Geotechnical design for severe liquefiable ground improvement with SCRR technique: Waikato case study

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ABSTRACT

This paper introduces an innovative earthquake geotechnical design approach for severe liquefiable ground, adopting ground improvement using the patented Subsurface Compacted Rubble Raft (SCRR) technology in a Waikato Region case study, New Zealand. This paper is derived from one of the three design cases that emerged from the collaborative research conducted by Wintec and GECNZ, with the objective of introducing the innovative SCRR technology to the Waikato Region. The primary goal of this methodology is to guide SCRR construction, mitigating severe liquefaction hazards at the Endeavour Avenue site in Flagstaff, Hamilton, with the aim of upgrading its Technical Category (TC) classification from TC3-like to TC1-like aligning it with Ministry of Business, Innovation, and Employment (MBIE) residential lot performance criteria. The study emphasizes the urgent need for disaster preparedness in the region, with over 20% of Waikato land susceptible to medium/high liquefaction damage and approximately 90% of Hamilton land facing medium to high liquefaction vulnerability. As a full land treatment solution, SCRR technology, versatile through five mechanisms, is identified as a promising solution to address severe liquefaction risks while avoiding excessive ground treatment. The paper outlines essential SCRR construction parameters such as thickness, depth, layer count, bulb specifications, and material requirements. It introduces four design methods for determining SCRR raft dimensions. As an emerging technology, the paper also offers a brief guide to SCRR quality control measures, including Cone Penetration Testing (CPT), and strict compliance with MBIE requirements. These insights aim to facilitate understanding among geotechnical engineering practitioners.

1 BACKGROUND

GECNZ has introduced an innovative ground improvement technique known as Subsurface Compacted Rubble Raft (SCRR or SCR Raft) (Du and Shahin, 2016; Du and Xu, 2023). This method utilises a vibratory hammer on a crane to introduce aggregate materials into the ground, forming solid and stable artificial interlocking bulbs. These bulbs constitute the lines and layers of the SCRR structure, creating a robust and stable raft at depth that effectively stabilizes land susceptible to liquefaction. The SCRR technology targets improving ground within TC3 and red zoned sites to achieve a MBIE TC1 / TC2 criterion, allowing for the construction of TC1 or TC2 type foundations and buildings.

The paper focuses on the proposed site at Endeavour Avenue, Hamilton, in the Waikato region. The vacant site encompasses approximately 19,700 m^2 of land (AECOM New Zealand Limited, 2019). It presents geotechnical investigations, ground condition assessments, stability analysis, and ULS design of ground improvement. The site serves as one of three samples in the region for future ground improvement projects utilizing SCRR technology.

GECNZ has recently completed a pilot project in Canterbury in December 2023, with the objective of transitioning SCRR from research and development into a tangible product. Sponsored by MBIE, Callaghan Innovation, and Christchurch City Council, the pilot project took place at 74 Wainoni Road, Wainoni, a land section within the red zone. The project aimed to evaluate SCRR functionality, refine its design specifications, and prepare for the next full-scale production. It is anticipated that one of the upcoming projects may resemble the Endeavour Avenue site in Waikato. This design serves as a demonstration and thorough preparation in advance.

The Waikato Regional Hazards Portal shows that over 20% of the land in the region falls under the high/medium liquefaction vulnerability category (Liquefaction Possible) (Waikato Regional Council, 2023). Furthermore, Tonkin & Taylor Ltd (2019) reported that around 90% area of the Hamilton region is susceptible to high liquefaction vulnerability, with 10% of the area marked as undetermined. These findings make it imperative to find suitable solutions to address this hazardous situation.

In response to these potentially widespread severe liquefaction hazards reported above for the Waikato region, a collaborative research project was launched since May 2023 by GECNZ and Wintec supported by Trust Waikato through a trust grant. This research consists of three site designs and concluded in Dec 2023.

