Lessons from liquefaction damage to bridges in Christchurch and strategies for future design

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ABSTRACT: Bridges performed well in the recent Canterbury earthquakes of 2010-2011, except when they were subject to liquefaction and lateral spreading. A large number of state highway and local bridges, both in areas of good ground and liquefiable ground, were inspected after the 4th September 2010 Darfield and 22nd February 2011 Christchurch earthquakes. Four state highway bridges and seven local authority bridges were also investigated, assessed and remediation concepts developed in the aftermath of the earthquakes, with detailed design completed for some of the bridges.

This paper presents the lessons learnt from the liquefaction damage, both for future design and from a professional practice perspective. Two broad approaches can be used to design bridges resistant to liquefaction induced lateral spreading, particularly for bridges that cross water courses. Case studies are presented to illustrate these approaches. One by using ground improvement to reduce the potential for liquefaction and displacement from lateral spreading. The other is to minimise the loads on the structure by isolation, and design of the structure to resist the loads imposed by lateral spreading.

The approaches are compared and the advantages and disadvantages are presented. Recommendations are presented for future liquefaction resistant design of bridges.

1 INTRODUCTION

The Canterbury Region of New Zealand experienced a significant and long sequence of earthquakes and aftershocks since 4th September 2010, which caused significant damage to buildings and infrastructure, particularly in Christchurch city, during the period of 2010-2011. Road networks were affected by the events, even though the highway structures performed reasonably well.

A number of reports and technical papers have reported on the performance of bridges in the Christchurch earthquake sequence (Brabhaharan et al, 2011; Brabhaharan, 2011; Palermo et al, 2011; Waldin et al, 2011; Wood et.al, 2012). These papers have highlighted the generally good performance of bridges and the damage to bridges from liquefaction in Christchurch City.

It is important to draw lessons from the observations that have been made for the repair of these bridges, retrofit of existing bridges, as well as the design of new bridges throughout New Zealand and further afield. Lessons comprise that for engineering practice as well as the development of concepts that are important to ensure the future resilience and sustainability of our bridge inventory.

2 THE EARTHQUAKES

The magnitude 7.1 Darfield Earthquake on 4th September 2010 had its epicentre approximately 40 km west of Christchurch City at a depth of 11 km. The associated peak ground accelerations were 0.7g to 1.25g in the epicentral area near Darfield, and about 0.25g in Christchurch City.

The most severe aftershock was a Moment M_w 6.2 event at 1251 hours on 22nd February 2011, centred in the Port Hills area, at a distance of about 5 km to 7 km from the Christchurch city centre at a depth of 5 km. The associated peak ground accelerations of 0.5g to 0.7g in Christchurch City, and up to 2 g in the surrounding areas to the east and south.

A further moment magnitude M_w 6.0 aftershock occurred on 13 June 2011. There were also a number of other aftershocks during 2010-2011.

The earthquakes caused extensive liquefaction in Christchurch City, particularly in the areas to the east of the city centre and in Kaiapoi in the Waimakariri District, and this has been well documented.

3 PERFORMANCE OF BRIDGES

3.1 Bridges in Areas of Good Ground resistant to Liquefaction

The bridges performed very well outside the areas of liquefaction in Christchurch City and Kaiapoi in the Waimakariri District. The old as well as new bridges in the epicentral area performed well with little damage. Figure 1(a) shows a relatively modern local road bridge (constructed in 1998) close to the epicentre which performed very well despite the very strong ground shaking (peak ground acceleration > 1g) it likely to have experienced.

