Examples of ground improvement applications for earthquake design

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ABSTRACT

The ground improvement applications and examples in this paper are planned to augment MBIE Module 5. This paper presents some ground improvement applications and their design and specification for earthquake hazard mitigation. Ground improvement methods by densification using vibro compaction and stone columns and solidification methods such as soil mixing and jet grouting are discussed. Design approaches are demonstrated through key considerations (applicability, construction methodology and quality control), and the applications of each selected method are discussed.

1 INTRODUCTION

MBIE's and the New Zealand Geotechnical Society's Module 5 (MBIE 2021) covers the principles of ground improvement design of soils prone to liquefaction. Module 5A (MBIE 2018) provides specifications for the design and construction of ground improvement for liquefaction mitigation works. The guidelines include comprehensive and up-to-date ground improvement methods and practices as part of the Earthquake Geotechnical Engineering Practice series. This paper aims to augment the guidelines by providing additional considerations for the design, construction and quality control of select ground improvement methods. The following sections discuss ground improvement methods of liquefaction mitigation using densification (vibro-compaction and stone columns) and solidification (soil mixing and jet grouting).

Before delving into the ground improvement methods, below are some definitions of the terminologies used in further sections of this paper.

- *Depth vibrator*, sometimes called a probe, is an oscillating, usually electric-driven tool used to impart horizontal vibrations or compaction effort to the ground. This tool can be attached to extension tubes to suit the required depth and is mounted on a crane or a rig.
- *Vibro-compaction* is the compaction of granular soils with low fines with the help of depth vibrator(s) to rearrange and achieve optimum compaction of the soil particles.
- *Vibro-replacement*, or commonly known as *stone columns*, is the process of installing and compacting granular aggregates in the ground to create stiff columnar elements using a depth vibrator.
- *Dynamic compaction* is a densification ground improvement technique that uses a heavy drop weight.

- *Solidification* is a ground improvement approach where improvement is effected by changing the chemical composition or the particle structure of the in-situ soil. This is typically done by introducing cementitious materials into the ground.
- *Soil mixing* is a solidification process where a binder is introduced into the ground and mechanically mixed with the help of mixing paddles on a rig. Deep soil mixing is a typical soil mixing method where solidified columns can be installed in the ground.
- *Jet grouting* is the process of introducing a binder into the ground and creating a soil-cement mix (soilcrete) using a high-pressure jet through a specially designed nozzle.

2 DENSIFICATION BY VIBRO-COMPACTION

Densification is a way of mitigating liquefaction by improving the shear strength and stiffness of the soil. Densification methods aim to minimise the tendency of the soil to deform at small strains by increasing the confining stress. An increase in the effective confining stress also means that the shear stiffness of the soil increases. Therefore, denser soils will have lower cyclic and shear deformations even if liquefaction is triggered.

An energy source or compaction effort is needed to densify soils. In the case of vibro-compaction, the energy transfer is by sinking a depth vibrator attached to extension tubes to suit the required depth. The process includes penetration with the help of a water jet to the design depth, compaction of the soil during withdrawal of the probe and topping up with soil (clean sand backfill) as needed to maintain the ground level as a result of soil volume loss due to densification (refer to Figure 1).

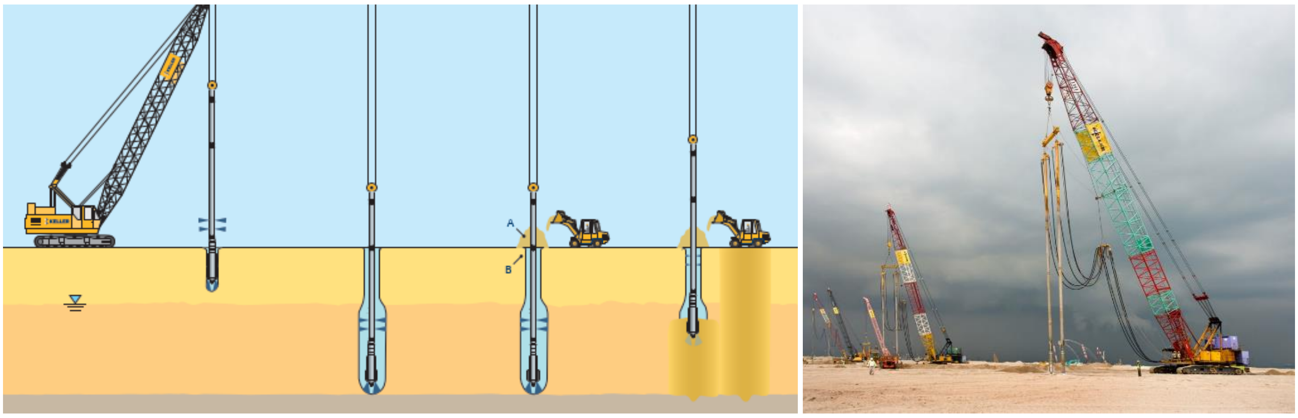

Figure 1: Illustration of densification process by vibro-compaction and a photo of vibro-compaction ground improvement in action using twin vibro floats

