Field miniature prototype development and pilot project design of subsurface compacted rubble rafts (SCRRs)

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ABSTRACT

Subsurface compacted rubble rafts (SCRRs) constitute a patented wide-area ground improvement treatment for solving liquefaction problems and associated hazards. SCRR treatment targets liquefaction layers by constructing a horizontal artificial layer (crust) in the shallow subsurface at a depth generally less than 10 m. The technique works by installing a single or multi-layer continuous densified aggregate mass compacted with high power. Thus, SCRR treatment represents a cost-effective way of upgrading land with severe liquefaction or potential liquefaction to TC1/TC2 criteria. This paper presents a field miniature prototype development of the SCRR treatment, discusses the soil improvement outcomes, and establishes the SCRR mechanisms of ground improvement. The paper also examines the installation parameters for the pilot project scheduled to commence in early 2023, which is partially sponsored by a Callaghan Innovation grant and the provision of a red-zoned land section by the Christchurch City Council. The consideration of the pilot project design is based primarily on the requirements and recommendations made by the MBIE guidance and modules currently in place. New Zealand GNS Science recently released the revised National Seismic Hazard Model, and more sites and land sections will subsequently be released and be categorized under the criteria of high liquefaction vulnerability and will require specific geotechnical design and wide ground improvement. Accordingly, SCRR treatment provides a flexible and affordable option to free up tens of thousands of land sections with high liquefaction vulnerability.

1 BACKGROUND

Throughout New Zealand, tens of thousands of sections are considered unsuitable for housing because of land instability resulting from liquefaction and a lack of a suitable foundation construction methodology. As an example, Christchurch has land equivalent to some 10,000 house sections (8000 red zoned and 2000 TC3 seriously damaged sections, with a total asset value of approximately $3 billion) (Tonkin & Taylor Ltd 2015). These groups and institutions have the dilemma of continuing foundation construction or leaving the land vacant because of concerns about costs and have been waiting for more than 12 years for a new technology that will feasibly upgrade such land with respect to TC1/TC2 criteria.

Our initial research has shown that the percentage of land with high liquefaction vulnerability in each major city in New Zealand is estimated as not less than 10% (corresponding to a total value of $30 billion). For example, by 2020, of the 502 sites or development zones mapped in the greater Wellington region, 13.5% of the land has been assessed at high (11.35%) and very high (2.19%) liquefaction risk (Greater Wellington Regional Council 2021).

Subsurface compacted rubble rafts (SCRRs) constitute a novel patented proprietary ground improvement system that involves the construction of thick artificial strata/crust composed of rubble spheres (or “bulbs”) at a depth generally below 3 m with a typical thickness of 4–6 m. Once a SCRR is installed, a standard foundation can be constructed on the ground above, ready for the construction of a new house or structure. The SCRR is quick to install, and the method can be implemented at any time of the year.

It is anticipated that a large number of earthquake-prone sections will be released from the 2 year national liquefaction mapping project (Steeman 2019) for SCRR treatment to be utilized in upgrading land to TC1/TC2 level. The SCRR technology has highly extensive market coverage residentially, commercially and industrially. Previous studies have identified that approximately 100 large cities worldwide have liquefaction problems, the treatment costs for which have been estimated at well over one trillion New Zealand dollars.

Importantly in New Zealand, one of the outstanding advantages of SCRRs is that the wide-area improvement can target the problematic layer or multiple depths at sites as specified in MBIE Module 5 (MBIE 2021). Herein, the area-wide measure or full land repair refers to the SCRR treatment and improvement of a large area of land entirely to TC1/TC2 level ground at low cost range from \$100k to \$200k per $600m^2$. The SCRR method thus contrasts with conventional ground treatment solutions, which deal only with land covered by the building footprint at high cost and leave roads, networks, lawns, and underground services in the adjacent areas/neighbourhood prone to future earthquake liquefaction damage. Thus, SCRR treatment may be the only feasible solution currently available to rehabilitate land types that have been severely damaged by liquefaction.

In Oct 2022, New Zealand GNS Science released the revised National Seismic Hazard Model. This model revealed that the likelihood of future earthquake shaking hazard has increased by 50% or more on average, highlighting the need to boost national resilience strategies and readiness, and meaning that more land sections will be categorized under high liquefaction vulnerability criteria (Houtte et al. 2022).

For a new technique, a pilot field test project is necessary to test and refine the design and specification, in this case as suggested by MBIE Module 5 (MBIE 2021). Fortunately, our SCRR pilot project has received much support. Christchurch City Council has provided a red-zoned land section to GECNZ for the pilot project, and MBIE has been sponsoring the SCRR R&D project with a Callaghan Innovation grant since October 2022. The SCRR project is scheduled to start site mobilization in early 2023.

Before a real pilot project takes place, a field miniature prototype was implemented and offered obvious benefits in the R&D programme of SCRR treatment, namely, to perform an initial examination of the physical 3D model and concept, reduce overall R&D time and costs, and partially test the SCRR treatment mechanisms. This paper presents two major components: the SCRR field miniature prototype development and the SCRR pilot installation initial design. Further details about SCRRs can be found in the study of Du and Shahin (Du and Shahin 2016).

