Improvement mechanisms of stone columns as a mitigation measure against liquefaction-induced lateral spreading

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ABSTRACT: Liquefaction-induced lateral spreading is a common phenomenon after strong seismic events. Typically lateral spreading occurs in sloping ground close to waterways in regions with liquefiable underlying soils and may result in significant damage. There is little literature on stone columns being used to mitigate liquefaction-induced lateral spreading. This paper presents findings of a study to evaluate the effectiveness of stone columns to mitigate liquefaction-induced lateral spreading. A case study from the recent 22 February 2011 Christchurch Earthquake was used as a basis of the research which was carried using effective stress analysis with the finite element software package FLAC v7.0. Current state-of-the-art design procedures for stone columns to prevent liquefaction have been used to assess its applicability to mitigate lateral spreading. The main improvement mechanisms of stone columns – densification, drainage and reinforcement and their individual effects on the improved ground have been investigated. It was found that considering the densification and drainage effects in the analyses improved the performance of the stone columns, while the reinforcement effect made only a small difference. Generally, stone columns remediation was found to be effective in reducing the lateral displacement that was caused by liquefaction due to the seismic event in the numerical analyses. However, complementary ground improvement measures may be required to eliminate lateral displacement at the crest of the waterway.

1 INTRODUCTION

Liquefaction has been responsible for many failures of man-made and natural structures. Liquefaction-induced lateral spreading has been commonly documented after strong seismic events such as the sequence of Christchurch earthquakes that began on 4 September 2010. In this paper, two dimensional numerical analyses were used to assess the effectiveness of stone columns and its improvement mechanisms, in mitigating liquefaction-induced lateral spreading. The state-of-the-art design procedures for stone columns to prevent liquefaction were used in the numerical modelling as basis of assessing their applicability to mitigate lateral spreading. A case study from the recent Christchurch 22 February 2011 Earthquake was used to calibrate the numerical model for the study. Focus is placed on the reduction in accumulated surface lateral deformation and excess pore water pressure within the improved ground.

2 STONE COLUMNS

The installation stone columns mitigates the potential for liquefaction by increasing the density of surrounding soil and allowing drainage to control pore water pressure generated. The introduction of stiffer elements, which can potentially carry higher stress levels and reduce the stress levels in the surrounding soils (Priebe 1991), provides resistance to deformation. These effects may reduce the build-up of excess pore water pressure which in turn, reduces the liquefaction potential, and the associated ground deformations.

Recently, installation of stone columns to mitigate liquefaction-induced lateral spreading has been investigated (e.g. Elgamal et al, 2009) and it was concluded that stone columns were effective in reducing lateral deformation in sandy stratum. However, the current stone column design methods for liquefaction mitigation available in literature (Priebe 1998; Baez and Martin 1995) are largely focussed on its implementation on level ground and foundation design, and not for lateral spreading.

3 METHODOLOGY

3.1 Representative site location

The selected site for the analysis is adjacent to the Avon River in the suburb of Dallington. It is located to the east by the artificially straightened reach of the Avon River known as Kerrs Reach, about 2km from the Christchurch CBD. Figure 1 below shows the site location map of the representative section.

Following the 4 September 2010 and 22 February 2011 earthquakes, Robinson et al. (2011) took field measurements of lateral spreading. For the site location in this study, the results from the field measurements show that the cumulative displacement along the closest transect, which was approximately 200m away, was approximately 0.8m. The lateral displacement data from this study was used as basis to calibrate the FLAC numerical model.