2 GEOTECHNICAL INVESTIGATIONS

2.1 Geotechnical investigation methods

Extensive investigations were undertaken on the site by Drillforce in 2019 and Drillcore in 2022. Supplementary shallow investigations have also been undertaken by AECOM during the time from 2017 to 2022 at various design phases. Sub-surface testing completed for this site comprised 9 cone penetration tests (CPT) to 20m or refusal, 36 Hand Auger (HA) tests, and 33 Dynamic Cone Penetration (DCP) tests (AECOM New Zealand Limited, 2019).

2.2 Investigation results

The CPT data from eight tests were analysed using GeoLogismiki CLiq v.3.5.2.19 software. Unfortunately, one CPT data file could not be opened. The ground conditions encountered during these tests revealed a subsurface profile primarily consisting of sand and silty sand layers extending to a depth of 20 m. These layers were interspersed with intermittent clay and silt layers. In the sandy segments, the average cone resistance values ranged from 5 to 15 MPa. On the other hand, the clay and silt lenses exhibited much lower resistance readings, ranging from less than 1 MPa to 2 MPa.

2.3 Ground Earthquake Geotechnical Classification

Various approaches have been developed to assess, evaluate, and approximate liquefaction hazards, including methods such as Liquefaction Vulnerability Category (MBIE, 2017), Liquefaction Severity Number (LSN) (Ballegooy *et al.*, 2014), Liquefaction Potential Index (LPI) (Maurer *et al.*, 2015) Technical Category (TC) (MBIE, 2012), and the Lateral Displacement Index (Zhang, Robertson and Brachman, 2004). When liquefaction poses a significant hazard, it is advisable to categorize land zones according to foundation Technical Categories, as specified in the MBIE Residential Building Guidance 2. While the use of Technical Categories is mainly applied to residential properties in the Canterbury Earthquake region, similar classifications (like 'TC1-like', 'TC2-like', etc.) could serve as a means to assess and communicate potential land performance concerning liquefaction within various sites in other regions. Moreover, when adopting this approach, it can be valuable to identify areas particularly prone to lateral spread, as recommended by the Ministry of Education New Zealand (2020).

For the sake of clarity and convenience, this report initially adopts the Technical Category approach. This approach facilitates the analysis of CPT data, SCRR design, and construction validation, providing a well-defined method to guide these processes. Other methods, such as LSN and LPI are employed as valuable tools to offer additional insights and support within this paper.

3 EARTHQUAKE LIQUEFACTION ANALYSIS

The following sections delve into subsoil liquefaction analysis, assessment methods, vertical settlement, lateral movement, and culminate with site classification.

3.1 Liquefaction analysis methodology

A study of the seismic behaviour of the soil was conducted using CLiq v.3.5.2.19, a software developed by GeoLogismiki (Geologismiki, 2018). The analysis employed results from CPT tests and adhered to the methodologies recommended by MBIE Module 3 (MBIE, 2021):

- Analysis method: Boulanger and Idriss (2014)
- Fine correction following Boulanger and Idriss (2014)
- Vertical Settlements in line with Zhang et al. (2002)

To gauge the susceptibility of the soil's seismic response, an evaluation was performed based on in-situ CPT testing conducted at the Site. For this assessment, a groundwater level of 2.5 m Below Ground Level (BGL) was adopted for all CPT tests (AECOM New Zealand Limited, 2019).

3.2 Vertical Settlement

Referring to the MBIE guidelines from December 2012, a comprehensive liquefaction analysis of the entire soil profile is typically essential for foundation design. However, for the SCRR technique, an analysis of the soil profile under Ultimate Limit State (ULS) level shaking is necessary. Ensuring the site's safety under ULS shaking guarantees safety in less severe shaking, such as SLS1 and SLS2 events. A summary of the analysis results is provided in Table 1 below.

Table 1 highlights that among the eight CPTs, vertical settlements exceed 100mm (in bold) for all except CPTs 180093 and 180097, which have values of 76mm and 81mm respectively. These two CPTs possess low LSN values of 9 and 10. Remarkably, the remaining six CPTs exhibit high LSN readings surpassing 15 (in bold), along with high vertical settlement larger than 100mm, indicating TC3 criteria soil. Referring to MBIE's assessment guidance 2012 and Table 1, the site is categorized as a Technical Category 3 (TC3) site. Moderate to severe land damage is expected to occur in a ULS-level event. The proposed SCRR ground improvement solution in the design aims to upgrade this site to meet TC1 criteria, or at the very least, achieve a TC2 classification at a ULS event, aligning with MBIE's stipulations.