2 FIELD MINIATURE PROTOTYPE DEVELOPMENT

This section presents the field miniature prototype development, explores the basic SCRR mechanisms, analyses several important construction parameters, and discusses the design of the forthcoming real-scale installation of an SCRR during the pilot project.

The field miniature prototype development was conducted over a 2 month period during October–November 2021 at 82 Hampshire Street, Aranui, Christchurch, to experiment with the SCRR at a small scale. The tools and materials used included:

- A Gilson pocket penetrometer HM-500. Pocket dial penetrometers are ideal instruments for rapidly determining soil penetration resistance and unconfined compressive strength in compliance with Standard(s) OSHA 29 and CFR 1926 (Gilson), especially when the test object is small, for which other test methods (i.e. cone penetration tests or CPTs, and standard penetration tests or SPTs) have limited use (Gilson Company 2019). The pocket penetrometer uses direct-reading scale in kg/cm^2.
- Rapidmesh 25.4 mm × 1.2 mm × 1 m galvanised steel round tube, used as casing to provide a pathway for the gravel to reach the hole bottom and for the screw rod to stand in the casing to transfer compacting power onto the filled gravel, and to maintain the hole wall in a stable condition during SCRR installation.
- A Craftright 1.8 kg sledge hammer to provide compaction power to drive the gravel/rubble into the soil through a screw rod placed in the installed tube.
- Rubble materials used for creating the bulb: white limestone with a particle size of 5–10 mm.
- Oxbuild M16 × 1 m galvanised steel to transfer hammer compaction to the gravel at the hole bottom.

2.1 SCRR bulb installation

The setup of the miniature experiment site is shown in Figure 1. Two zones are defined. Zone 1 was used for the installation of two separate bulbs (i.e. bulbs 00 and 05). Zone 2 was used for constructing the SCRR with two layers of bulbs, consisting of six bulbs (bulbs 01, 02, 03, and 04) installed in the bottom layer at a spacing of 15 cm, and bulbs Up01 and Up02 installed in the top layer at a spacing of 10 cm to examine their connection characteristics at a shorter installation distance.

Initially, the tube was driven with the screw bar inside to a depth of 0.8 m. Then, the bottom feed and compact methods formed continuously expanding dense and stiff bulb (SCRR sphere) until the designed volume was achieved. Next, the casing was withdrawn, and the hole was filled with cement to form a solid shaft with a diameter of approximately 2.6 cm, which helped to locate the bulb during subsequent extraction.

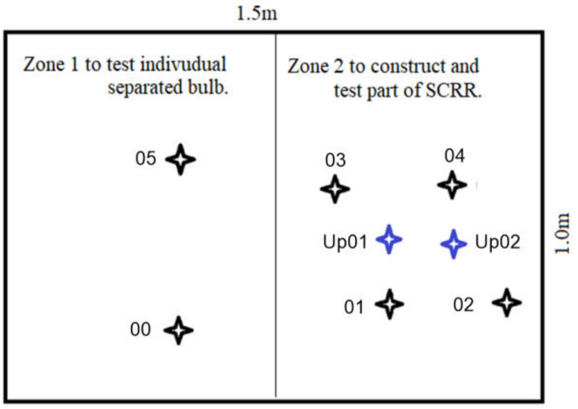


Figure 1: Site plan showing the site dimensions and bulb locations (Not in Scale).

2.2 Site geology

After the prototype raft and bulbs had been installed, tested, and extracted from the ground, a pit was formed as shown in Figure 2. The geological features revealed from surface to bottom were as follows:

- Layer one: Moist, firm, dark-brown fill composed of silty fine sand with traces of clay, with a depth from 0.0–0.5 m, and an average thickness of 30–50 cm.
- Layer two: Moist, medium-density, black ash layer with some fine sand (the site may have been affected by land clearance burning), with a thickness of 5–10 cm.
- Layer three: Moist, loose, fine sand at a depth of 0.4 to 1.2 m. This layer accommodated the installed SCRR miniature raft and bulbs.

2.3 SCRR miniature

The SCRR miniature consisted of six bulbs in total, with four bulbs in the base layer and two bulbs installed on top (Fig. 3). Each of the top bulbs was located on top of the centre of the triangle formed by three base bulbs, forming an equilateral-triangle-based pyramid installation structure. Two such integrated pyramids provide a solid and stable interlocked structure under the tight passive resistance force of the surrounding soil. An SCRR is an underground formwork comprising a number of such pyramid units. The bulb diameter varied from 9 to 12 cm. Details of the SCRR installation structure can be found in the study of Du et al. (2016).

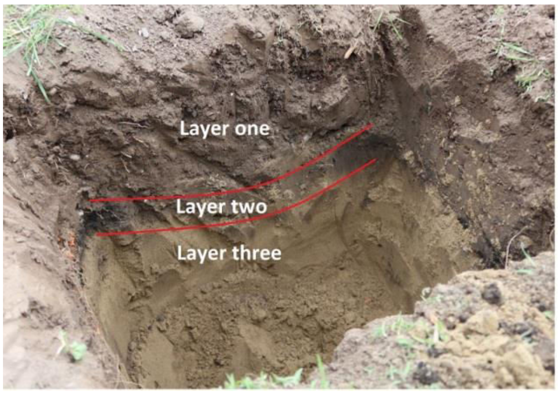


Figure 2: Pit exposure after extraction of SCRR bulbs.