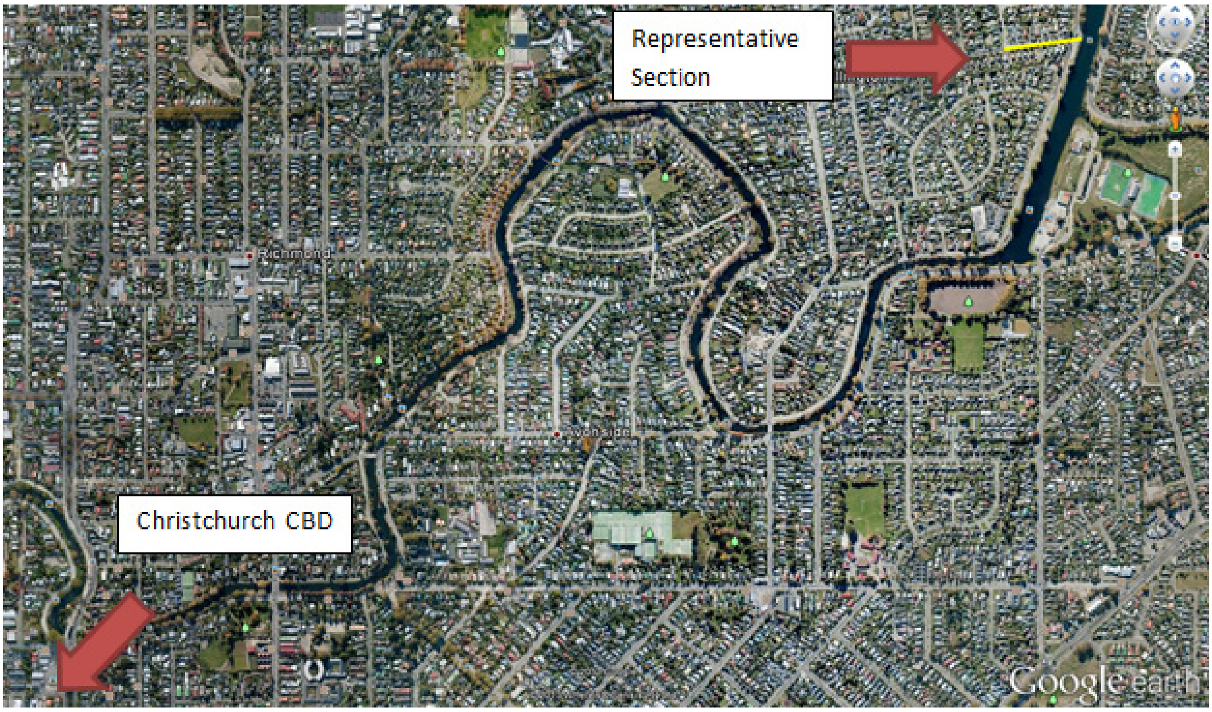

Figure 1. Site location map of the representative section

3.2 Geological Section

To avoid complex geometries in the numerical modelling, the subsurface geological profile has been simplified to represent a generalised profile in the vicinity of the site and subsoil strata have been assumed to be horizontal. The slope geometry has been approximated from LiDar surveying results. Based on available CPT data (CGD 2012), the site is assumed to consist of three geological units: a sandy gravel crust 1.7m thick, overlying 8.2m of loose to medium dense sand which is underlain by dense sand with interbedded silt layers. Figure 2 shows a FLAC screenshot of the geological section used in numerical analyses. The groundwater levels which underlie the subject area are assumed to range from 0.9m to 3.2m below the existing ground surface.