Table 1: Summary of performance levels: liquefaction analysis of full CPT trace at ULS ground shaking.

CPT ID	ULS Vertical settlement (mm)	Technical Category	Liquefaction Severity Number (LSN)
170045	**140**	TC3	**18**
170046	**226**	TC3	**33**
170047	**192**	TC3	**27**
170048	**220**	TC3	**31**
170049	**200**	TC3	**27**
180093	76	TC2	9
180097	81	TC2	10
180098	**148**	TC3	**25**

Given the site's relatively flat topography and the absence of nearby water bodies or exposed slopes in its vicinity, it's reasonable to anticipate that there will likely be no lateral displacements during a seismic event.

4 SCRR GROUND IMPROVEMENT

4.1 SCRR treatment mechanisms

Five main mechanisms are employed 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 instance, the stone column method can involve the mechanisms of the densification, replacement, reinforcement, and drainage (Tang and Orense, 2014). However, in stone column ground improvement, the strain between the stone column material and the surrounding improved soil may not be significant and the reinforcing effect of stone columns to mitigate liquefaction effects is likely very small (Nguyen *et al.*, 2013; Rayamajhi *et al.*, 2014; Oregon State Government USA, 2023).

SCRR incorporates all five mechanisms, making it versatile and applicable across a broad range of soil types. Specific details can be found in the paper by Du and Xu (2023). Furthermore, during SCRR installation, the use of high compaction power generates significant strain in the surrounding soil as the aggregates compact, forming strong interlocked particles in a SCRR bulb. This process further assembles interlocked bulbs in a line, a layer, and ultimately creates a stiff SCRR raft mass. This enhances the ground's resistance to settlement, lateral movement, and improves bearing capacity.

According to Elias et al. (2017), the vibratory replacement method that SCRR treatment uses suits most soil types ranging from clay to large gravel. The integration of all five mechanisms provided by SCRR treatment renders the method suitable for a diverse range of geological conditions, making it a highly feasible solution for rehabilitating land susceptible to high liquefaction vulnerability.

4.2 Principles and standards for SCRR solution

Our SCRR assessment and design align with the guidance, practices, and manuals provided by MBIE. The advantages and limitation refer to the literature by Du and Shahin (2016) and Du and Xu (2023). Several key principles applicable to the SCRR design and construction are highlighted as follows:

- Targeting problems directly and avoiding excessive treatment.
- Direct thickening of CRUST/RAFT.
- Strong pyramid structure: Each bulb in the upper layer is positioned at the centre of the three lower bulbs in the bottom layer, creating a stable and robust pyramid structure, providing high vertical and lateral resistance.
- Large interlocking of mixed-sized particles: the use of mix-sized, non-purposely processed aggregates in SCRR yields optimal compaction effects, resulting in a high interlocking force between aggregate particles, SCRR bulbs, lines, and layers. This facilitates the formation of a dense conglomerate at a reduced cost, providing high vertical and lateral resistance.
- SCRR encompasses five mechanisms, as discussed previously.

5 DESIGN OF THE SCRR CONSTRUCTION AT ENDEAVOR AVENUE

5.1 Design Considerations

Design considerations encompass:

- Geotechnical investigation: The geotechnical investigation for cuts, fills, foundations, and retaining walls, which generally furnishes adequate information for the proposed soil improvement technique (Oregon State Government USA, 2023), this principle applies to SCRR requirements.
- Alignment of In-Situ Soil Testing Methods: Ensuring alignment between in-situ soil testing methods employed during investigation and those specified in the contract is crucial for accurate verification of ground improvement performance.
- Machine Feasibility: Addressing machine feasibility concerns, with a focus on equipment penetration ability and vibrations affecting nearby structures.
- Enhanced Drainage: Acknowledging enhanced drainage resulting from filled casing voids after bulb installation for liquefaction hazard mitigation.
- Target Cone Resistance (CPT qc) Profile: Formulating a target cone resistance (CPT q_c) profile exclusively for granular soil liquefaction mitigation through SCRR improvement, aligning with the MBIE (2021) stone column method.