Figure 3: SCRR miniature consisting of six bulbs, with four bulbs in the base layer and two bulbs installed on top as the top layer. The bulbs have a diameter of 9 to 12 cm.

2.4 Pocket penetrometer tests

Thirty days after installation of the SCRR bulbs, a pit was dug out starting from the side of the installed SCRR bulbs and raft. Each bulb was tested at its edge, in the soil between pairs of bulbs in one layer, and between the two layers of bulbs.

2.4.1 Pit wall and casing-hole wall readings

The average pocket penetrometer test (PPT) values measured in the pit walls at depths of 0.25 m, 0.60 m, and 0.80 m were 1.5, 0.9, and 0.95, respectively (Fig. 4). For the four casing walls (formed after casing removal), the average PPT values were quite uniform, varying from 0.9 to 1.0 in the depth range of 0.6 to 0.8 m in the sand layer (Fig. 4). The values for the casing wall were slightly higher than those for the pit wall at the same depth. This difference is ascribed to the casing installation effects of displacement compaction of the casing on the surrounding soil during bottom-driven installation. A PPT value of 0.95 was used as a datum for comparing the values obtained for the installed bulbs at the same depth as reported in the following sections.

2.4.2 PPT values at interfaces of the bulbs and surrounding soil

PPT values were measured by penetrating the PPT device into the soil at the interface of the bulb and the surrounding soil without touching the rubble material (Fig. 5). Table 1 lists the values of PPT for the five bulbs at various test points from P1 to P7. Average PPT values were 1.8, 1.2, 1.6, 1.3, and 2.3. The increase in soil resistance varies from 31% (for bulb 01) to 146% (for bulb Up02) with respect to the reference PPT value of 0.95.

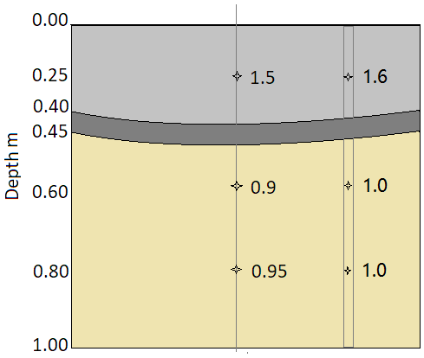


Figure 4: Typical PPT values tested in pit walls (left) and in casing walls (right).

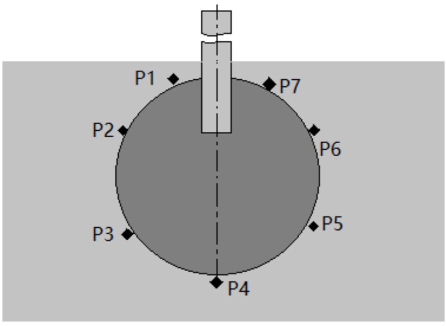


Figure 5: PPT test points from P1 to P7 adjacent to the bulb surface. No PPT measurement was obtained from the bulb centre. The bulb diameter is 12 cm. Cement shafts were used to locate and protect the bulbs during excavation for removal.

Table 1: Increases in soil resistance at the interface between bulbs and soil.

	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**Average**	**Datum value**	**Increase (%)**
Bulb 00		1.6	1.7	1.75	1.8	2		1.8	0.95	86%
Bulb 01	1.3	1.2	1.2	1.3	1.2	1.5	1	1.2	0.95	31%
Bulb 02	1.5	1.5	1.7	1.5	1.6	2	1.3	1.6	0.95	67%
Bulb 05	1.5	1.2	1.2	1	1	1	1.9	1.3	0.95	32%
Bulb up02		2.5	3.5	2	1.5	2.2		2.3	0.95	146%

2.4.3 PPT values of soil resistance between bulbs and between layers

The excavation was performed gradually. Near the pit bottom, when bulbs 01 and 02 had been exposed to half their side, PPT measurements were performed as shown in the side view of the installation structure presented in Figure 6. Except for one abnormal value of 0.8 and one penetration test that caused soil surface collapse, the other four values ranged from 1.1 to 1.6, corresponding to increases in soil resistance of 0.15 to 0.65 over the reference datum of 0.95, or increases of 16% to 68%, respectively.

Figure 7 shows a side view of the installation structure of bulbs 01, 02, and Up02 when their full diameters were exposed in the pit. The values were measured from penetration of soil at the midpoint between each bulb pair to examine the increase in soil resistance after SCRR bulb installation. The values summarized in Table 2 reveal that the soil resistance between bulbs increased by 24% on average compared with the reference value of 0.95.