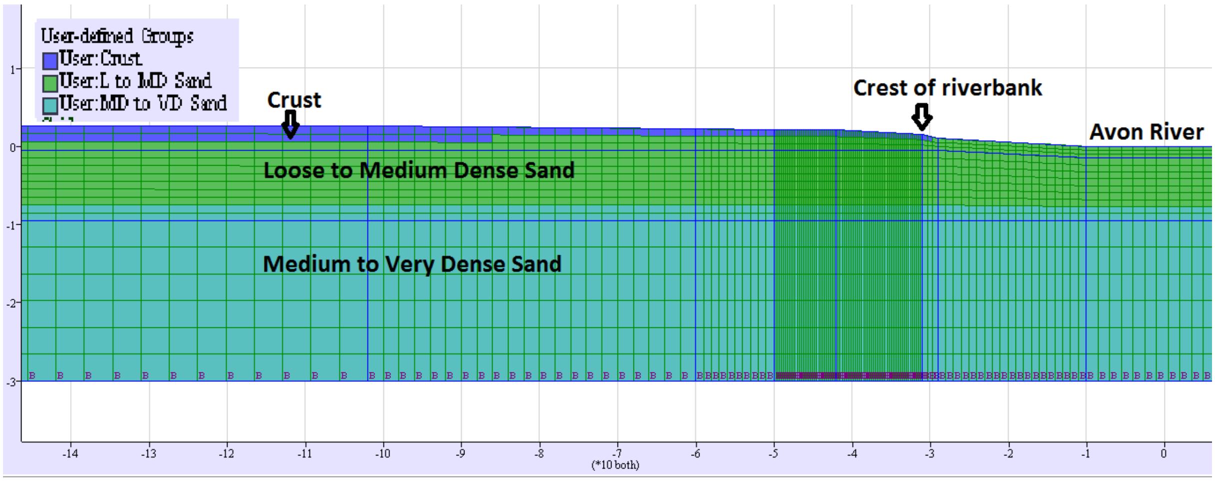

Figure 2. Screen shot of the FLAC geological section

3.3 Static and dynamic material parameters

Subsoil material parameters have been interpreted from the borehole and CPT logs results. The materials subsurface shear wave velocities and dynamic characteristics were derived from the MASW geophysical testing results in the area. The dynamic characteristics of all soils in the model were assumed to be governed by the Seed and Idriss (1971) modulus reduction and damping ratio curves.

3.4 Strong motion record used for analyses

Seismic records from Riccarton High School (RHSC) station was considered to be a suitable station because no liquefaction was observed here. The strong motion record was corrected for direction and deconvoluted to the depth of engineering rock prior to input to the numerical model. Figure 3 shows the input motion for the numerical analyses.

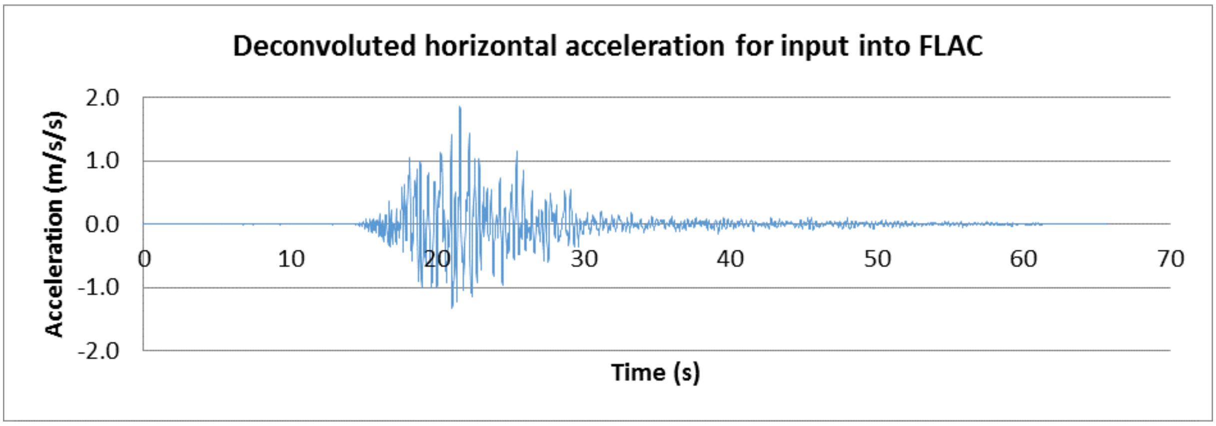

Figure 3. Deconvoluted horizontal acceleration for input into FLAC

3.5 FLAC numerical modelling

For this study the finite difference numerical analysis program FLAC v. 7.0 (Fast Langrangian Analysis of Continua) in 2D has been employed. A coupled effective stress analysis was performed using a simple material model to simulate the behaviour of the soils including liquefaction. The soil behaviour is based upon the Mohr-Coulomb plasticity model with material damping added to account for cyclic dissipation during the elastic part of the response and during wave propagation through the site. Liquefaction was simulated using the Finn-Byrne model, which incorporates the Byrne (1991) relation between irrecoverable volume change and cyclic shear-strain amplitude into the Mohr-Coulomb model. Further details of the modelling is presented in Tang (2012).