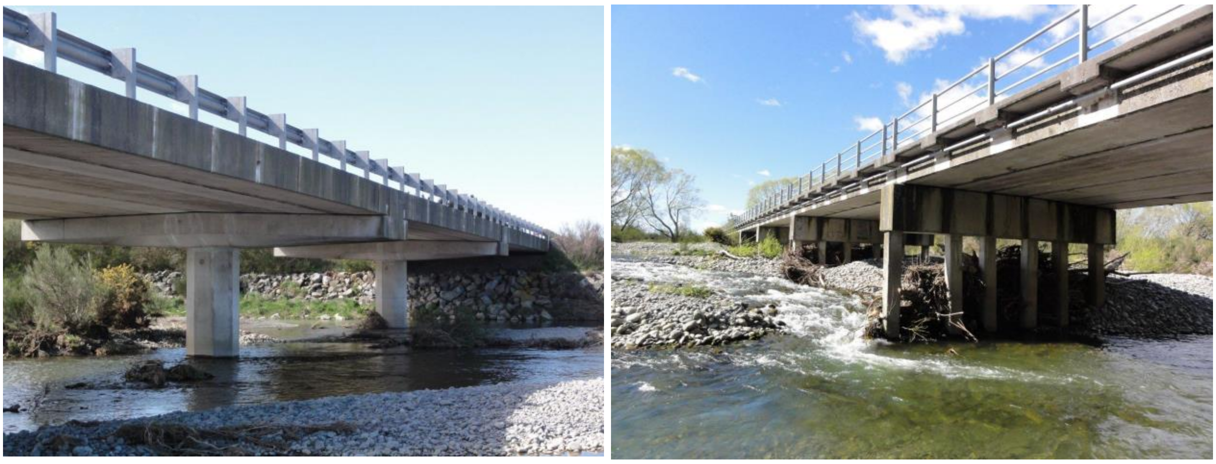

Figure 1. (a) Left: Local road bridge (b) Right: State Highway Bridge, near the epicentre of Darfield Earthquake

Figure 1(b) shows an older 1969 bridge across the Hawkins River on State Highway 77, which also suffered little damage despite being close to the epicentre of the Darfield earthquake.

The geology of these bridge sites is alluvial gravels, which are generally coarse and dense and are resistant to liquefaction. There was little evidence of ground displacement at these sites, despite the strong ground shaking in the magnitude 7.1 Darfield earthquake.

The bridges in areas underlain by such competent ground performed very well despite their age and regardless of their type of construction. The bridges appear to have been well designed for the sites and ground conditions in these areas.

3.2 Bridges in Areas of Poor Ground and Prone to Liquefaction

In comparison, bridges in areas that liquefied in both the 4 September 2010 Darfield Earthquake as well as the 22 February 2011 Christchurch Earthquake, suffered significant damage. Although most of these bridges remained in service, some with significantly reduced capacity, they required extensive repairs or have had to be demolished and replaced with a new bridge.

Figure 2 shows the South Brighton Bridge across the Avon River, which experienced severe damage to its abutments due to liquefaction and lateral spreading. This was constructed and opened in 1981.

Figure 3 shows the State Highway 74 ANZAC Bridge which was constructed in 2000, and suffered severe damage as a result of liquefaction and associated lateral spreading. This caused damage to the abutments as well as to the piers that were relatively close to the river banks.

Figure 2. Damage to bridge abutment at South Brighton Bridge in the Darfield Earthquake of 4th Sep 2010

Figure 3. Damage to SH74 ANZAC Bridge in the Canterbury Earthquakes

Other bridges in the areas that liquefied in the Canterbury Earthquakes also experienced significant damage due to liquefaction and lateral spreading.

4 LESSONS FROM THE PERFORMANCE OF BRIDGES

4.1 Did the Bridges provide Resilience?

Lessons from the performance of bridges in the Canterbury earthquakes are provided by Wood et al (2012). One of the key lessons is that while bridges generally performed well in the area of good ground with no liquefaction, generally bridges that were prone to liquefaction and lateral spreading experienced significant to severe damage, and require significant repairs and some have had to be demolished and rebuilt.

While the bridges were able to provide at least limited access relatively quickly after the earthquakes, the post-earthquake scenario has shown that it takes a long time to reinstate bridges to their full capacity, and this affects recovery after the earthquake.

