A review of colloidal silica stabilisation and microbial-induced calcite precipitation and their use to mitigate liquefaction using passive site remediation

L R Buhagiar
Coffey Geotechnics, Christchurch, NZ
Lee.buhagiar@coffey.com

Keywords: liquefaction, colloidal silica, calcite precipitation, passive site remediation, nanoparticles, resilient infrastructure, sustainability.

ABSTRACT

The damage to Christchurch’s lifelines has been observed widely across the region as a result of the Canterbury earthquake sequence. In order to incorporate earthquake resilience into infrastructure repair and design, a cost effective and non-intrusive method of liquefaction mitigation is required. Commonly applied methods of ground improvement to mitigate liquefaction are best suited to coarse grained soils, are intrusive and they may require dewatering and a large green-field site to be cost effective.

The purpose of this paper is to review two emerging methods of ground improvement to mitigate liquefaction-induced land deformation using passive site remediation. Emerging ground improvement methods that will be effective in fine grained soils and can be applied with minimal disturbance to existing structures have a potential to provide significant environmental and cost savings in the future.

Two of the most promising emerging methods of ground improvement are passive site remediation using colloidal silica and microbial-induced calcite precipitation (MICP). Several studies have indicated that colloidal silica treated sands have shown significantly increased resistance to cyclic loading. The primary focus of biological engineering research to date, MICP has been shown to increase resistance to liquefaction of loose sand. Successful field trials have been carried out for both methods.

1 INTRODUCTION

1.1 Background

The 22 February 2011 earthquake event created the largest lifeline disruption to a New Zealand city in 80 years, with much of the damage caused by extensive and severe liquefaction in the eastern Christchurch urban area (Giovinazzi et al. 2011).

As a result of the 22 February 2011 earthquake approximately half of the population lost power as a result of damage to approximately 50% of the 66kV underground cable network and 14% of the 11kV cable network. All the 66kV lines located in the northeast of Christchurch, where liquefaction was most severe, were damaged beyond repair. Additionally, 86% of the damaged 11kV lines were in areas mapped by the Earthquake Commission (EQC) as having suffered moderate to severe liquefaction (Giovinazzi et al. 2011).

Christchurch's water and waste networks suffered extensive damage as a result of the 22 February 2011 earthquake and subsequent aftershocks. Estimates are that it will take many years to return water and waste water functions to pre-earthquake functions.

One of Christchurch's treasured natural resources, the artesian water supply, was either disrupted or cut off to many parts of the city, and was contaminated in others. More than a third of households were without a water supply for over a week and 5% of occupied houses had no water for over a month (Giovinazzi et al. 2011). Once reinstated, the city's water supply was required to be chlorinated for 10 months due to contamination from wastewater. Wastewater systems had been severely damaged and raw sewerage was discharged into the rivers and estuaries. The city relied on a temporary sewerage service facilitated by chemical and portable toilets, with some areas still currently using this system.

Local roads in the eastern suburbs were most affected, with five out of six bridges across the lower Avon River and 83 sections of 57 roads closed due to damage from the 22 February 2011 earthquake. In general the transport network performed well, with most major roads remaining open. However, two years later the disruption is to continue with over 98 infrastructure repair projects underway and another 230 yet to begin (SCIRT, 2013). Roadworks, road closures and detours are now a way of life in post-earthquake Christchurch.

1.2 Liquefaction mitigation

In order to incorporate earthquake resilience into infrastructure repair and design, a cost effective and non-intrusive method of liquefaction mitigation is preferable. The commonly applied methods of ground improvement to mitigate liquefaction are dynamic compaction and permeation grouting. These methods require a high hydraulic conductivity (Mitchell, 2008) and are likely to be complicated by the complex geology of the Christchurch soil profile. Soil types in Christchurch can vary over short distances, from gravel and sand to interbedded sand, silt, and peat. Alternative methods such as stone columns, deep soil mixing, and ex- and in-situ cement stabilisation are all common ground improvement methods used in soils with high fines contents. However, all these methods are intrusive, may require dewatering and require a large green-field site to be cost effective.

Ground improvement methods that will be effective in fine grained soils and can be applied with minimal disturbance to existing structures have the potential to provide significant environmental and cost savings in the future. The author has selected two promising emerging ground improvement methods; Colloidal silica stabilisation, and microbial-induced calcite precipitation. These two methods are reviewed and assessed on their suitability to mitigate liquefaction in Christchurch using passive site remediation.