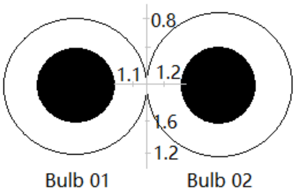


Figure 6: Side view of the installation structure of bulbs 01 and 02. PPT tests were conducted on the vertical surface where the two bulbs were exposed at half their profiles.

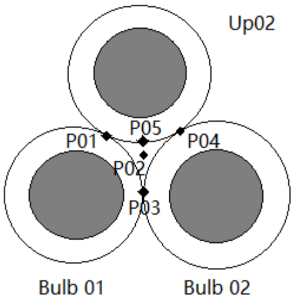


Figure 7: Side view of the installation structure of bulbs 01, 02, and Up02 with an average spacing of 12 cm between bulbs. The PPT measurements were carried out on the vertical surface of the pit wall where the three bulbs were exposed at their maximum profiles.

Table 2: Summary of PPT values of soil between bulbs 01, 02, and Up02.

	P01	P02	P03	P04	Average	Datum value	Increase (%)
PPT value	1.25	1	1	1.5	1.2	0.95	24%

2.4.4 Bulbs Up01 and Up02

Bulbs Up01 and Up 02 were installed at a smaller spacing of 12 cm to test their connection characteristics. PPT measurements yielded a maximum value at the midpoint between the two bulbs (Fig. 8). Twelve months after their removal from the pit, the two bulbs remained tightly connected without any sign of deterioration.

2.4.5 Production of SCRR bulbs

Here, we describe how an SCRR bulb is produced; using gravel batches coloured purple, white, black, and green, respectively (Fig. 9), with each batch having a volume of approximately $1E^{-6}$ m^3. The four batches form a sphere with an approximate diameter of 12 cm after compaction (compaction factor = 0.9).

Figure 10 shows the bulb produced using the four batches of coloured gravel. The SCRR bulb consists of four layers from outermost to kernel (core). The layered structure can be clearly seen. During bulb construction, the first batch of gravel forms the outermost layer, intermediate layers are formed by intermediate batches, and the final batch forms the kernel of the bulb. The height of the cylindrical part of the core (Fig. 10) depends on the final volume of fill gravel. The void left after withdrawal of the casing can be filled by clean sand or other engineering material. From the outermost layer to the core, the thickness of the annular layers increases because of the reducing diameter of the bulb closer to the core.

Figure 8: PPT measurement points (marked in red) between bulbs Up01 and Up02. Twelve months after their removal from the pit, the bulbs and the connection between them remain solid and stiff

Figure 9: Photograph of the four batches of gravel (with each batch having a volume of approximately $1E^{-6}$ m^3) coloured purple (1), white (2), black (3), and green (4) used to produce one SCRR bulb. The batches were placed in the bottom of the hole in order and compacted.

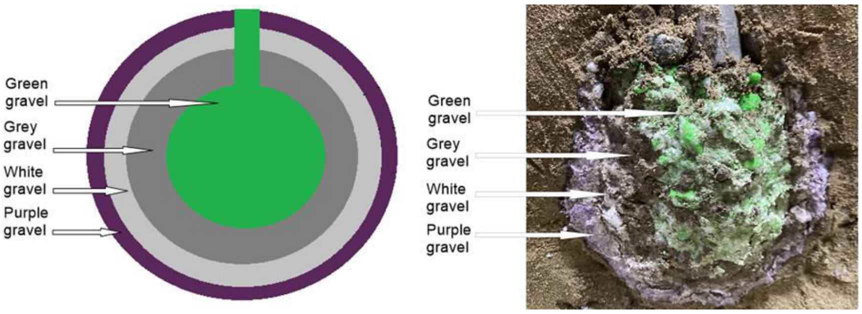


Figure 10: Left - Simplified bulb layer structure and layer development sequence (purple to green gravels) during SCRR bulb construction. Right - Layer structure and development sequence (purple to green gravels) during SCRR bulb production.

2.5 Summary and discussion

This report of the field miniature prototype development has described the installation of an SCRR, demonstrated its ground improvement mechanism, and revealed the layered structure of SCRR bulbs. PPT measurements show effective increases in soil resistance varying from 31% to 146% between the installed SCRR bulbs and of 24% between SCRR layers. The measured increases in soil resistance agree well with the findings in stone column improvement reported by Tomlinson and Woodward (2007) (Table 3).

Table 3: Comparison of the increase in soil resistance measured using CPT and PPT methods.

Equivalent distance from base/bulb axis, d/D	(Tomlinson and Woodward 2007)	SCRR miniature test (this study)
	Increase in CPT value (%)	Increase in PPT value (%)
1	50–100	31–146
2	~33	16–68
3.5	Negligible	Negligible

3 SCRR MECHANISMS, DESIGN, AND VERIFICATION

A pilot programme and design specification are required by MBIE Module 5 (MBIE, 2021). This section discusses the SCRR design for the pilot project and predicts the main installation parameters and configurations. Liquefaction triggering values are examined, as well as the aspects of Canterbury geology that influence liquefaction. SCRR layout, depth, and thickness, and the equipment energy used for installation are discussed, as well as the verification, quality control and quality assurance of the SCRR method.