2.1 Design specification

The increase in capacity as a result of vibro-compaction can be quantified in terms of an increase in relative density (hence an increase in *CRR*). Typically, relative densities of 65% to 85% are targeted by vibro-compaction works depending on the suitability of the in-situ soil and desired target improvement (e.g. bearing capacity, stiffness/settlement reduction).

The main design consideration for vibro-compaction is setting a target penetration resistance with depth. This is done by first calculating the demand (*CSR*) and choosing a factor of safety against liquefaction triggering (F_L, Module 3), depending on the level of shaking. The target or improved *CRR* can then be evaluated and converted to an equivalent relative density (D_r) and penetration resistance (q_c or N_{60}).

The main controlling factor in achieving the design specification is the spacing between points, which is typically decided based on field trials. Generally, triangular grids with spacings of 2.5 to 5.0 m are common, depending on the design specification, soil suitability, and vibrator power. Kirsch and Kirsch (2016) have shown how the penetration resistance change with distance based on field trials. Mitchell (1981) also suggests the evaluation of design spacing based on the initial and target void ratios of the sand and the diameter of the compaction hole. This approach assumes compaction in the horizontal direction only and should, at best, be used for initial spacing prior to field trials.

In addition to design specification in terms of relative density or penetration resistance, Elias et al. (2006) also state that specifying the minimum amount of backfill material or the minimum bearing capacity requirement is also possible and sometimes practised.

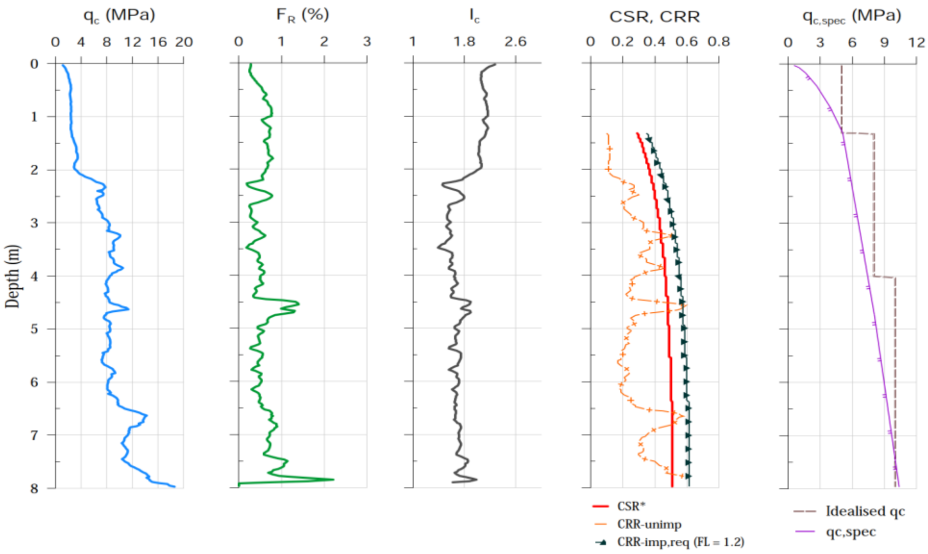

Figure 2. Sample plot of a cone penetration test showing the computed CSR and CRR values and design value of CRRimp. Specification values of qc for densification are based on a target 75% relative density and converted to qc using Baldi et al. (1986). The idealised curve can then be drawn and used.

2.2 Suitability of soils

The suitability of soils for treatment by vibro-compaction is mainly controlled by the particle size distribution of the soil and the fines content in particular. Sandy soils with fines content less than 10% are ideal for vibro-compaction, although up to 15% may also be compactable to a lesser extent. Saito (1977) has shown how the ratio of N_{imp} / $N_{un\text{-}imp}$ diminishes with increasing fines content (refer to Figure 3). Kirsch and Kirsch (2016) showed that when the fines content was more than 30%, the soils did not respond to densification by vibro compaction. However, they also argue that the clay content has a more decisive impact on the densification of sands than the overall fines content.