Resilience can be defined as the ability to recover quickly to provide a level of service prior to the event, as illustrated by Brabhaharan (2006). This is illustrated conceptually in Figure 4.

Three years after the 4th September 2010 and 22nd February 2011 earthquakes, much of the damaged bridges have not been fully repaired and restored to their full capacity. This indicates that the liquefaction and lateral spreading damage to the bridges have compromised the resilience of the bridges and the transportation network in which they are an integral part of.

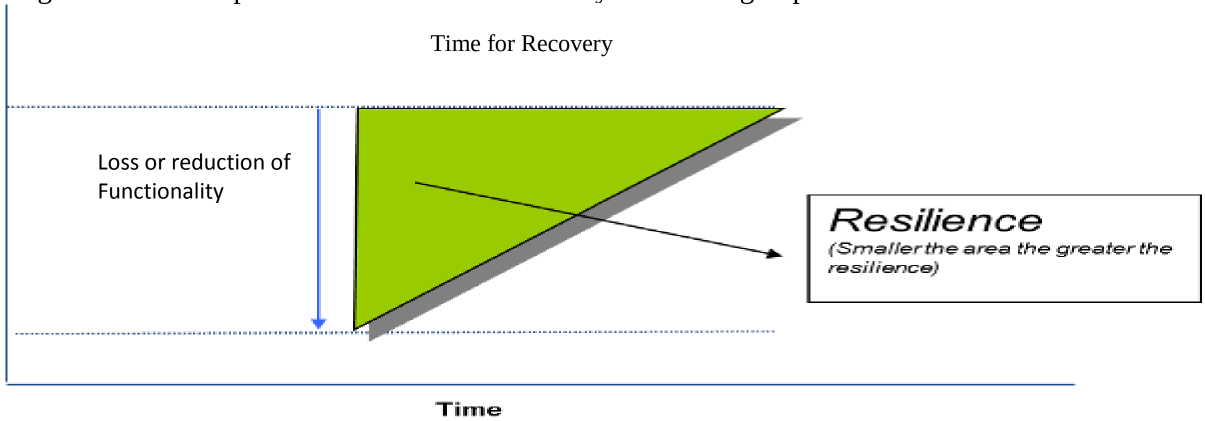

Figure 4. Conceptual Definition of Resilience (after Brabhaharan, 2006)

4.2 Sustainability

From a sustainability perspective, large amounts of scare resources are required to restore the bridges damaged by earthquakes and bring them up to an acceptable level of performance in future earthquakes. In addition, the disruption caused by the damage leads to significant consumption of scarce resources due to detours or congestion that affects vehicles that use these transportation arteries.

One consideration is how much additional resources and cost is required to construct transportation links that are more resilient to earthquakes. As illustrated by Brabhaharan (2009), greater resilience does not necessarily cost more, but requires greater focus on resilience from an early stage.

4.3 Why did the Bridges not perform well in Liquefaction?

Awareness of Liquefaction

The phenomenon of liquefaction has been better understood in the last 50 years. The 1964 Niigata Earthquake was a landmark earthquake where the effects of liquefaction caused widespread damage to buildings and infrastructure, including the collapse of bridges, see Figure 5.

Figure 5. Collapse of Bridge in the Niigata Earthquake attributed to Liquefaction and Lateral Spreading

The Niigata Earthquake gave a widespread awareness worldwide on the effect of earthquake induced liquefaction on the built environment. Bridges built over 40 years ago are not likely to have had the benefit of the knowledge of liquefaction and its effects.

Bridge Design Standards

In New Zealand, the early bridge design standards did not adequately address the importance of the need to address the effects of liquefaction in the design of bridges. Geotechnical design requirements for bridges were gradually incorporated into the Bridge Manual since the mid to late 1990s and specific requirements for design of bridges for liquefaction was incorporated into the second edition of the Bridge Manual (Transit New Zealand, 2003; Brabhaharan, 2006). This has been further enhanced in the third edition of the Bridge Manual (2013), and is expected to be improved further. So the lack of design standards may have been a significant contributing factor to bridges not being designed for earthquake induced liquefaction as late as in the 1990s and early 2000s.