3.1 Liquefaction triggering values

This section analyses liquefaction triggering factors and their values in a wider context that is relevant to the site conditions, soil properties, shallow-subsurface geology, and groundwater at a generic site. The seismologic factors and parameters involved in triggering a liquefaction event, termed “creation thresholds” by Nelson et al. (2006), are referred to as “seismic triggering thresholds” in this paper (cited by (Quigley et al. 2016)).

Numerous studies have sought to define liquefaction safe threshold values. Ishihara (1985) found that for a site characterized by a crust with a thickness larger than the underlying liquefiable layer (Ishihara 1985), the ground damage due to liquefaction will be mitigated or avoided. The thickness of the liquefiable layer can apply to a single critical layer or to the collective thickness of multiple liquefiable layers in the case where a non-liquefiable layer is no greater than 0.5 m in thickness (Bainbridge 2013). In addition, a soil behaviour type index (I_C) value of 2.6 has been used as a cut-off to predict the occurrence of liquefaction, with values exceeding this threshold corresponding to non-liquefiable soil (Bainbridge 2013). Various studies have reported that a cone resistance (qc) value of less than 15 MPa indicates that the site is prone to liquefaction (Ige 2018; Moss et al. 2006). A brief summary of some safe thresholds of liquefaction triggering with respect to soil properties, geological features, seismic parameters, crust characteristics, and groundwater conditions is presented in Table 4. At a particular site, if any one of the factors or parameters lies beyond the safe threshold, then the site has a high potential for earthquake-induced liquefaction; otherwise, liquefaction is unlikely to be triggered.

The objective of the SCRR method is to treat the site by improving at least one or multiple of the factors/parameters to mitigate or eliminate the liquefaction hazard. SCRR treatment should ensure that liquefaction triggering values lie within a safe threshold after improvement. However, SCRR treatment is not intended to inevitably remove all likelihood of liquefaction of all foundation soils. As an alternative, a performance-based design principle would involve the mitigation of destructive differential deformations to allowable levels in the superstructure (MBIE 2021). SCRR treatment should improve factors/parameters 1 to 9 in Table 4. Generally, factors/parameters 10 to 12 are not changeable by most current ground improvement methods.

Table 4: Summary of safe thresholds of liquefaction triggering.

No.	Type	Factor/Parameter	Unit	Notes	Safe Threshold	Reference
1	**Crust**	Crust theory	m	Crustal thickness H_1, liquefiable layer thickness H_2	$H_2 > nH_1$	(Ishihara, 1985)
2	**Soil**	CPT *qc*1 (normalized)	MPa	$qc1 = Cq.\ qc\ (Cq < 1.7)$	≥15	(Moss, Seed, and Kayen, 2006; Ige, 2018)
3		CPT *Ic*		Soil behaviour type index (Ic)	≥2.6	(Tonkin & Taylor Ltd, 2013)
4		Vs (shear-wave speed)	m/s	Magnitude 7.5	≥200	(Andrus and Stokoe, 2000)
6		SPT count (correlates with shaking intensity)	Blows	0.2 g	≥13	(China Earthquake Administration, 2018)
				0.3 g	≥17	
				0.4 g	≥20	
7		Relative density (correlates with earthquake magnitude)	%	Magnitude 6	≥65%	(Ministry of Hydropower of China, 2009)
				Magnitude 7	≥70%	
				Magnitude 8	≥75%	
				Magnitude 9	≥85%	
8		Plasticity index (PI)		Not prone	>18	(Puri et al., 2016)
9		Clay content and liquid limit	%	Clay >10% (LL > 32%)	>10%	(Andrews and Martin, 2000)
10		Prone-soil depth	m	Top layers above	≥20	(MBIE, 2012, 2021)
11	**Ground water**	Groundwater level	m		Soil above saturation level	(MBIE, 2012, 2021)
12	**Shaking**	Earthquake shaking (intensity)	g	0.2–0.4g	Various	(MBIE, 2012, 2021)

It should be noted that the triggering threshold values listed in Table 4 can be applied in two stages of SCRR treatment:

- In the design stage, the threshold values help in the determination of the SCRR depth range of bulb installation; and
- For verification purposes with respect to the completed SCRR, the threshold values can be used to test whether resistance to liquefaction is met (i.e. the CPT resistance).

3.2 Primary mechanisms involved in SCRR treatment and ground improvement

Five main mechanisms have been utilized in ground improvement, namely, replacement, densification, reinforcement, solidification, and drainage. A specific ground improvement method utilizes one or a combination of these mechanisms to increase the resistance of the ground to liquefaction and improve seismic performance, as identified in MBIE Module 5 (MBIE 2021). For example, the stone column method can include the densification, replacement, reinforcement, and drainage mechanisms (Tang and Orense

2014). SCRR performs all five mechanisms, meaning that SCRR has a wide application range across the majority of soil types.

Moreover, SCRR treatment includes a secondary mechanism of improvement to the soil initial state. This improvement is achieved during the casing installation with a closed-end tube, especially during the expansion and formation of rubble bulbs. The forces involved in this process considerably increase the lateral stress within the soil, thereby improving its resistance to liquefaction. This secondary mechanism has been identified as a ground improvement bonus in MBIE Module 5 (MBIE 2021).