Massarsch (1994) has also provided a compaction suitability criterion based on the soil's cone penetration resistance and friction ratio to be treated (refer to Figure 3). The criterion indicates that compactible soils have less than 1% friction ratios, while 1 to 1.5% friction ratio means marginally compactible soils. Kirsch and Kirsch (2016) also suggest that if the soil has a steep D_{60} / D_{10} ratio (i.e. less than 2 or poorly graded), vibro-compaction may not be effective. Greenwood and Kirsch (1983) also suggest that a permeability range between 10^{-5} to 10^{-2} m/s is suitable for improvement by vibro-compaction. Another gradation criterion suggested is that of Brown (1977), who suggested a suitability number to gauge suitability for vibro-compaction.

Robertson (2016) and Kirsch and Kirsch (2016) also propose the soil behaviour type index (I_c) from CPT testing as another criterion to assess the suitability of soils for vibro compaction. Similar to assessing the liquefaction potential of sandy soils, the I_c value can be used to check if the soil will respond to densification by vibro-compaction. Soils with Ic of more than 2.6 are therefore considered non-treatable by vibro compaction, while low I_c values increase the improvement and efficacy of densification treatment by vibro-compaction.

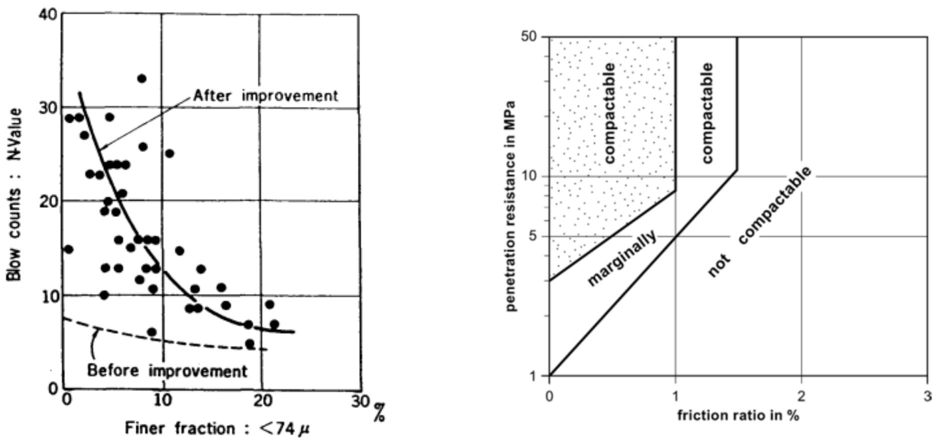

Figure 3: Soil suitability for vibro-compaction plots, from (Saito 1977), left, and (Massarsch 1994), right.

Soil interbedding is another challenge for improvement with vibro-compaction. If intermediate layers that do not meet the suitability criteria mentioned above are encountered, the treatment to the target depth may not be achievable. This is mainly due to the construction process, as penetration to the target depth is by using water jetting, which can cause fines migration into the sandy layers and inhibit effective compaction. When sandy soils overlay silty layers, combinations of vibro-compaction and stone columns have been done to target the sandy and silty soils, respectively.

When selecting the design specifications for calcareous sands (sands with shell or carbonate content), care should be taken into account for these soils' lower cone penetration resistance. Wehr and Sondermann (2012) discuss this and present recommendations.

2.3 Construction considerations

The installation parameters for vibro compaction include specifying the following: selection of the depth vibrator (power rating), design spacing and arrangement, design depth, vibrator withdrawal rate and vibrator holding time. The selection of the vibrator is based on the power rating of the vibrator. Different vibrators have different energy levels, and choosing the right type of vibrator is key when deciding the design specification and spacing between compaction points. Depth vibrators are usually proprietary, and different ground improvement specialists may have different types. Green and Mitchell (2004) have proposed an approach to estimate the power rating or energy transfer rate of electric-powered depth vibrators.

A typical installation record is shown in Figure 4. The electronic record is a real-time log of the installation process of the vibro-compaction process from a data acquisition system. Nowadays, such logs are commonplace and typically required in all projects. BS EN 14731 (BSI 2005) outlines what information needs to be captured in such logs as a minimum. From the log, the operating parameters for the compaction were: compaction steps of 0.75 m and duration of 45 seconds per step, and compaction target depth is from 5 m to 12.7 m below ground.

Another construction consideration of the vibro-compaction process is ground vibration and its potentially detrimental effects on nearby structures and services if no controls are in place. Weng et al. (2020) have presented an approach to assess the effect of ground vibrations due to vibro-compaction and stone column processes prior to the field works.

