pavement reconstruction should minimise the contamination of the pavement materials, which would build some resilience into the reconstructed pavements, but their use will not prevent the liquefaction from occurring or rising up into or through the pavement. The pavement resilience added would be the protection of the materials so that they could be recycled or reused in the event of another episode. However geo-fabric may prevent future stabilisation and be a one-off protection. Also once modified the materials may not be suitable for further modification.

Surfacing Types
The three predominant pavement surfacing treatments used on Christchurch City pavements are: chipseal, thin asphalt surfacing (TAS) and deep lift or structural asphalt. The chipseal and TAS surfacings did not resist the forces of the silt and generally failed wherever liquefaction broke through the pavement. In some areas the liquefaction lifted the surfacing without breaking it and then deposited it in a lens between the pavement and the surfacing. The layer of silt is likely to cause the surfacings to fail under loading in the future. The structural asphalt pavements performed well, however there are isolated areas where the liquefaction has uplifted, broken through and/or undercut them. The asphalt layer is reusable but needs to be reshaped and/or overlain.

Surfacing treatment selection to encourage pavement resilience in seismic events should be as per normal surfacing treatment selection criteria, but there should be closer attention to the detail of adhesion of the surfacing to the pavement surface because there were issues regarding the adhesion of the surfacings to the pavement. Some improvement in the rebuild designs will ensure better adhesion of the surfacing to the pavement.
Sustainability and Environmental Issues
Where possible, the contaminated pavement materials should be modified in place or removed and reused elsewhere as required. Also, the transportation of large quantities of aggregate into the worst affected areas will aggravate the deterioration of the existing pavements and cause extra stress for residents by causing increased vibrations and shaking of residences. A number of pavements are contaminated with coal tar and when identified, this material should be removed and reused where possible as a layer on top of the fabric in pavements where full reconstruction has been justified, as the fabric retains the coal tar contamination within the pavement.

Laboratory Performance Testing
Liquefaction has three major effects on pavements:

1. Pavement disturbance (humps and hollows)
2. Subsidence
3. Contaminates subbase and basecourse

Items 1 and 2 are easily remedied with cut and fill activities; however both are likely to be accompanied by item 3 and the affect of the contamination on the material properties is unknown but is expected to cause a reduction on bearing capacity.

To ensure that reusable materials are not wasted and that repairs are not carried out on top of poor materials, laboratory testing was undertaken to ascertain the actual effect of the liquefaction contamination of the materials by the contamination.

Repeated Loading Triaxial (RLT) testing and permeability testing were conducted on representative samples of basecourse with liquefaction material blended in to evaluate the effects of contamination. Repeated load triaxial test conditions approximately replicate the dynamic stress conditions in a pavement layer under a rolling wheel load, and the RLT test is used in New Zealand and overseas to assess the expected performance of stabilised and unbound aggregate.

Based on observations in the field, experience and engineering judgement, the authors selected 30% as the level of contamination with liquefaction which would definitely adversely affect the performance of the unbound aggregate. Virgin basecourse aggregate was taken from Christchurch’s major source of pavement aggregates (an alluvial source) and split into samples. Some samples were blended with liquefaction material taken from stockpiles. Both contaminated and uncontaminated samples were tested in soaked and unsoaked states, in the first stage of this laboratory testing. Then, depending on the outcome of the first stage, the same material would be tested with different modifiers (such as cement or bitumen) and concentrations of modifiers in the second stage. Finally, if the performance of the modified contaminated material was still less than desired, then the test schedule would be repeated at a lower concentration of liquefaction.

The RLT testing was undertaken using the stress conditions show in Table 1 (5). The RLT tests from the first stage showed no significant difference in performance between the samples containing 0% and 30% liquefaction (Figure 4). Thus, the subsequent stages described above were not done, because of the urgency of completing the investigation; Canterbury was still experiencing daily aftershocks while this investigation was undertaken.