1.3 Passive site remediation

Passive site remediation is a concept which has been proposed for non-disruptive liquefaction mitigation on developed sites (Gallagher, 2000). Passive site remediation takes advantage of a site's natural groundwater flow. The concept involves introduction of a stabiliser at the up gradient (hydraulic) edge of a site, allowing the groundwater flow to distribute the stabiliser to the target area (refer Figure 1). The set time (or gel time) of the stabiliser is controlled to allow sufficient time for the stabiliser to reach the target area before setting, gelling or precipitating. If the natural ground water flow is inadequate it can be enhanced using extraction wells and low pressure injection. Passive site remediation was found (using numerical analysis) to be feasible for an area of approximately 3,700m^2 in formations with hydraulic conductivity of 0.05cm/s or more and hydraulic gradients of 0.005 and above. This numerical analysis was validated in later field trials (Gallagher et al. 2007).

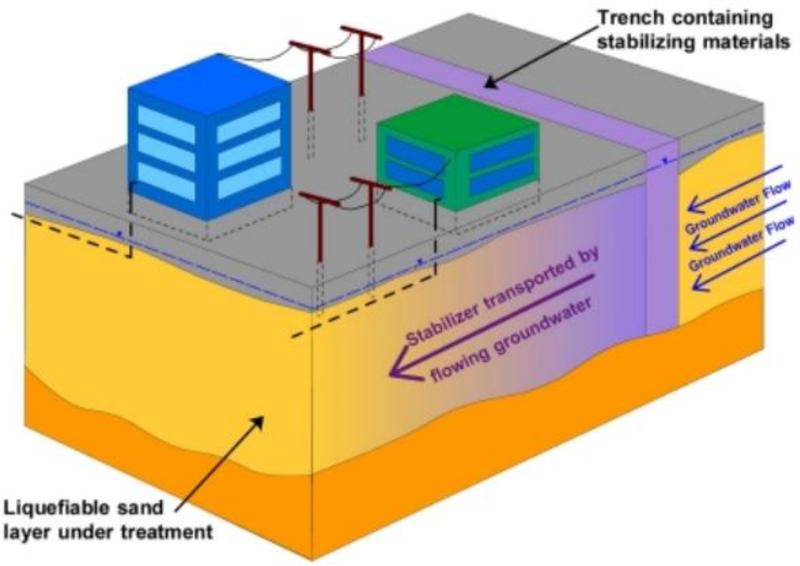

Figure 1: Passive site remediation (Gallagher, 2000)

1.4 A sustainable approach

"*The consideration of soil as a living ecosystem offers the potential for innovative and sustainable solutions to geotechnical problems*." (DeJong et al. 2013)

One of the attractive attributes of biotechnology is the utilisation of natural biogeochemical processes to improve soil. These processes also have the potential for significant reductions in embodied energy and carbon emissions. Biological ground improvement has the potential to treat large volumes of soil with less injection points than traditional ground improvement methods and can be applied beneath existing structures.

Two of the most promising sustainable, emerging methods of ground improvement to mitigate liquefaction are colloidal silica stabilisation and microbial-induced calcite precipitation (MICP).

Several studies have indicated (Diaz-Rodriguez & Antonio-Izarraras, 2004; Gallagher & Mitchell, 2002; Mollamahmutoglu & Yilmaz, 2010) that colloidal silica treated sands have shown significantly increased resistance to cyclic loading. The primary focus of biological engineering to date, bio-augmentation MICP, has been shown to increase the resistance to liquefaction of loose sand (Montoya et al. 2013) and several successful field trials have been carried out (DeJong et al. 2013).

In both of these emerging methods, the stabilising solution has a viscosity and density similar to water, making them prime candidates for passive site remediation. The methods have been shown to be effective in fine grained sands and gravels, which are common soil types in Christchurch. However, the efficacy of the processes will need to be assessed for complex fluvial deposits with interbedded fine grained soils. While the stabilising solutions require a hydraulic conductivity similar to that of a fine sand to be transported to the target area, the ground improvement does not need to be activated throughout the entire soil profile. This scenario is similar to traditional ground improvement methods such as deep soil mixing, where surface installed columns of cement grout reduce the shear stresses across a soil profile.