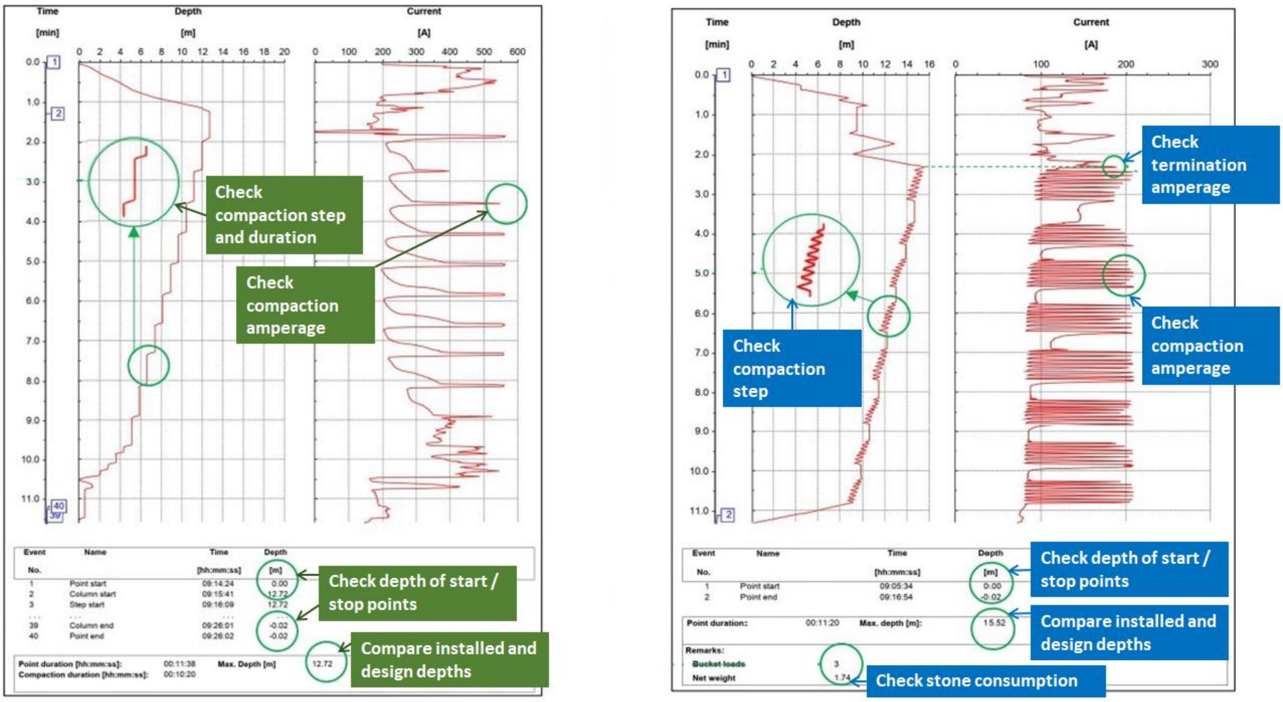

Figure 4: Typical vibro-compaction (left) and stone columns (right) installation logs, with key quality control considerations (courtesy of Keller Holding PLC)

2.4 Quality control aspects

The quality control aspects of vibro-compaction works involve pre-, during and post-compaction checks. Pre-compactions controls include: checking the suitability of the soils, pre-compaction investigations (typically CPTs), field trials and setting the operating parameters. A continuous and rigorous check of the operating parameters and any change to the ground conditions (as evidenced by the installation records) is required. Measurements of backfill material being added and surface level measurements are also important aspects to gauge the efficacy of the treatment.

Post-compaction quality controls entail post-treatment investigations (CPTs, SPTs, or shear wave velocity measurements), surface-level measurements, field density checks or load tests (if required). For post-treatment ground investigations, an important consideration is the effect of time-dependent strength gain. Post-compaction investigations should not be done immediately after the treatment works, or this could result in an apparent low improvement. It is recommended that the verification investigations are done after at least a week (Elias et al. 2006) and up to six weeks (Seed et al. 2003) after the treatment.

3 STONE COLUMNS

The use of stone columns is one of the common and earliest approaches of ground treatment for liquefaction mitigation, especially in the US and Japan (Bohn and Lambert, 2013). Due to the nature of their installation and the materials used to construct it, stone columns offer multiple advantages to mitigate the effect of liquefaction. Figure 5 shows the installation process of stone columns.

Densification and an increase in the lateral effective confining process are the main mechanisms by which stone columns boost the ground's resistance against liquefaction (i.e. $CRR_{imp} > CRR_{un\text{-}imp}$). Due to the porous nature of the gravels used for stone column construction, stone columns act as drainage conduits and facilitate the dissipation of excess pore pressure by shortening the effective drainage path. The reinforcement effect of stone columns is another mechanism for counteracting the effects of liquefaction. The stiffer columns in the ground help redistribute the shear stress in the ground during an earthquake, resulting in a lower seismic demand (i.e. $CSR_{imp} < CSR_{un\text{-}imp}$).