Design Practice

Although the bridge design standards did not specifically cover liquefaction design, geotechnical engineers were well aware of the phenomenon of liquefaction, and this has been considered in the design of other infrastructure facilities, for example the Gas to Gasoline Plant in New Plymouth and water treatment facilities (Brabhaharan and Vessey, 1992).

It is also possible that there was lack of collaboration between bridge and geotechnical engineers, particularly outside design offices with capability in both bridge and geotechnical earthquake design.

Lack of Knowledge of Design of Bridges for Liquefaction

In 1994, the Institution of Civil Engineers (UK) under the auspices of the United Nations Disaster Reduction Plan held an international competition to promote liquefaction resistant design of bridges (Institution of Civil Engineers, 1994; Chapman and Brabhaharan, 1994).

However, liquefaction resistant design of bridges and other facilities were more extensively researched after the 1995 Kobe Earthquake in Japan, and some of this information came through after 2000.

Designers may have not been aware of approaches for methods of analyses and the design of bridges for liquefaction (Chapman and Brabhaharan, 1994; Cubrinovski et al, 2009; Brabhaharan et al, 2009).

Costs and Procurement Methods

Liquefaction resistant design of bridges may have been seen as costly, and the changes in the New Zealand construction sector since the late 1980s, with the restructuring the Ministry of Works, and increased emphasis on costs and benefit cost ratios may have led to acceptance of the risk from liquefaction to reduce the costs of transportation projects.

The introduction of design-build form of construction procurement, together with the lack of definitive design standards enshrined in the Bridge Manual may have also led to lack of design for liquefaction.

It should be noted that achieving a resilient design does not necessarily cost more (Brabhaharan, 2009), but requires early focus on resilience to influence design concepts that are more resilient.

Form of foundation construction

Many of the bridges damaged by liquefaction and lateral spreading were founded on a large number of small size driven piles. This was an easy form of construction in areas underlain by loose sands to found the piles in the dense sands or gravels below, or in some cases in the loose sands itself.

The driving of the piles would likely have locally densified the sands around the piles. This densification together with the close proximity of the piles appears to have created a narrow “wall” in a direction parallel to the river bank. No ground improvement was adopted. These piles were pushed outwards by the lateral spreading soil loads as a consequence of the liquefaction of the soils, causing extensive damage to the bridge abutments. Where the piers were located close to the river banks, they were also laterally deformed by the lateral spreading of the river banks towards the middle of the river.

4.4 **Lessons for Future Resilience of Bridges to Liquefaction**

Observations of the performance of bridges subject to liquefaction in the Canterbury Earthquakes and reflection on why the bridges may have performed poorly will enable us to draw some lessons for future resilience of bridges in areas prone to liquefaction.

1) Enhance Awareness

   Enhancing the awareness of bridge design practitioners as well as others such as clients and transportation professionals as to the damage caused by liquefaction in earthquakes, and our ability to design for these situations, is fundamental to achieve designs resilient to liquefaction.

2) Early Focus of Resilience

   It is important that there is early focus on resilience of transportation projects and bridges. This will enable the identification of liquefaction and the consequences for the bridges to be understood early. This will allow the development and selection of routes and design concepts that are resilient, and can be designed and constructed in an economical manner.

3) Integrated Practice

   It is important that transportation professionals, bridge designers and geotechnical engineers work together from an early stage to achieve the early focus on resilience discussed above. It is also important to develop cost effective and integrated concepts, rather than the liquefaction mitigation being ignored or added in at a later stage as an afterthought at additional cost.

   It is also important to ensure that resilience and liquefaction performance is written into contracts such as for design-build of transportation and bridge projects, to ensure that there is an enforceable focus on resilience and performance.