According to Elias et al. (V. Elias, J. Welsh, J. Warren, R. Lukas, J. Collin 2017), the vibratory replacement method that SCRR treatment uses suits most soil types ranging from clay to large gravel. Combining the five mechanisms contributed by SCRR treatment makes the method suitable for most geological conditions and a highly feasible solution for rehabilitating land subject to high liquefaction vulnerability.

3.3 Canterbury geology and ground conditions

Christchurch is situated on deep alluvial soils of the Canterbury Plains. The plains are composed of complex interlayered soils deposited by rivers flowing eastwards from the Southern Alps and discharging into the Pacific Ocean. In Christchurch, the plains consist of very thick soil deposits ranging between 15 m thickness on the eastern edge of the city and 40 m on the western edge. These soils overlie sequences of gravel layers interbedded with sand, silt, clay, and peat layers, with total thicknesses of 300 to 500 m. These interlayers of fine-grained soils and gravels host an extensive aquifer system. Land for residential and commercial development in Christchurch was originally formed from swamps, estuaries, and lagoons, as well as gravels and fine-grained soils of river-channel and flood deposits of the coastal Waimakariri River floodplain (Cubrinovski et al. 2011; Environment Canterbury 2011).

Across Christchurch, the groundwater level is high, with a water table about 5 m deep in the western suburbs, rising gradually towards the coast, where it varies between 1.0 and 1.5 m deep. Materials constituting the top 10 m of soil are geologically new (<4000 years old) and soft and have a low level of consolidation, meaning that these soils offer low resistance to liquefaction (Cubrinovski et al. 2011; Environment Canterbury 2011).

3.4 Natural crust and natural rafts

It has been observed that most buildings that sit on denser, stiffer, and thicker non-liquefiable crust sustained much less damage during the Canterbury earthquake sequence compared with structures on looser, less stiff, and thinner near-surface natural rafts. These denser, stiffer, and thicker non-liquefiable natural rafts have superior CPT and cross-hole geophysical parameters of soils, such as shear-wave velocity. Shallow-subsurface ground improvement methods aim to enhance the thickness and/or stiffness of near-surface soil to improve liquefaction resistance, essentially duplicating as closely as possible natural soil rafts that performed well during earthquakes (Earthquake Commission New Zealand 2011; MBIE 2021).

MBIE have suggested that where a "natural raft" is unavailable or is insufficient to resist liquefaction, an "artificial raft" can be an ideal substitute formed by the implementation of a specialised ground improvement approach (MBIE 2021). SCRR treatment aims to meet this need by thickening the near-surface crust from the bottom of the natural crust, by displacing the uppermost liquefiable layer directly underlying the natural raft and simultaneously densifying the underlying liquefiable layer. Stiff SCRR crust performs more resiliently compared with a less stiff natural raft or crust, thus offering better mitigation of possible differential settlement and lateral spreading (Earthquake Commission New Zealand 2011; MBIE 2021).

3.5 Layout and spacing of SCRR bulbs and raft

The layout and spacing of SCRR elements involve bulbs being arranged typically in a triangle pattern with a bulb spacing of 1.5 to 2.0 m and a bulb diameter of 1.0–1.3 m, and in a typical two-layer installation structure (Fig. 11). Each bulb has a surrounding densified soil zone. According to the cavity expansion theory, the annular layer of the densified soil has a thickness equivalent to the bulb radius (Du and Xu 2022).

3.6 Depth and thickness of SCRRs

SCRRs should be sufficiently thick to restrain and bridge over any liquefiable or weak soils. For a site with a relatively small thickness of liquefiable soil, full-depth treatment is feasible. However, for most sites in Christchurch, the liquefiable layer(s) thickness varies from 5 to 10 m, and full-depth improvement beneath a land section therefore becomes unlikely owing to costs and technical considerations (MBIE 2021).

Data from more than 60,000 investigations on the performance of family bungalows during the Canterbury earthquake sequence have revealed that less damage was sustained by those dwellings that were supported by a natural stiff raft/crust of at least 3 m thickness (Wansbone and Ballegooy 2015). As such, partial depth treatment can provide an acceptable level of performance by mitigating the settlement and lateral spreading as recommended (Earthquake Commission New Zealand 2011; MBIE 2021).

Accordingly, the SCRR ground improvement method directly targets the uppermost liquefiable layer(s) to control settlement and lateral spreading. TC3 sections and red-zoned land that are categorized as high liquefaction vulnerability can be treated by full land improvement to TC1/TC2 criteria. This not only reduces the cost of improvement and saves time, but also helps to control the early heave that is typically generated by excessive ground treatment. The buried depth of an SCRR is generally greater than 3 m to control ground heave. The thickness of the SCRR is referred to Figure 12, obtained from MBIE (2012), and is calculated by the following series of equations:

PGA	SCRR thickness, Hs (m)
0.2 g	$H_s \geq (H_2 - H_1)/2$
0.3 g	$H_s \geq (1.5H_2 - H_1)/2$
0.4 g	$H_s \geq (2.5H_2 - H_1)/2$

where H_1 = the thickness of the uppermost natural crust (m); H_2 = the thickness of the underlying liquefiable layer (m); Hs = the thickness of the SCRR (m) to be installed immediately beneath the layer of thickness H_1 and in the top part of the layer of thickness H_2.