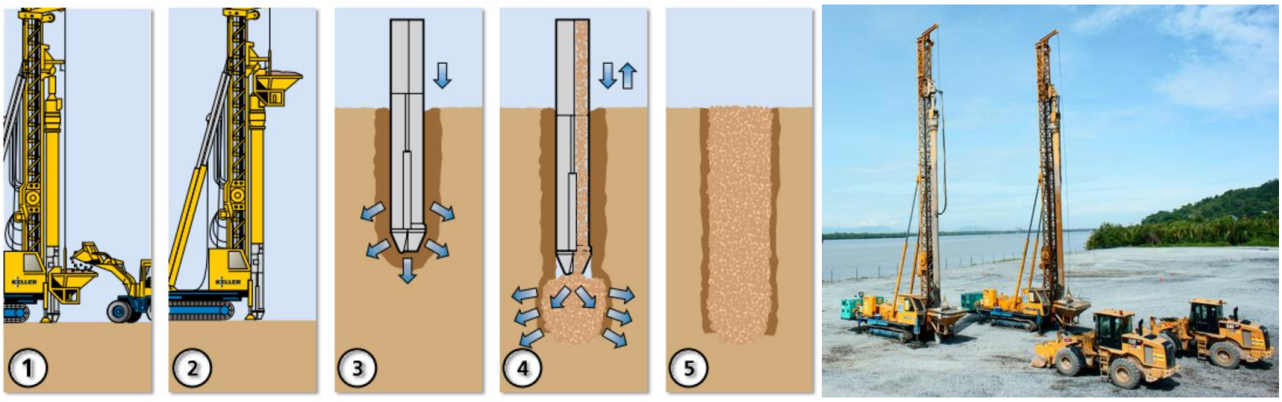

Figure 5: Stone column installation process (left) and photo showing a dry, bottom-feed installation method (right)

3.1 Design specification

The main controlling parameter in designing stone columns is the area replacement ratio (i.e. area of a stone column divided by the total tributary area it improves). The area replacement ratio typically ranges from 10 to 35%. For static loading, stone columns can be designed by several methods (refer to Kirsch and Kirsch 2016, Sondermann et al. 2016). The design of stone columns for liquefaction mitigation would depend on the mechanism considered in improving the ground.

Design for densification

Module 5 recommends the design of stone columns for liquefaction mitigation by only considering the effect of densification. For improvement considering densification only, the design is much like vibro-compaction, as covered in Section 2.1.

Design for drainage

The use of stone columns to mitigate liquefaction by dissipating excess pore pressure was first proposed by Seed and Booker (1977). In their mathematical solution, the gravel columns were considered perfect drains (i.e. infinite permeability and storage), arguing that the column needed to be at least 200 times more permeable than the soil to be considered a perfect drain. However, Onoue (1988) demonstrated that well resistance effects should be considered when designing stone columns for drainage. He modified the Seed and Booker (1977) mathematical model by considering a well resistance factor. When well resistance is considered, the efficacy of the stone columns in mitigating liquefaction is reduced significantly. Pestana et al. (1997) developed the *FEQDrain* computer program, an axisymmetric finite element program, to predict the expected performance of stone columns during earthquakes. In addition to including the stone columns' well resistance effects, they considered storage capacity as an option in the assessments. A comparison of these methods and the specific application of 'gravel drains' for liquefaction mitigation is elaborately discussed by Woeste et al. (2016).

Boulanger et al. (1998) have also discussed the potential effect of the in-situ soil intermixing with the stone column during installation. Pal and Deb (2019) have proposed a mathematical approach to consider the clogging of stone columns and subsequent effects on the drainage capacity during liquefaction.

Design for soil reinforcement

Another aspect of mitigating liquefaction using stone columns is considering the effect of soil reinforcement. Baez and Martin (1993) and Baez (1995) suggested an approach to reduce the seismic demand of ground improved by stone columns. Their approach assumed strain compatibility, and the columns deform in pure shear and together with the soil. However, Goughnour and Pestana (1998) considered the effect of the flexural response of the columns. They modified Baez (1995) to include the stress concentration factor. This approach yields a more conservative reduction factor when compared with Baez (1995).

Priebe (1998) acknowledges that the improvement using stone columns to mitigate liquefaction is difficult to predict. He suggested a similar approach to reduce the seismic demand by modifying his unit cell design approach.