3.6 **Stone column modelling**

3.6.1 *Stone column parameters*

The basic design parameters of stone columns include the stone column diameter, *D*, pattern, spacing and the backfill material to be used. The diameter of the stone columns in this study has been chosen to be 750mm. For the purpose of this study, a square pattern has been modelled with an effective diameter (*De*) equal to 1.13*S* where *S* is the spacing of stone columns. The resulting equivalent cylinder of material having a diameter *De* enclosing the tributary soil and one stone column is known as the unit cell. For this site, Area Replacement Ratio, ARR (ratio of area of the stone column after compaction (*Ac*) to the total area within the unit cell) was determined to be 15%.

3.6.2 *Modelling a 3D problem in 2D*

To represent the 3D stone column grid in 2D, a series of parallel trenches was used. The stiffness as well as the permeability of both soft soil and coarse grained inclusion needs to be adapted in order to model the deformation behaviour and drainage conditions correctly. Hird et al. (1992) and Indraratna & Redana (2000) recommended methods to perform a conversion of permeability. These transformations are also applicable to smear effects.

3.6.3 *Stone column mechanisms*

3.6.3.1 Densification effect

The effect of granular pile installation on the modifications induced in loose to medium dense granular deposits was studied by Murali Krishna and Madhav (2009). This was presented in the form of design charts that can be used design the required degree of treatment for the expected improvement or to estimate the improved values of treated ground. The improved SPT N_1 value for this case has been determined to be 26. Moreover, studies have shown that densification of the in-situ soil surrounding the stone columns decreases with distance away from the stone column (Obhayashi et al. 1999 and Weber et al. 2010). They determined that the extent of the disturbed zone is approximately 2.5 times the radius of the stone column and this was adopted in this study.

3.6.3.2 Reinforcement effect

As the current study is a 3D problem being modelled in a 2D model, the stiffness of the stone columns needs to be adapted in order to model the deformation behaviour correctly. In a 2D plane strain model, the stone columns will be represented as an infinite trench with a width equal to the diameter of the stone column rather than a single column. The equivalent vertical stiffness of the column material in 3D and in 2D were made to be equal.

3.6.3.3 Drainage effect

The drainage condition needs to be adapted from a 3D problem into a 2D simulation. The excess pore pressure dissipation should be similar in both systems – the radial drainage system must equal the plane drainage system. The Idraratna & Redana (2000) equations to estimate plane strain permeabilities were used in the study. Weber et al. (2010) studied the smear zone and densification zone around stone columns and the smear zone was described as a strongly sheared and remoulded zone. In this study, the smear zone was assumed to be 1/3 of the column radius, i.e. 0.125m.

4 **NUMERICAL RESULTS**

4.1 **Control model – no stone columns**

Figure 4 illustrates the calculated surface displacements by the FLAC numerical model and the measured cumulative lateral displacements at transect CH_DAL_15 by Robinson (2011). The figure shows that there is a similar conventional ‘exponential decay’ distribution where the spreading displacements rapidly decrease with the distance from the waterway. This is consistent with the conventional liquefaction induced lateral spread mechanism. The calculated surface lateral displacements by FLAC were compared to the field measurements by Robinson (2011). The magnitude of lateral spread between the field measurements and the FLAC calculations at the crest differed by about 20%. This could be due to the stream bank in FLAC to be constructed on the loose silty GRAVEL, where in real life the bank may be supported by vegetation or small man-made structures. The difference in lateral displacements between the calculated and measured values reduces to zero at some locations. Such difference is considered acceptable and comparable considering the displacement trend is reasonably similar.