Subsequent sections will explore SCRR design aspects, encompassing SCRR dimensions and depths, bulb characteristics, intervals, patterns, layers, and material options, with the aim of achieving comprehensive ground improvement.

5.2 Determination of SCRR thickness and depths

SCRRs should possess adequate thickness to effectively restrain and bridge over any underlying liquefiable or weak soils. In cases where the liquefiable soil layer is relatively thin, full-depth treatment is a viable option. However, for most sites in Christchurch, the thickness of liquefiable layers typically ranges from 5 to 10 m. Due to cost and technical considerations, achieving full-depth improvement throughout an entire land section becomes impractical (MBIE, 2021).

Over 60,000 investigations into the performance of family bungalows during the Canterbury earthquake sequence has revealed that structures supported by a natural stiff raft or crust, with a thickness of at least 3 m, suffered less damage (Wansbone and van Ballegooy, 2015). Consequently, partial depth treatment can yield satisfactory performance by effectively mitigating settlement and lateral spreading, as recommended by the relevant guidelines and practices (Earthquake Commission New Zealand, 2015; MBIE, 2021). Therefore, SCRR solutions aims at adding a SCR raft immediately below the top natural crust to increase the crust total thickness larger than 3 m. Multiple methods are employed to estimate SCRR thickness and installation depth:

Method One – Using CPT settlement graph to estimate SCRR treatment depth range

The settlement graph (Figure 1) below illustrates the results of 8 CPT analyses, depicting variations in vertical settlement. These variations are predominantly observed within the range of 3 to 14.5 m on the right graph. The left graph LPI variations also indicate the higher liquefaction potential at the same depths. This signifies that the SCR raft needs to mitigate the occurrence of liquefaction hazards from 3 to 14.5 m. The more accurate depth of treatment will be introduced in the following methods.

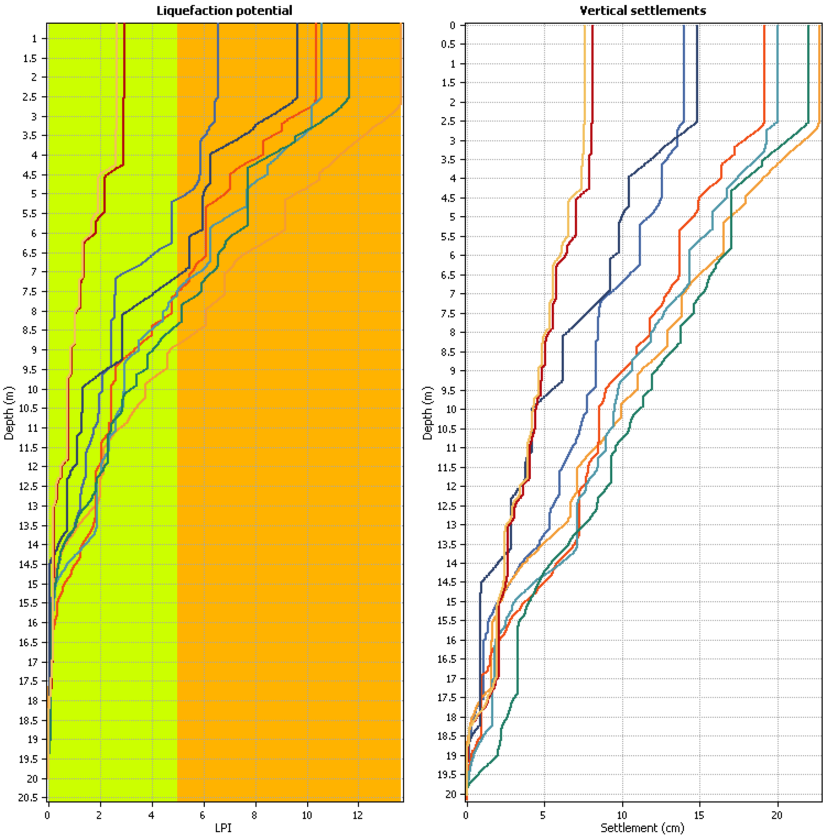

Figure 1: Using settlement graph of 8 CPTs to estimate SCRR treatment soil range.