4) Design Standards

   The design standards for liquefaction should continue to be developed and stipulated in design manuals and guidelines, so that these provide guidance to designers as well as provide an enforceable standard when subject to competitive procurement practices.

5) Analyses Methods

   The methods of analyses for liquefaction, lateral spreading and the soil-structure interaction between the soil and the structure, should be better understood by designers, and requires knowledge sharing and training to ensure that the knowledge from research and advanced design practices are quickly transferred to the profession.

6) Design Approaches

   The possible approaches for developing design concepts that are resilient to liquefaction needs be developed and shared within the profession, so that design practitioners are able to consider and select appropriate and cost effective solutions to enhance resilience.

5 DESIGN APPROACHES FOR BRIDGES RESILIENT TO LIQUEFACTION

5.1 Performance based Design

It would be prudent to adopt a performance based design approach to design for an acceptable level of performance and resilience, where any displacement is limited and any damage can be easily and quickly repaired. This would give a cost effective design as well as provide resilience.

5.2 Bridge Siting

The Canterbury earthquakes have shown that there is considerable variability in the ground conditions in alluvial materials with significant variability in liquefaction of the soils. Gaining an understanding of the geology and geotechnical conditions through investigations may enable the bridge to be sited at locations with a lower hazard of liquefaction and lateral spreading.

5.3 Bridge Configuration

Single span bridges across water courses require protection of the abutments from liquefaction and lateral spreading. Piers of multi-span bridges located close to the river banks were also affected by lateral spreading associated with the river banks in the Canterbury earthquakes.

Where multiple spans are required, locating bridge piers outside the zone of influence of lateral spreading from the river banks would reduce the more damaging effects of lateral spreading arising from liquefaction.

5.4 **Founding of Piles**

In Christchurch, it was observed that bridge piles founded within liquefiable ground led to settlement of the bridge structure and consequent damage. Bridges in liquefiable ground would need to be supported by piles founded below the zone of lateral spreading and substantial liquefaction.

5.5 **Design approaches for Lateral Spreading**

Loads imposed by lateral spreading on the abutment structures including their foundations was the predominant cause of damage to many of the bridges in areas that suffered from liquefaction.

Two design approaches have been developed for mitigating the effects on liquefaction induced lateral spreading, which are:

1) Structural Approach - designing bridge structure including foundations to accommodate lateral spread loads.
2) Ground improvement Approach –improving the ground at the river banks to reduce liquefaction and consequent lateral displacements.

Both approaches require close collaboration between the structural and geotechnical engineers to consider the interaction between the structure and the ground, and tailor the design to be resilient.

Structural Approach

The structural approach involves a structural concept where the loads imposed on the substructure (including piles) can be resisted by the structure. A variation of this approach is to make the bridge superstructure continuous so that the loads can be resisted by passive pressure on the opposite abutment of the bridge. Such an approach was used for the design of the trench structure at the Wellington Inner City Bypass. This approach requires careful consideration of the lateral spread loads on the sub-structure, and tailoring the sub-structure and foundations to minimise the loads imposed on the structure.

This design approach adopted for the Ferrymead Bridge that is being reconstructed following damage to the earlier bridge in the Canterbury earthquakes is described by Kirkcaldie et al (2013). Figure 6 shows a long section of the Ferrymead Bridge showing how the lateral spread loads were minimised by using a void and short land span behind each of the abutments, and using small abutment piles.