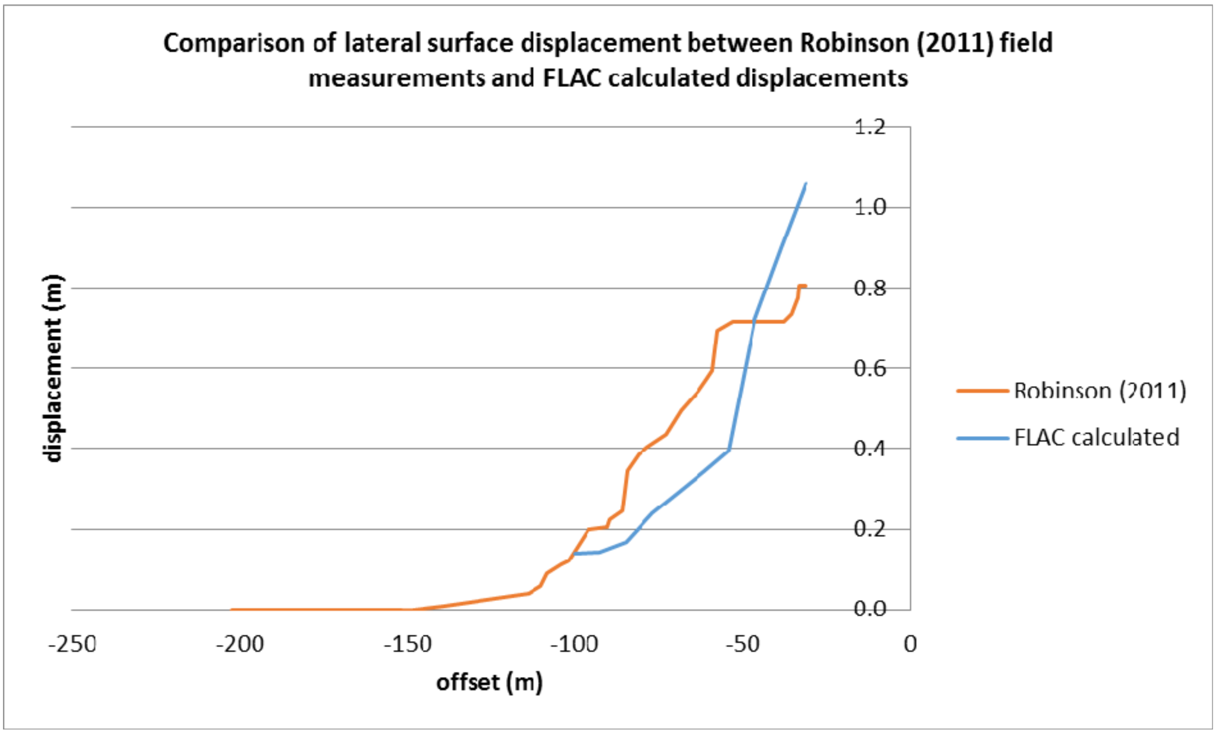

Figure 4. Comparison of lateral surface displacement between Robinson (2011) field measurements and FLAC calculated displacements

4.2 Stone column models

4.2.1 *Individual effects models*

The individual effects mentioned above were modelled separately and compared to the control model to assess their effectiveness. Figure 5 illustrates the final surface displacements from the crest of the river bank to 100m from the middle of the river for each of the individual effects model and the control model with no stone columns. It can be seen that all three mechanisms have reduced surface displacements at the end of shaking from the crest of the riverbank to approximately 55m from the centre of the river. Densification has reduced the surface displacement the most, by up to 49% at the edge of the improvement zone at approximately x=-39m.

The reinforcement effect reduces the surface displacements the least. At the crest of the riverbank, the reduction in surface displacement is minimal but the reduction becomes larger and reaches a maximum of approximately 25%. In theory, the cyclic stresses felt by the cross section will be concentrated in the stiffer areas (i.e. the stone columns) and the shear stress in the soil will be lower than without the stone columns. This could explain the relatively smaller reduction in surface displacements in the improved zone compared to that just outside the improved zone, as more shear stresses are borne by the improved zone.