Method Two – Using the CLiq back calculation method to find liquefiable range

The results of the back calculation for representative CPT 175046 under TC3 criteria (as outlined in Table 1) is presented in Figure 2. The design cone profile is highlighted in red, overlaying the measured cone profile in black.

As depicted in Figure 2, the segments necessitating ground enhancement are situated within the 2.5 ~ 18 m range, which are composed with liquefiable sections in red, and separated with non-liquefiable soil in blank in the right graph. Notably, in the left graph, most red lines surpass the black lines, signifying the possible need for ground improvement in these zones. It can be seen that the accumulation of the liquefiable soil is less than 8 m up to 15 m depth, which will be used in Method Four.

Method Three – Using target soil-densification criteria approach to determine delta q_c

It is possible to draw a line in a CPT curve graph using the target data recommended by MBIE guidance, as shown for the typical CPT 175046 profile in Figure 3. It is noted that the upper dot line section indicates the proposed resistance in the soil above groundwater level, which are non-liquefiable, so it does not need densification. The lower dot lines in each graph represents the proposed CPT resistance of soil below 10 m, where the liquefaction risks are minor after treatment above 10 m, as, mostly, the liquefaction potential below 10 m after SCR raft installation will be bridged.

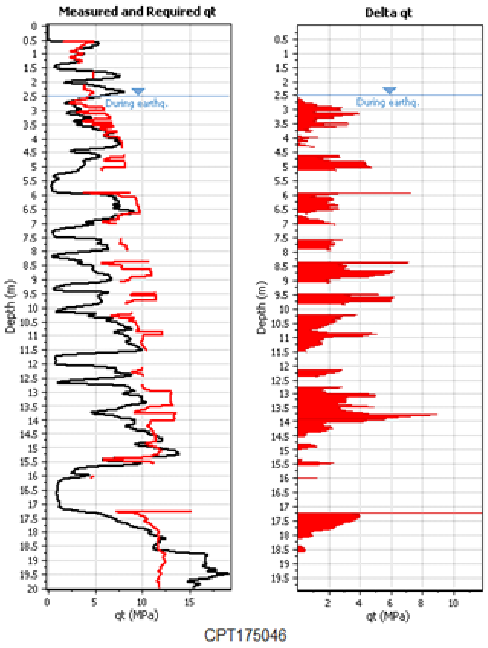

Figure 2: CPT 175046 back calculation shows liquefiable layers in red (in the right graph) requiring improvement. The red and black lines in the left graph stand for the required and measured CPT resistance qt.

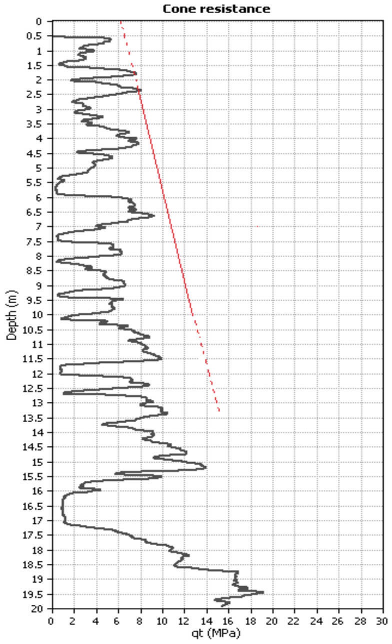

Figure 3: CPT 175046 profile with the target resistance line (only effective to sand soil). The red and black lines stand for the target values and measured CPT resistance qt.