Aided by physical and numerical modelling, Rayamajhi et al. (2012) proposed a reduction factor that considers the effect of incompatible flexure and shear strains between the ground and the columns in a linear elastic condition. Based on the modified equation (*equation 1*), the reduction factor based on this approach is marginal for ground improvement using stone columns, i.e. G_r is in the range of 2 to 10 in sandy soils (Rayamajhi et al. 2014). As a result, Woeste et al. (2016) recommend that the reinforcement effect of stone columns should be neglected in design and considered an added resilience.

$$R_{rd} = \frac{1}{G_r\left[A_r\gamma_r C_G + \frac{1}{G_r}(1-A_r)\right]} \leq 1.0 \qquad (1)$$

where R_{rd} = ratio of shear stress reduction for improved and unimproved ground, A_r = area replacement ratio, G_r = the shear modulus ratio (= G_c/G_{soil}), C_G = equivalent shear factor for discrete columns, depends on the shape of the improvement (1.0 for discrete circular columns, 0.5 for rectangular grids depending on A_r), γ_r = shear strain ratio ($\gamma_r = 1.04(G_r)^{-0.65} - 0.04 \leq 1.0$).

Figure 6 shows a comparison of the methods of Rayamajhi et al. (2014) with Baez (1995), Goughnour and Pestana (1998), and Priebe (1998). The plot shows a large difference in predicted CSR reduction from the different methods. It should be noted that only Rayamajhi et al. (2014) supersedes the other methods and should be the only method for design purposes.

3.2 Suitability of soils

Stone columns are generally more versatile in terms of suitable ground conditions than other applications, such as vibro-compaction and dynamic compaction. For typical static loading ground improvement applications, stone columns are the ideal choice of improvement by densification when the fines content is more than 15% to 20% (i.e. outside of the suitable range from Figure 2). Interbedding of layers is also not a concern when using stone columns. However, when the fines content is more than 10%, densification would be marginal, and stone columns would not be a suitable application for liquefaction mitigation purposes. Their vertical load-carrying capacity can also be compromised during an earthquake due to liquefaction-induced ground damage (e.g. clogging of columns with ejecta, bulging, shearing due to lateral spreading, etc).

The gradation of the stone column material is an important consideration when checking the suitability of soils. This is an important consideration in terms of construction (whether the stone column is installed by the bottom feed or top feed methods) and compatibility with in-situ soils (to minimise clogging during installation and earthquake loading). Module 5A provides a gradation envelope for stone columns; however, it does not elaborate on why the gradation is provided. BS EN 14731, Brown (1977) and Kirsch and Kirsch (2016) have made recommendations for the gradation of stone columns from an installation perspective. Due consideration is also required for the gradation of aggregates, as uniform grading of the stone column aggregate could result in the clogging of voids.

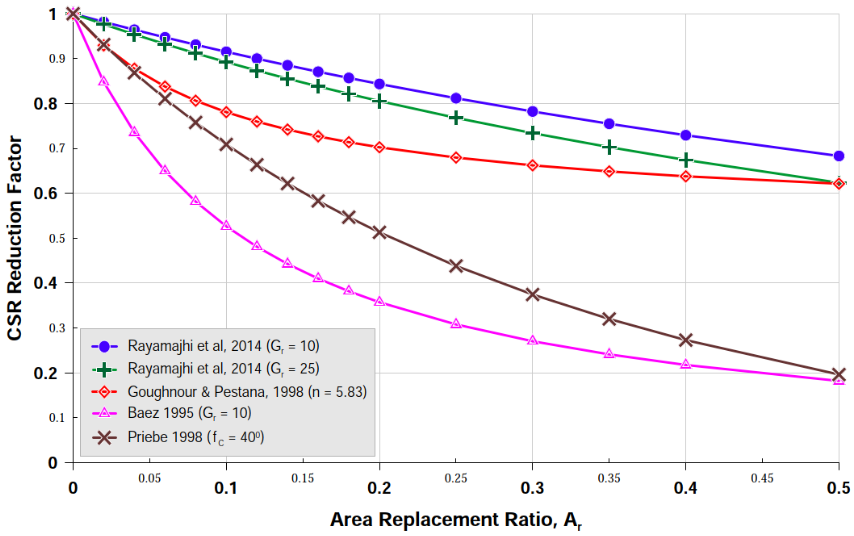

Figure 6: Comparison of the different soil reinforcement design approaches in terms of expected improvement (reduction of CSR). Rayamajhi et al. (2014) are to be used for design; other references are included for comparison only.

3.3 Construction considerations

Stone column diameters of 0.6 to 1.1 m are typical; however, for improvement in sandy soils, the range of diameters that can be realistically targeted and achieved is 0.6 to 0.9 m. Therefore, the spacing should be decided based on the realistically achievable diameter when targeting a design area replacement ratio.