On many streets, the amount of liquefaction contamination of the basecourse varies significantly so to obtain sufficient samples to quantify this variability was not cost effective. The use of visual assessment, FWD and GPR to help identify suitable locations for sampling will optimise the sampling and testing to ensure that enough information to make an informed decision is gathered.
TABLE 1 Repeat Load Triaxial Testing Stress States (5)

<table>
<thead>
<tr>
<th>RLT Testing Stress State</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deviator stress ( q_{\text{max}} ) (kPa) (cyclic vertical stress)</td>
<td>90.0</td>
<td>100.0</td>
<td>180.0</td>
<td>330.0</td>
<td>420.0</td>
</tr>
<tr>
<td>Mean stress ( p_{\text{max}} ) (kPa)</td>
<td>150.0</td>
<td>75.0</td>
<td>150.0</td>
<td>250.0</td>
<td>250.0</td>
</tr>
<tr>
<td>Cell Pressure, ( \sigma_{\text{3max}} ) (kPa)</td>
<td>120.0</td>
<td>41.7</td>
<td>90.0</td>
<td>140.0</td>
<td>110.0</td>
</tr>
<tr>
<td>Major Principal Vertical Stress, ( \sigma_{\text{1max}} ) (kPa)</td>
<td>210.0</td>
<td>141.7</td>
<td>270.0</td>
<td>470.0</td>
<td>530.0</td>
</tr>
<tr>
<td>Cyclic Vertical Loading Speed</td>
<td>Sinusoidal/Haversine at 4Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Loads ( (N) )</td>
<td>50,000 for each test stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RLT test apparatus (vertical loading pulse)</td>
<td>To suit available RLT pneumatic or hydraulic equipment and control software in New Zealand Sinusoidal/Haversine pulse at 4 times a second (4Hz) using pneumatic or hydraulic equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Triaxial Cell and Instrumentation</td>
<td>External load cell and 2 external displacement transducers mounted between loading caps to measure whole-sample strain. Use air, water or silicon in the cell to apply confining pressure.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 4 Effect of liquefaction contamination on modulus and strain

CONTEXT SENSITIVE TREATMENT SELECTION
A pavement treatment selection flowchart (Figure 5) was developed based on the following:
- Identifying liquefaction susceptibility of the site
- Determining the sites position within a developed traffic hierarchy
- Site Investigation and determining the degree of liquefaction contamination of the pavement materials.
- An economic analysis of the life cycle costs of the selected treatments
FIGURE 5 Pavement treatment selection flow chart

Note: The flowchart starts after the site has been justified as requiring treatment by the Road Controlling Authority.
A life cycle cost analysis should be carried out for each site to ensure that the lowest cost engineering solution is used. The residual lives and expected lives will be critical components of these calculations and must be based on the tables developed for the purpose.

Pavement design guidelines are proposed in Figures 6 and 7.

**FIGURE 6 Pavement design flowchart for high volume roads**
**CONCLUSIONS AND RECOMMENDATIONS**

The main conclusions regarding seismic resilience of pavements are:

- It will be cost prohibitive to prevent liquefaction over large areas of the road network. The cost of modifying the liquefaction susceptible materials to provide system resilience may be justifiable on small isolated areas within collector, arterial and main roads.

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**FIGURE 7 Pavement design flowchart for low volume roads**
Overall, the relative performance of different pavement structures corresponded to the amount of liquefaction that occurred, which was related to the liquefaction susceptible materials up to 30 m beneath the pavement and not the pavement structure itself.

- The forces generated by the liquefaction vary considerably site to site, suburb to suburb, even lane to lane, depending on ground conditions, groundwater level, seismic shaking amplitude; duration of shaking etc. In some cases the upward forces have been relatively large with the liquefaction material finding any weak point within the pavement regardless of the pavement type. Treatment selections must take this variation into account, repairing only sections that have experienced damage.

- Surfacing treatment selection should be as per normal surfacing treatment selection criteria, but there must be improvements in the rebuild designs to ensure better adhesion of the surfacing to the pavement.

**Recommended Design Principles**

The following design principles are recommended for pavements to be constructed in locations with high probability of seismic activity:

- Each pavement design should include site-specific assessment of liquefaction susceptibility to ensure that conservatively designed pavements are not constructed over areas with high risk of liquefaction reoccurrence.

- Designers must consider resilience against liquefaction contamination of the pavement layers.

- Pavement designers must select sensible cost effective solutions based on realistic expected lives of new, repaired, and rehabilitated pavements and include realistic residual lives for retained contaminated pavements.

- Pavements must be designed and programmed holistically to ensure that the effects of the construction process of each site on the surroundings are assessed and taken into account.

- Pavements designs must be sustainable, maximising the utilisation of recycled materials in the pavement construction including the pavement materials themselves.

- Designs must be context sensitive – treatment must be cost appropriate for the location.

- The pavement structure must be selected and designed based on engineering best practice within the economic constraints – ie have similar pavements performed well in previous events.

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**REFERENCES**