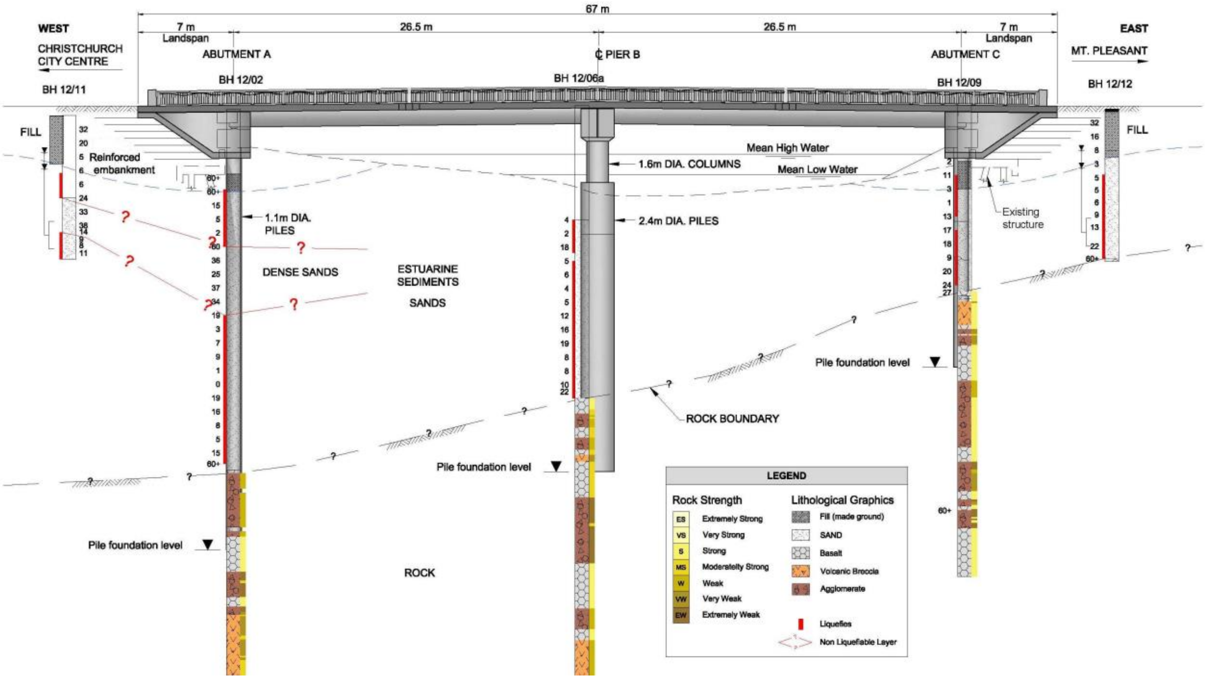

Figure 6. Ferrymead Bridge – using structure to resist lateral spread loads (after Kirkcaldie et al, 2013)

The small abutment piles were spaced well apart to allow the liquefied ground to flow around and minimise the loads on the structure. The lateral spread loads were resisted by passive pressure on the opposite side of the river using a continuous superstructure to transfer the loads, and by larger pier piles socketed into bedrock.

Some damage to the approaches and possibly the abutments is likely with this approach, and these need to be detailed so that they are easily and readily repairable to restore the bridge to its original functionality.

Ground Improvement Approach

The ground improvement approach aims to improve resilience by making the ground immediately behind the bridge abutments to be more resistant to liquefaction. The reduced liquefaction would significantly reduce the displacement of the ground through lateral spreading, so that the bridge structure can accommodate the displacements without significant damage. The ground improvement will need to be tailored to minimise displacements as well as limit the costs of ground improvement. A variety of methods of ground improvement are available and needs to be carefully chosen to suit the ground conditions and the required level of improvement and performance.

The ground improvement approach was used to retrofit the Cobham Bridge in Wanganui to provide resilience given the liquefiable soils present at that site as described by Brabhaharan et al (2009). In that case ground improvement using stone columns and wick drains and shallow ground replacement by excavation and replacement were used to minimise the liquefaction and consequent displacement of the abutment structure. A triangular area of stone columns was used to minimise the lateral spread loads in a cost effective manner. The stone columns were constructed by drilling in a casing and placing and compacting gravel using a vibrating casing and probe as the casing was withdrawn. This gave high quality stone columns without inter-mixing with the in situ soils.

The pier closest to the abutment was protected from liquefaction and lateral spreading by a combination of excavation and removal of liquefiable ground between the abutment and pier and replacement with compacted gravel, and gravel filled counterfort trenches.