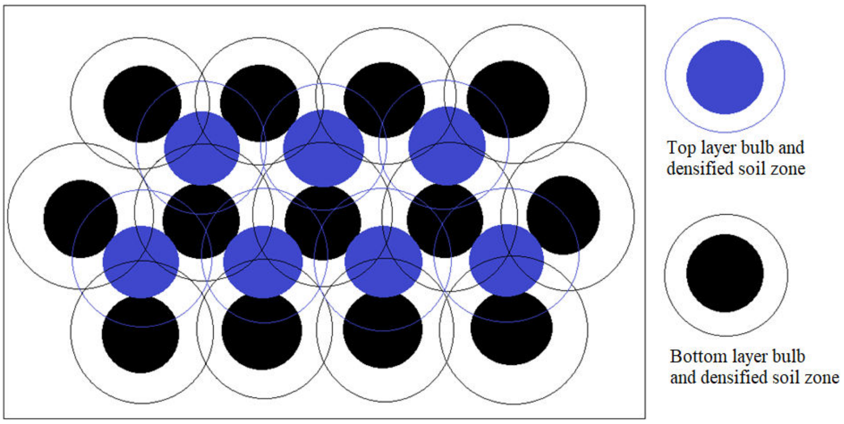


Figure 11: Sketch of the triangle arrangement of SCRR bulbs in a two-layer installation structure. Each bulb has a surrounding zone of densified soil. The bulb diameter is 1.0–1.3 m, and the bulb spacing is 1.5–2.0 m.

3.7 Energy per unit area

It has been found that there is a certain level of "saturation energy intensity" involved in ground improvement above which there is no more measurable improvement in the material density and resistance to liquefaction. Thus, MBIE (MBIE 2021) recommended a method for predicting the energy used for dynamic compaction, which is referred to here for the SCRR ground improvement pilot project.

The information in Table 4 (Section 3.1) suggests that the cut-off SPT value is 20 blows for a seismic event with a PGA of 0.4 g. According to (MBIE 2021), the applied energy at 20 blows is around 1.5 MJ/m^2 for sand and gravel. In the case where a closed-end casing with a diameter of 400 mm is chosen to compact rubble under vibratory hammer compaction, the required level of power for SCRR compaction is at least $\pi \times (0.2)^2 \times 1.5 = 0.19$ MJ = 190 kN m.

3.8 Inert materials, raw materials, and cleanfill

Most ground improvement practices use inert materials as the main construction materials. These inert materials do not undergo any significant chemical, physical, or biological reactions or transformations and are unlikely to contaminate ground that accommodates these materials. These waste materials, which include concrete, brick, hardcore, and subsoils, are not generally reused/recycled as major construction materials (MBIE 2021). However, SCRR rubble includes waste materials such as brick, concrete, hardcore, quarry tailings, and river run, as these materials comply with MBIE requirements (Du 2019; Du and Shahin 2016).

Uniformly graded gravels do not compact well to form a dense conglomerate and are also expensive because of pre-processing (Penn State University 2021). The use of mix-sized non-purposely processed aggregates in an SCRR provides the best compaction effect and allows a dense conglomerate to be obtained at low cost.

3.9 Quality control and assurance

QA for SCRR construction includes the following: testing of rubble materials and liquefiable soils, CPT testing of soils between SCRR bulbs to confirm that soil between the bulbs has been densified to the required criteria, SCRR mass testing by SPT, and SCRR profile verification by coring and cross-hole shear-wave testing (MBIE 2021).

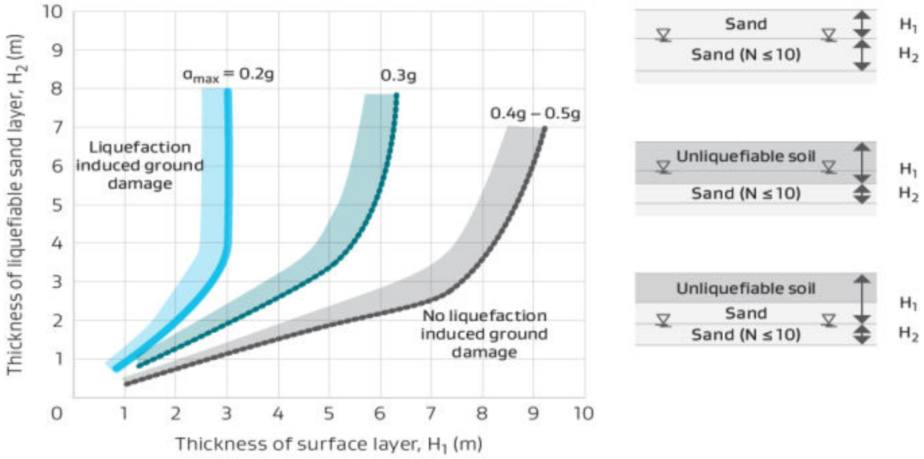
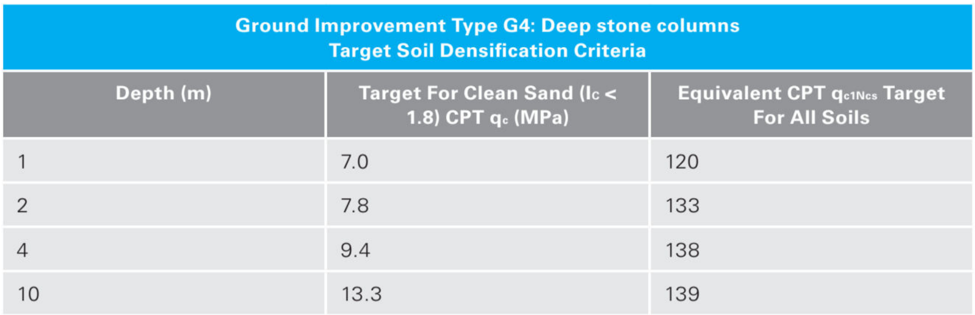