2 COLLOIDAL SILICA STABILISATION

2.1 Process

Colloidal silica is a non-toxic and inert solution of silica nanoparticles in water which has a density and viscosity similar to water at low concentrations. The gel time of the colloidal silica stabiliser is controlled by the size and concentration of silica solids, pH of solution and the salt concentration. The addition of a (sodium chloride) saline solution is commonly used as a reagent to shorten gel time (Mollamahmutoglu & Yilmaz, 2010). Studies have reported gel times of between 49 and 200 days (Gallagher, 2000; Noll et al. 1992).

Samples of colloidal silica grouted sand have been preserved for periods of 1 year to 1000 days without any occurrence of syneresis, which is a common form of degradation of some chemical grouts. Furthermore, the unconfined compressive strength was shown to increase by as much as 28% after a 1000 day curing period (Mollamahmutoglu & Yilmaz, 2010).

Gallagher & Mitchell (2002) have carried out cyclic triaxial tests on 5% to 20% concentrations of colloidal silica treated Monterey sand No. 0/30 which comprises a fine to medium sand, similar in grading to the Christchurch Formation sands encountered along the coastal fringe of Canterbury. Results of the testing indicated the following:

- Treatment with colloidal silica grout significantly increases the deformation resistance of loose sand to cyclic loading
- For passive site remediation, a 5% concentration of colloidal silica is expected to achieve adequate mitigation for earthquake loading.

Stress controlled cyclic simple shear tests on colloidal silica treated samples of sand from the Port of Lazzaro Cardenas, Mexico have been performed. Results indicate that a small amount of colloidal silica significantly increases the cyclic strength and resistance to liquefaction of untreated loose sand (Diaz-Rodriguez & Antonio-Izarraras, 2004).

Costs of colloidal silica grouting are expected to be competitive with other chemical grouting methods depending on the concentration of colloidal silica used (Gallagher, 2000).

2.2 Field trials

Gallagher et al. (2007) performed a full-scale field trial to assess the performance of a dilute colloidal silica stabiliser in reducing the settlement of liquefiable sand. A 9m diameter test area was treated at a depth of 6.5m to 8.5m with a 7% concentrated solution using eight injection wells around the perimeter and one extraction well in the centre. The efficacy of the treatment was tested by inducing liquefaction using blasting techniques in the treated area and in an adjacent untreated area. Measured maximum settlements were 0.5m in the untreated area and 0.3m in the treated area. They concluded that that the settlement in the treated area to have occurred in layers underlying the treated zone, with the reduction in settlement being attributed to the treated layer.

3 MICROBIAL-INDUCED CALCITE PRECIPITATION

3.1 Process

The process of microbial-induced calcite precipitation (MICP) occurs when calcium carbonate (calcite) is produced as a result of microbial metabolic activity (DeJong et al. 2013). The most energy efficient method of MICP involves the introduction (bio-augmentation) of the reagents urea and calcium chloride, with a bacterial solution, to the treatment area. The ensuing enzymatic hydrolysis of urea (known as urease activity) raises the pH of the proximal environment, initiating the precipitation of calcium carbonate (DeJong et al. 2006). The process produces a by-product of ammonium chloride, which can be extracted via groundwater. In some cases calcium carbonate may already be present in the groundwater and does not need to be added.

The bacterial species most commonly known for producing urease and hydrolysing urea is *Sporosarcina pasteurii*. This species is well known for its ubiquity in nature and resistance to chemical and physical agents, which suits the use in open field environments (Qabany et al. 2012).

Geotechnical centrifuge tests (Montoya et al. 2013) have demonstrated an increase in resistance to liquefaction of MICP-treated sands when compared to untreated loose sand. Under dynamic loading ranging from 0.2g to 0.7g, pore pressures generated were greatly reduced in the MICP treated samples. MICP treated samples showed a reduction in shaking-induced settlements when compared to untreated samples, until the cementation began to break down under high dynamic loading.

In a study into the effects of the subsurface environment on MICP which may be encountered in commercial applications, Mortensen et al. (2011) has shown that the treatment is robust over a wide range of soil types and salinities ranging from distilled water to seawater. Qabany et al. (2012) have also shown that the MICP process can be optimised for different ground conditions by adjusting reagent and bacterial concentrations.