Based on the above analysis, a preliminary conclusion can be drawn that the treatment depth provided by the SCR raft can be tentatively determined to range from approximately 2.5 m to around 10 m. A more precise treatment depth will be elaborated upon in the subsequent methodological discussion.

Method Four – Calculation using Ishihara Crust theory

The Ishihara Crust Theory (Ishihara, 1985) elucidates how liquefaction can transpire below the surface without resulting in visible harm to structures. It posits that during liquefaction occurrences, a "crust" develops near the ground surface, halting the ascent of sand boils and surface cracking. Associated graphs illustrate the factors impacting crust formation, facilitating comprehension of its implications for surface liquefaction expression. In essence, the theory aids in comprehending and mitigating liquefaction hazards in seismic regions. In this paper, the Ishihara theory serves as a tool for estimating the requisite thickness of a new crust to prevent surface liquefaction and structural damage.

For the Site, where the natural crust is estimated to be 2.5 m thick (H_1) at all 8 CPTs, the SCRR is installed from a depth of 2.5 m downwards. The liquefiable layer in all eight CPTs has a cumulative thickness less than 8 m (H_2), then the thickness of the SCRR H_S can be calculated, by the following step:

- First, locate H_2 = 8 m in the curve line that is matching the right shaking value 0.25g (Figure 4), the new total crust thickness H_1' required can be read out as 4.7 m.
- Then, the SCRR thickness can be computed:

$$H_S \geq (H_1' - H_1) = 4.7 - 2.5 = 2.2 \text{ m}. \quad (1)$$

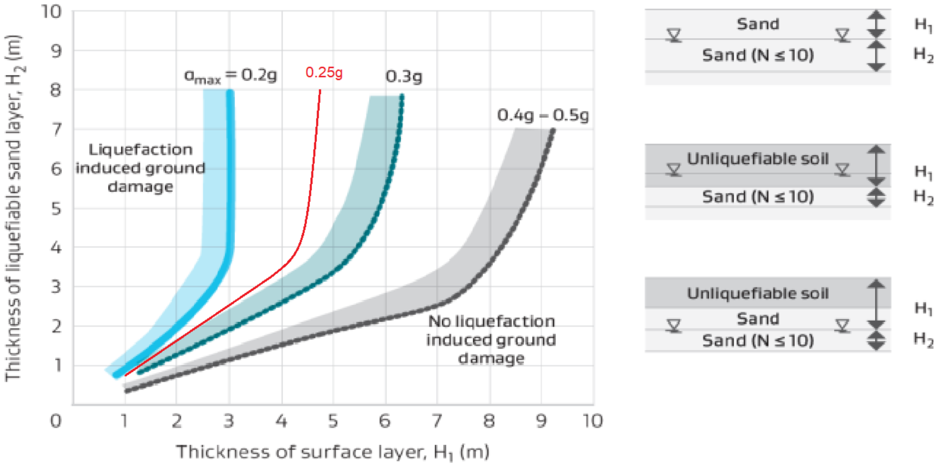

Figure 4: Estimate of new SCRR crust thickness, adapted from Ishihara (1985).

Consequently, the SCR raft will be installed starting at a depth of 2.5 m, with a two-layer SCRR structure, the ground can be upgraded to TC1 level, and with one-layer structure, the site can be improved to a TC2 criteria. The lower interface of SCRR raft is positioned at a depth of 4.5 and 6.5 m, respectively below ground level (BGL). The ultimate choice between TC1 and TC2 criteria for this site remediation depends on the landowner's preferences, budget constraints, and the significance of the building on the site.

5.3 Other parameter design of the SCRR bulbs and layers

- Each bulb is designed with a diameter of 1.2 m and consumes rubble material at a volume of 1.01 cubic m (rubble compaction factor 0.9). The diameter of the densified soil zone is estimated at 2.4 m.
- The SCRR bulbs are installed in a typical triangular pattern with a spacing of 2.0 m (Du and Xu, 2023). To treat the entire 19,700 m^2 site, the number of bulbs/layer is approximated as 19700/2/1.73 = 5700.
- A single-layer SCRR installation would necessitate 5,757 m^3 of aggregates, while a two-layer SCRR installation would require approximately 11,500 m^3 (The SCRR layer structure refer to literature by Du and Xu (2023)

5.4 Material option and amount

The primary source of this natural aggregate is local quarries. Mixed-sized aggregates are utilized, and they are pre-washed to eliminate fines before transportation to the site.