Figure 7 shows the ground improvement used at the abutments to reduce liquefaction and consequent lateral displacement of the ground towards the abutment. The ground displacement was assessed to reduce the displacement to a limited amount that could be tolerated by the existing piles.

Some ground deformation of the approaches is likely and would be readily repairable to provide full access quickly after an event.

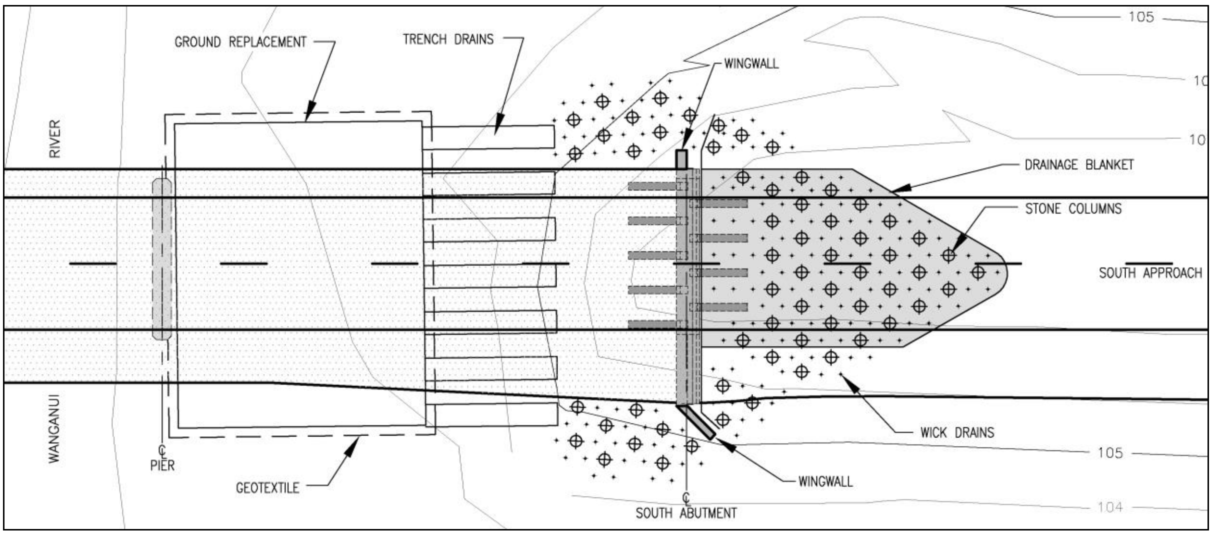

Figure 7. Layout of Ground Improvement at South Abutment (after Brabhaharan et al, 2009)

6 CONCLUSIONS

a) Bridges performed very well in areas on good ground that was not vulnerable to liquefaction, but experienced significant damage in areas of liquefaction and lateral spreading.

b) Liquefaction damage affected resilience for a long period and resulted in poor sustainability.

c) The liquefaction damage is likely to be the result of poor awareness of liquefaction, its consequences to bridges and design methods to mitigate its effects; lack of design standards; the perception that liquefaction mitigation is not possible or costly; and possibly lack of collaboration between bridge structural and geotechnical engineers.

d) Early focus on resilience and integrated practice will help enhance resilience of the bridges.

e) Focus on bridge siting, configuration, founding of piles and approaches to address lateral spreading, and use of a performance based design approach will help achieve a resilient design in an economical manner.

f) Lateral spreading can be mitigated by either of two approaches – configuring the structure to minimise the lateral loads and designing them to resist the loads; or ground improvement to reduce liquefaction and lateral displacements of the ground and consequently the structure. Both approaches require careful consideration of the interaction of the ground and the structure, and detailing to enable quick restoration after earthquake events.

g) Early and greater focus on resilience in an integrated manner will enable the design and construction of resilient bridges, even in areas prone to liquefaction and lateral spreading.

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