An alternative method of MICP involves the bio-stimulation of in-situ, native bacteria in the soil. This process involves the introduction of reagents such as urea and calcium carbonate (if required) to stimulate the native bacteria. Research is on-going into the use of pre-treated waste streams as a reagent for the MICP process (Van Paassen et al. 2013). This method could have a real potential in New Zealand using farm waste as a reagent.

3.2 Field trials

Two, full scale treatments using MICP have been documented to date, the first using a bio-augmentation strategy and the second stimulating the indigenous species to induce precipitation (DeJong et al. 2013).

3.2.1 MICP gravel stabilisation, Netherlands 2010

An MICP treatment was applied to a loose gravel deposit to enable horizontal directional drilling (HDD). The treatment comprised the addition of urea, calcium chloride and a bacterial suspension of *Sporosarcina pasteurii*. Groundwater was extracted until ammonium concentrations returned to background levels. The treatment was considered a success as HDD was possible without instability (DeJong et al. 2013).

3.2.2 MICP to immobilise heavy metals, USA 2010

A set of field trials using biological-stimulation to immobilise heavy metals (strontium-90) was initiated at the Idaho National Laboratory and is on-going at the US Department of Energy site in Rifle, Colorado. The treatment comprised the injection of molasses and urea, with groundwater extraction at a nearby extraction well. Native microbes have been successfully stimulated and calcite precipitation is in progress. The rate of precipitation is as expected, slower than the bio-augmentation application in the Netherlands (DeJong et al. 2013).

3.3 Biogas dentrification

Another method of microbial-induced ground improvement which deserves further research as a method of liquefaction mitigation is biogas dentrification, where soil is “de-saturated” via the addition of bacteria which produce nitrogen bubbles within the soil (He et al. 2013).

Initially this method was explored by injecting gas directly into the soil however it proved to be difficult to inject gas into the sand in a uniform manner. This problem was overcome by using bacteria to deliver the gas. The dominant species of denitrifying bacteria used in the He et al. (2013) study were extracted from anaerobic wastewater sludge. The bacterial suspension has a low viscosity and can be easily distributed in sand.

Results from shaking table tests have demonstrated the biogas method is effective in lowering the degree of saturation and significantly reducing the liquefaction potential of saturated sand.

One area where the He et al. (2013) has indicated more research is required is the longevity of the gas bubbles in the soil.

4 DISCUSSION

While the environmental benefits of these emerging technologies have not yet been quantified, Egan & Slocombe, (2010) have shown that traditional ground improvement methods have significantly lower embodied carbon dioxide (ECD) than piled solutions. By further reducing the need for cement based grouts, emerging technologies which use inert and non-toxic grouts, can provide even greater opportunities to reduce the environmental impact of ground improvement methods.

The achieved strength and resistance to cyclic loading, low viscosity and controllable gel time of colloidal silica stabilisation makes it a suitable stabiliser for passive site remediation.

Using the passive site remediation method, colloidal silica has been shown to be cost effective and has the potential to be used as a commercially viable ground improvement method for the mitigation of liquefaction.

For passive site remediation in fine grained soils the low hydraulic gradient is likely to lead to the use of pumps, and may require extended precipitation or gel times or smaller sites (i.e. a residential site).

Further research is required to assess the suitability of MICP and colloidal silica for use in fine grained soils. However, the author considered that as long as suitable continuous layers within the soil profile are present to deliver the stabiliser solution, and a significant proportion of the profile can be treated; an effective reduction in liquefaction potential will be achieved.

The production of reagents, the process of cultivating the bacteria and removal of resulting by-products needs to be assessed in terms of embodied energy and carbon dioxide to quantify the environmental benefits of MICP.

Issues such as the unpredictability of the homogeneity of cementation, costs of reagents, cultivation of bacteria and removal of by-products are all issues which could limit the commercial viability of bio-augmentation methods of MICP. Bio-stimulation methods may address these issues and the author sees great potential using an existing by-product or waste stream to stimulate native in-situ bacterium in New Zealand.

The emerging methods of ground improvement discussed in this paper are based on processes which strengthen the soil and decrease the hydraulic conductivity. The author is unaware of any research into the effects of the reduction of hydraulic conductivity on the rate of pore pressure dissipation during and after seismic loading. It is presumed that as long as the strength increase is sufficient the reduced permeability should not be an issue.