5.5 Casing and machine

The casing serves the purpose of penetrating the hole to a predetermined depth and establishing a pathway for material feed and mandrel compaction. Through the pilot project, it has been found that the crucial function of the casing is to ensure the bulbs are installed at the accurate depth designed. The casing's diameter is approximately 300 to 400 mm, and its length measures less than 7 m (SCRR bottom depth plus 1-2 m above ground surface). The piling machine chosen for this task is a vibratory hammer known for its minimal vibration and noise output. The initial driving force of the machine is designed to be 80 tons.

6 QUALITY ASSURANCE AND CONSTRUCTION VERIFICATION

6.1 Quality control and quality assurance

Quality Control (QC) for SCRR construction may include various measures such as CPT testing of rubble materials, CPT testing of liquefiable 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 or Multichannel Analysis of Surface Waves (MASW) (MBIE, 2021). MBIE (2021) has provided verification guidance for testing ground improvement criteria for the deep stone column method (Table 2), which SCRR design adopts for its construction verification.

Table 2: Target soil-densification criteria for the deep stone column method (MBIE, 2012).

Depth (m)	Target for Clean Sand (I_c <1.8) CPT q_c (MPa)	Equivalent CPT q_{c1Ncs} Target for all Soils (atm)
1	7.0	120
2	7.8	133
4	9.4	136
10	13.3	138

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

6.2 Construction verification approaches

The finalized SCRR raft can be verified using three approaches: CPT settlement analysis and TC2/TC1 check through Cliq, confirmation of CPT target values, and assessment based on the formed crust theory. The first approach is the primary method, while the latter two serve as supplementary methods.

Method One – Using CPT settlement analysis and TC2/TC1 check by Cliq

Following the SCRR completion, the post-CPT test data is input into Cliq, generating settlement and lateral movement graphs with final readings. These readings allow the classification of the improved ground as per Table 1 into TC1 or TC2 category. This method stands out for its simplicity and comprehensively accounts for the ground's seismic conditions and geological traits.

Method Two – Using target soil-densification criteria to determine treatment effect

Combining the requirements for typical deep column constructions as recommended in MBIE Guidance C, the target for clean sand (Ic < 1.8) (the middle column in Table 2) is initially used for the SCRR target validation; for other soils the data in the right columns in Table 2 should be compliant. It is noted that even in a maximum densification zone, the average CPT resistance is generally less than 20 MPa (Sinclair, 1991).

Method Three – Verification Using Ishihara Crust Theory and Graph

This method will follow the step described in Sections 5.2 for certificating if the new crust is meeting the Ishihara theory requirements.

7 CONCLUSION

- The estimated thickness of the SCRR is approximately 2 and 4 m for remediating to TC2 and TC1 respectively. Consequently, the bottom interface of the installed SCRR is situated at a depth of 5 and 7 m respectively below ground level (BGL).
- SCRR bulbs with a diameter of 1.2 m, are spaced in a triangular pattern with intervals of 2.0 m. To treat the entire 19,700 m^2 site, the total number of bulbs per layer is calculated as 5700.
- This sit employs a 1-layer or 2-layer SCRR structure, resulting in a total volume of rubble/aggregates of 5,757 or 11,500 m^3 for TC2 and TC1 treatment levels, respectively.
- The locally quarried natural aggregate with particle size from 5 mm to 200 mm will be used. The aggregates are pre-washed to remove fines before transportation to the site.
- A vibratory hammer mounted on a crane is chosen as the SCRR construction machine with a power output required of at least 190 kN m.
- Quality Control (QC) for SCRR construction mainly encompasses testing of rubble materials and liquefiable soils using CPT tests in compliance with the MBIE guidance.

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