The drainage effect is between the densification and reinforcement effect. The maximum reduction that was achieved by the drainage effect is approximately 37%. It can be noted that there is a significant change in gradient of the displacement curve in the improvement zone – the reduction of displacements compared to the control model becomes greater in the improvement zone. The provision of smaller drainage paths capable of dissipating pore water pressures more rapidly than they are generated during earthquake loading is an effective way to mitigate liquefaction potential.

Figure 5 shows that between approximately x=-54m and the crest of the riverbank, there is a significant reduction in lateral surface displacements where stone columns have been modelled. The maximum reduction in lateral surface displacements occurs at the crest of the riverbank, by a percentage of approximately 50%. For the geometry of the subject site it could be concluded that for an improvement zone of 8m, the effects of stone columns are significant up to 15m away from the edge of the zone of improvement. The reduction in lateral surface displacement between x=-54m and x=-100m is on average 25%.

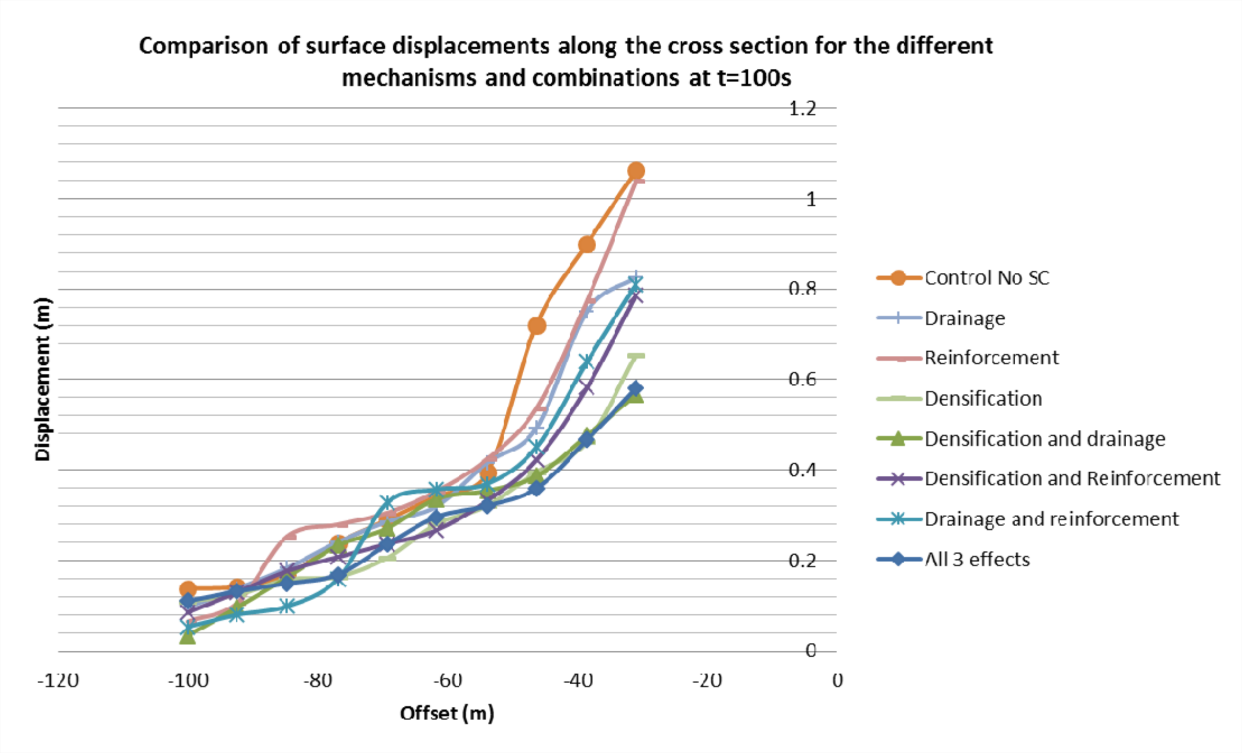

Figure 5. Resulting surface lateral displacements at t=100s.