5 CONCLUSIONS

Liquefaction-induced ground deformation was one of the major factors affecting infrastructure damage in the Christchurch earthquake. This paper has reviewed two emerging methods of ground improvement which have the potential to be used as sustainable and cost-effective methods of mitigating liquefaction in design and repair of infrastructure.

The achieved strength and resistance to cyclic loading, low viscosity and controllable gel time of colloidal silica stabilisation makes it a suitable stabiliser for passive site remediation. Using the passive site remediation method colloidal silica stabilisation has the potential to be used as a commercially viable, environmentally sustainable ground improvement method for the mitigation of liquefaction. While this method has been proven in fine to medium grained sand, further investigation is required to assess the suitability in fine grained soils. However, due to the long and controllable gel time the author sees no reason why this method could not be successful in a fine grained soil.

While research is still needed into the cost effectiveness of bio-augmentation methods of MICP, the author believes there is a real potential for bio-stimulation methods in New Zealand using farm waste as a reagent.

6 ACKNOWLEDGEMENTS

Review by Jay Ameratunga and comments from Professor Harry Poulos are greatly appreciated.

7 REFERENCES

DeJong J.T. et al. (2006) Microbially Induced Cementation to Control Sand Response to Undrained Shear. *Journal of Geotechnical and Geoenvironmental Engineering.* ASCE 132, 1381-1392.

DeJong J.T. et al. (2013) Biogeochemical processes and geotechnical applications: progress, opportunities and challenges. *Geotechnique 63.* No. 4, 287-301.

Diaz-Rodriguez, J.A. & Antonio-Izarraras, V.M. (2004) Mitigation of liquefaction risk using colloidal silica stabilizer. *13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada August 1-6, 2004 Paper no. 509.

Egan, D. & Slocombe, B. (2010) Demonstrating environmental benefits of ground improvement. *Ground Improvement.* ICE Publishing, 163, G11, 63-69.

Gallagher, P.M. (2000) *Passive Site Remediation for Mitigation of Liquefaction Risk*. PhD thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Gallagher, P.M. & Mitchell, J.K. (2002) Influence of colloidal silica grout on liquefaction potential and cyclic undrained behaviour of loose sand. *Soil Dynamics and Earthquake Engineering.* 22, 1017-1026.

Gallagher, P.M. et al. (2007) Full-Scale Field Testing of Colloidal Silica Grouting for Mitigation of Liquefaction Risk. *Journal of Geotechnical and Geoenvironmental Engineering.* ASCE, 133, 186-196.

Giovianazzi, S. et al. (2011) Lifelines performance and management following the 22 February 2011 Christchurch Earthquake, New Zealand: Highlights of Resilience. *Bulletin of The New Zealand Society for Earthquake Engineering.* 44(4), 402-417.

He, J. et al. (2013) Mitigation of liquefaction of saturated sand using biogas. *Geotechnique 63.* No. 4, 267-275.

Mitchell, J.K. (2008) Mitigation of Liquefaction Potential of Silty Sands. *From Research to Practise in Geotechnical Engineering Congress 2008.* 443-451

Mollamahmutoglu, M. & Yilmaz, Y. (2010) Pre- and Post-cyclic loading strength of silica-grouted sand. *Geotechnical Engineering.* ICE 163(GE6), 343-348.

Montoya, B.M. et al. (2013) Dynamic response of liquefiable sand improved by microbial-induced calcite precipitation. *Geotechnique 63.* No. 4, 302-312.

Mortensen, B.M. et al. (2011) Effects of environmental factors on microbial induced calcium carbonate precipitation. *Journal of Applied Microbiology.* 111(2). 338-349.

Noll, M.R. et al. (1992) In-situ permeability reduction and chemical fixation using colloidal silica. *Proceedings of the 6th National Outdoor Action Conference, Las Vegas, NV.* 443-457.

Qabany, A.A. et al. (2012) Factors Affecting Efficiency of Microbially Induced Calcite Precipitation. *Journal of Geotechnical and Geoenvironmental Engineering.* ASCE. 138, 992-1001.

SCIRT (2013) http://strongerchristchurch.govt.nz. *Stronger Christchurch Infrastructure Rebuild Team.* Website.

Van Paassen, L.A. et al. (2013) BIOFIX *Bio-meditated ground improvement to mitigate liquefaction and piping of granular sediments.* NARCIS. http://www.narcis.nl/research/RecordID/OND1352038/Language/en.