Figure 12: Chart for evaluation of the effect of crust thickness on liquefaction triggering (Ishihara 1985).

Dynamic compaction generally shows late strength gains at least 2 weeks after compaction (MBIE 2021). SCRR testing is scheduled with a 2 week delay between finishing ground treatment and undertaking the final QA testing.

Verification of densification after SCRR ground improvement can be performed by setting a target of a minimum SPT N60 value or CPT tip resistance obtained between SCRR bulbs and within bulbs. MBIE (MBIE 2021) has provided guidance for testing ground improvement criteria. Table 5 gives the requirements for the deep stone column method.

Table 5: Target soil-densification criteria for the deep stone column method (MBIE 2012).



Ground Improvement Type G4: Deep stone columns Target Soil Densification Criteria		
Depth (m)	**Target For Clean Sand (I_c < 1.8) CPT q_c (MPa)**	**Equivalent CPT q_{c1Ncs} Target For All Soils**
1	7.0	120
2	7.8	133
4	9.4	138
10	13.3	139

Combining the requirements for typical surface gravel rafts recommended in MBIE Guidance C, the target for clean sand (*Ic* < 1.8) in an SCRR installation is initially defined for the SCRR pilot project as follows; it is noted that in a maximum densification zone, the average CPT resistance is generally less than 20 MPa (Sinclair 1991):

- CPT (uncorrected), q_c > 7.0, 7.8, 9.4, and 13.3 MPa at depths of 1, 2, 4, and 10 m;
- SPT (uncorrected) > 20; or
- Dynamic cone penetrometer (Scala) > 10 blows per 100 mm.

CPTs should be conducted at the midpoint between SCRR bulbs and undertaken at a minimum frequency of 1/100 m^2 of treated ground with no less than three tests per residential house site for the pilot project. All CPTs should extend to a minimum depth of 1.0 m below the base of the SCRR. Where the minimum degree of improvement defined by the applied criteria is not achieved, then the contractor shall advise the engineer for rework (MBIE 2021).

4 CONCLUSIONS

This paper has presented the field miniature prototype development for individual bulbs, interlocking and bulb layer structure, and SCRR installation. It has also discussed factors/parameters relevant to the triggering of liquefaction and to SCRR installation, which should inform the installation design of the pilot project.

Our investigation of the field miniature prototype development allows the following initial conclusions to be drawn:

- Soil resistance between bulbs and layers is improved significantly compared with the original resistance.
- The distance between bulbs may influence the connection strength between adjacent bulbs. If bulbs are installed with a spacing that is less than the bulb diameter, the connection is especially tight and long lasting. However, more testing is required to verify this conclusion.

- A bulb is constructed with several rubble batch fills and by compaction. The batch order proceeds from the outermost layer to intermediate layers to the core.

SCRR treatment involves all five mechanisms of ground improvement, namely, replacement, densification, reinforcement, solidification, and drainage. The incorporation of these mechanisms means that SCRR treatment has a wide application range from clay, silt, and sand to gravelly soils, making it one of the most feasible solutions for rehabilitating land with high liquefaction vulnerability.

The defined threshold values for triggering of liquefaction for various relevant factors/parameters can help in the design stage to determine the depth range of bulb installation for the SCRR, as well as for verifying whether the resistance of the SCRR to liquefaction is sufficient.

SCRR treatment aims to thicken the near-surface crust from the bottom of the natural crust by displacing the uppermost liquefiable layer directly underlying natural raft while densifying the underlying liquefiable layer.

This paper presented initial findings from the field miniature prototype development of SCRRs and discussed their preliminary design for the pilot project. More investigation will be required to refine the specifications and design parameters.

5 ACKNOWLEDGEMENT

We gratefully acknowledge Ms. X Wu for her invaluable support in the development of the SCRR miniature project, including preparation work, photography, and testing. Her dedication and attention to detail greatly contributed to the project's success.

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