Installation of stone columns for liquefaction mitigation is recommended using the dry bottom feed method with a depth vibrator. Since the top feed method of installation typically requires high pressure water or air jets to advance the vibrator, this method can result in the disturbance of the ground (Woeste et al. 2016). Therefore, if using the top feed method, the effect of using high pressure fluids to penetrate should be considered and checked.

Installation of stone columns with the help of a vibrated casing is another bottom-feed approach. A casing of the desired size of the stone column (or slightly smaller) is driven using a top-driven vibratory hammer to the required depth. The casing has a one-way flap at the base displacing the soil as it is driven. A stagewise extraction of the casing from the toe level is done while the gravel in the casing is charged into the hole and compacted by a downward movement of the casing. This method of stone column installation is not covered under BS EN 14731 as an acceptable installation method. This installation method could bring about some degree of densification in sandy soils for liquefaction mitigation. However, care should be taken to understand the shortcomings of this method and its possible effect on the end product (e.g. lower degree of compaction due to energy attenuation).

Heave is one issue to consider when improving ground with stone columns. The ground can exhibit heave during the construction of stone columns due to the compaction effort and the introduction of new materials. The amount of heave generally depends on the area replacement ratio and the relative density of the in-situ soil. Since cutting down the platform to the desired finished level is usually necessary, heave can mean that the desired degree of compaction may not have been achieved.

Vibrator power/type decides the degree of compaction to be achieved and the diameter of the columns to be targeted. Considerations for the effects of ground vibration should also be made similar to vibro-compaction works (refer to Section 2.3).

3.4 Quality control aspects

BS EN 14731 elaborately discusses the quality control aspects for the construction of stone columns. Post-treatment verification ground investigation schemes, like vibro-compaction, are usual when only densification type improvement is expected. Load tests with instrumentation (e.g. piezometers and load cells) are common to verify stone columns' reinforcement and drainage contributions against static loading. However, field verifications of drainage and reinforcement effects to mitigate liquefaction are neither common nor well-defined. Therefore, the verification of these mechanisms has been mostly from the observed performance of past projects, laboratory testing and numerical modelling.

Data acquisition systems, such as shown in Figure 4, are recommended by BS EN 14731. Such logs record the construction details of every column, enabling prompt quality assurance process and rectification where the desired improvement is not achieved. To minimise the risk of not achieving the desired design, the following are key considerations: construction methodology, total stone consumption, diameter check, setting of termination criteria and compaction. In addition, providing a granular drainage layer over the stone columns is good practice to ensure proper drainage.

The quality of aggregates is another important consideration, as the aggregates should withstand the installation actions and have long-term durability. Therefore, tests on the stone aggregates are typically specified, including (but not limited to) aggregate angularity, aggregate crushing value, Los Angels abrasion index, flakiness and elongation indices, and sulphate soundness.

4 GROUND IMPROVEMENT BY SOLIDIFICATION

This section discusses two solidification ground improvement methods: soil mixing and jet grouting. The soil mixing process is one of the most preferred methods, mainly due to being vibration-free and producing less spoil than other methods. Different geometric shapes are also possible, such as a circular column (deep soil mixing), a rectangular panel (cutter soil mixing), or a block (mass soil mixing or stabilisation). Verification and quality control methods are also relatively easier when compared with other methods.

Jet grouting generally requires a higher binder consumption than soil mixing for the same target strength. However, it has a smaller installation footprint and requires smaller rigs. As a result, it is a preferred method for underpinning works or in areas where physical barriers prevent soil mixing from being a viable application. Pressures of up to 400 bars and grout flows of up to 600 lt/min are common during the installation of jet grout columns. Jet grout can be installed using a single fluid system (grout only), dual fluid system (grout and air) or triple fluid system (grout, air and water).

4.1 Design specification

Solidification is one of the common forms of ground improvement for mitigating liquefaction. Some of the typical methods of solidification are soil mixing and jet grouting. One of the advantages of this type of ground improvement is the lack of vibration and noise or other construction-related ground disturbances associated with densification methods. Solidification also allows different geometries to be formed by arranging the ground improvement elements, e.g. discrete, lattice or cellular elements. These elements mitigate liquefaction potential by reinforcing the ground and redistributing shear stresses. Discrete columns can be applied where there is a risk of liquefaction only, whereas lattice or cellular treatments can be specified where there is a risk of lateral spreading.

The design of soil mixing and jet grouting ground improvement for liquefaction mitigation follows the recommendations of Rayamajhi et al. (2014), as described in Section 3.1. Solidification methods offer a higher shear modulus ratio (Gr) than stone columns, typically 10 to 100. The proper application of the ground reinforcement design using this approach depends on the correct estimation of the degree of improvement (i.e. stiffness of the ground improvement likely to be achieved). In the absence of local experience and lab/field testing, Kirsch and Bell (2013) recommend achievable degrees of improvement in different ground conditions.