4.3 Combinations of effects

Sensitivity analyses of each of the three above effects were performed as well as the effects of different combinations of the effects to assess to importance of each effect on the overall system. Figure 5 above illustrates the lateral surface displacements along the cross section at t=100s for the different combinations of effects as mentioned above and those from the control model with no stone columns.

Of the three combinations, the combination drainage and densification effects resulted in the largest reduction in surface displacement at the crest of the crest of the riverbank, estimated to be approximately a reduction of 46%. This is consistent with the analyses on the individual effects where the densification effect resulted in the biggest reduction in lateral surface displacement, then the drainage effect. The combination of drainage and reinforcement resulted in the least reduction of lateral surface displacement, of approximately 24% at the crest of the riverbank and a reduction of 37% outside the ground improvement zone. It can also be noted that the amount of lateral displacement at the crest of the slope for the model with all 3 effects and the combination effects of densification and drainage is very similar.

It is noted that the results from this series of analyses cannot be directly related with the models investigating the individual effects as the increased weight of the stone columns compared to the in-situ soil was not considered in the individual effects models, while the increased weight was modelled for the rest of the models, including these combination models. To investigate this observation further, one case where the individual densification effect with the consideration of increased weight of the stone column zones was run in order to compare the results with the combination cases. The results indicated that the models for the individual effects with and without the consideration in the increased weight of the stone column zones resulted in a very similar magnitude of surface displacement along the cross section, with the model without considering the increased weight. It shows that for the inside the improvement zone, the model that takes into account the increased weight of the stone columns results in a higher displacement. This confirms that the higher gravitational forces due to the increased weight in the columns may drive the soil mass towards the waterway more than without the increase in weight of the stone columns. However, there is only a difference in the crest lateral displacement of approximately 7% at the end of the model duration of 100s

5 DISCUSSION AND RECOMMENDATIONS

The current study showed that the reinforcement effect did not result in a significant effect on reducing liquefaction potential and lateral spreading in this particular model. The design procedure used in this study focuses on the densification effect on the ground improvement related to the installation of stone columns. There are other procedures for example Baez and Martin (1995) where a loosely coupled method of designing stone columns for densification, drainage, and reinforcement effects. These effects can be used alone or in combinations when designing stone columns. From the results, it can be recommended that for this particular study or similar problems, the reinforcement effect need not be considered during design. The consideration of the combination of densification and drainage effects would be adequate. However, this may not be applied for all cases of stone column design against liquefaction and associated lateral spreading. Depending on site conditions, and method of installation of the columns, the influence of the three different effects may be different. A more comprehensive study on would be required to investigate this problem.

6 LIMITATIONS AND FURTHER STUDY

With this study, many assumptions have been made. These assumptions have largely been made on the basis of current literature, but it understood that there are various limitations of the study. These have been summarised below.

- Only one input ground motion has been used
- Only one cross section has been analysed
- Results compared to lateral displacement data that was recorded at a site 200m away
- Numerical model in 2D for a problem that is essentially 3D

Further studies would be recommended to produce design charts for stone columns used for mitigating liquefaction induced lateral spreading. A much more comprehensive parametric study analysing different slope geometries, subsoil parameters, groundwater levels and varying input motions would be required to come up with design charts that would determine the area replacement ratio and the extent of improvement zone required. It would be recommended that these studies performed using three dimensional numerical modelling to mimic the physical problem as close as possible. The current study could be further developed into a three dimensional analyses using FLAC 3D, and results from the 2D model and 3D model may be compared to investigate any differences and the validity of the current 2D model.

7 CONCLUSION

A study was carried out to assess the effectiveness of stone columns against liquefaction induced lateral spreading using the finite difference programme FLAC. For this purpose, a site in Christchurch was used which was affected by the February 2011 earthquake.

The three main ground improvement mechanisms associated stone columns – reinforcement, drainage and densification effects were investigated on how each of them improved the mitigation against liquefaction and associated lateral spreading. It was found that the densification effect resulted in the most significant effect on the ground improvement system while the reinforcement effect had the smallest effect on the system.

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