4.2 Suitability of soils

The solidification methods of ground improvement apply to a wide range of soil types and conditions. A particular concern that can significantly affect the targeted design is the organic content of the in situ soil. If present, organic content can severely affect the strength of the improvement elements. Although not a common concern for liquefaction mitigation, this can be an issue if treatment is desired in interbedded layers or as a ground improvement to counter the cyclic softening of soft deposits.

Very stiff or dense ground offers high penetration and construction resistance (typically, SPT-N > 30). Nevertheless, such soils are usually not prone to liquefaction and do not require treatment. Figure 7 shows that soils typically deemed liquefiable are generally highly erodible and ideal for jet grout treatment. In these ground conditions, large diameters of jet grouting columns can be formed (Croce et al. 2014). Before specifying the ground improvement type, interbedded ground conditions where intermediate stiff or organic layers are present must be identified.

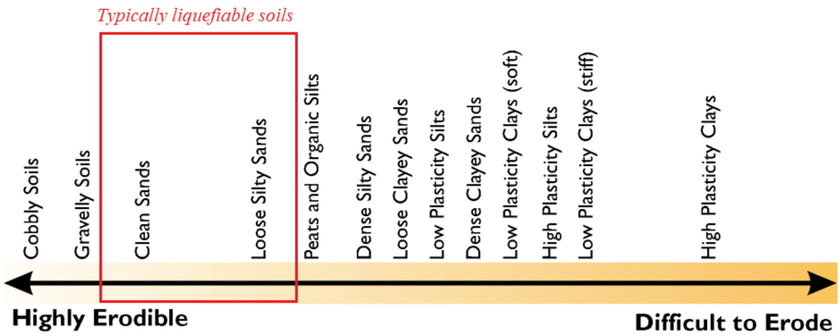

Figure 7: Erodibility scale for jet grouting application versus different soil types

4.3 Construction considerations

The main construction considerations of soil mixing include the construction methodology, binder in-place factor, and the required blade rotations per metre of a column. The blade rotation number is a derived parameter that depends on the number of mixing paddles, penetration and withdrawal rates and rotation speed of the mixing tool (Kirsch and Bell, 2013). A key consideration is also what binder to use and what state (slurry or dry) to achieve the target strength.

For jet grouting applications, the main or controlling parameters for construction are diverse, and Croce et al. (2014) categorise these as geometric, kinematic, and injection fluid parameters. The jet grouting system varies from one specialist contractor to another and depends on the proprietary equipment and capabilities of the specialist contractor. But in general, the withdrawal rate of the monitor, its rotation speed, size and the number of nozzles, inject pressure, the volume and pressure of eroding fluid, and the grout water-cement ratio are the main operating parameters.

4.4 Quality control aspects

Data acquisition systems of soil mixing and jet grouting works are similar to vibro-compaction and stone columns. In addition to recording the construction operating parameters, the logs can be set to capture the amount of binder used with respect to depth. This enables prompt identification of quality issues in the field, and rectification measures can be made.

Laboratory tests before the start of soil mixing and jet grouting works are recommended. The objective of the tests is to understand the suitability of the soil and estimate the binder requirements through laboratory mix preparations. However, caution is required when inferring field strengths from laboratory test results not to underestimate the binder requirements (BS EN 14679). Post-treatment verification methods are usually strength tests after strength gain (28 days, typically). Tests are performed on samples collected from the field during installation or collected from the field after a prescribed time. Topolnicki (2016) and Yohannes & Daramalinggam (2019) describe the laboratory and field quality control measures in detail. For jet grouting, a key verification is the diameter of the columns, unlike soil mixing, where the mixing tools' size determines the elements' size. State-of-the-art methods are available to check whether the required diameter is achieved at a specific depth, such as the acoustic column inspector (Vukotic and Diaz, 2016).

In addition to these considerations, BS EN 14679 (BSI 2005) and BS EN 12716 (BSI 2018) provide elaborate descriptions of quality controls required as a minimum for soil mixing and jet grouting works, respectively.

5 CONCLUSION

MBIE's and the New Zealand Geotechnical Society's Module 5 and Module 5A provide comprehensive and up-to-date ground improvement methods and practices as part of the Earthquake Geotechnical Engineering Practice series. This paper discusses additional considerations for designing, drafting the specification, construction and quality control of select ground improvement methods. Additional resources and references are provided to complete the modules' information and give a complete picture of the discussed ground improvement techniques.

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