National Design Guidelines for Ground Improvement of Soils Prone to Liquefaction

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ABSTRACT

One of the Canterbury Earthquake Royal Commission recommendations was that "ground improvement should be considered as part of the foundation system of a building and reliability factors included in the design procedures" and that "the Ministry of Business, Innovation and Employment should consider the desirability of preparing national guidelines specifying design procedures for ground improvement, to provide more uniformity in approach and outcomes". Opus International Consultants Limited (Opus) was engaged by MBIE to lead the preparation of the national ground improvement design guidelines - Module 5 (the Guidelines). The project team also included MBIE, EQC, University of Auckland, University of Canterbury, University of Southern California, University of California – Berkeley, Tokyo Denki University as well as a number of NZ consultants and ground improvement contractors. The Guidelines are based on the latest research and observations of the performance of ground improvement in earthquakes in New Zealand and internationally. The Guidelines were published for public comment in May 2017. The Guidelines identify the key issues that need to be addressed in the design and construction of ground improvement to mitigate the effects of liquefaction, cyclic softening and lateral spreading effects on buildings and provide a framework for resolving these issues through design and construction. In this paper, a summary of the Guidelines is given and complex design issues are discussed.

1 INTRODUCTION

International experience has shown that buildings founded on sites that would otherwise be liquefiable can perform well, where well-engineered, robust ground improvement has been carried out. The experience in Christchurch during the Canterbury earthquake sequence was more varied, noting that the ground shaking, in some areas, was more intense than that allowed for in design. The Canterbury Earthquake Royal Commission (CERC) recommended consideration be given to the preparation of national guidelines to improve uniformity in the design approach and outcomes.

The Guidelines are Module 5 in the MBIE / NZGS guidance series of geotechnical Modules that have been developed by MBIE and NZGS with support from NZ and international consultants, contractors and universities (MBIE, 2016a). The Guidelines cover the design of ground improvement and support the Canterbury Earthquake Royal Commission recommendations to prepare national guidelines specifying design procedures for ground improvement, to provide more uniformity in approach and outcomes. Opus was engaged by MBIE to lead the preparation of the Guidelines. The project team also included MBIE, EQC, University of Auckland, University of Canterbury, University of Southern California, University of California – Berkeley, Tokyo Denki University as well as a number of NZ consultants and ground improvement contractors.

The Guidelines identify the key issues that need to be addressed in the design and construction of ground improvement to mitigate the effects of liquefaction, cyclic softening and lateral spreading effects on buildings and provide a framework for resolving these issues through design and construction. A wide range of ground improvement techniques are available to mitigate the effects of liquefaction and many of these are briefly described in the Guidelines, including techniques that have not been used extensively in New Zealand to date. There is no attempt to provide a comprehensive discussion of all available liquefaction countermeasures in the Guidelines; rather, only commonly used methods in New Zealand are outlined in detail. A bibliography is provided that gives greater depth on specific topics and aspects of ground improvement and practitioners and constructors are encouraged to read these where relevant.

The objective of the document is to provide concise, practical advice and simplified procedures for the design of ground improvement by qualified, experienced engineers based on the latest research and observations of the performance of ground improvement in earthquakes in New Zealand and internationally. The Guidelines should also help to improve design consistency in New Zealand. The key issues covered by the Guidelines are summarised in this paper.

2 LIQUEFACTION CONSIDERATIONS

Where appropriate, the Guidelines refer to other MBIE modules. The topic of planning and undertaking site investigations for the purpose of characterising site geotechnical conditions and for the evaluation of liquefaction is discussed in Module 2 (MBIE, 2016b) and further in Module 3 (MBIE, 2016c) . Module 4 (MBIE, 2016d) gives guidance on the development of ground models and the selection of engineering soil properties for the design of foundations. The effectiveness of many ground improvement techniques is highly dependent on the fines content of the soils and the variability of the ground conditions to be treated. A comprehensive investigation should be undertaken to assess soil conditions and in particular, the fines content, location and extent of silt and clay layers at a site. Penetration testing undertaken as part of the site investigation also forms the basis for assessing the degree of treatment achieved. As discussed in Module 3, there is a high degree of uncertainty in the relationship between fines content and the soil behaviour index, I_c, calculated from cone penetration tests (CPT) and therefore fines content calculated from I_c should be calibrated against laboratory measured fines content and field descriptions of soils. Detailed recommendations on site investigations for assessment of liquefaction are given in Module 2. Guidance on the identification and assessment of liquefaction, and liquefaction induced ground deformation is provided in Module 3.

The seismic behaviour of a building on liquefiable ground is affected by the depth and stiffness of the structural foundation, magnitude of contact pressure, seismic response of the structure and soil, the thickness and properties of liquefiable soil layers and the non-liquefiable crust, the intensity of ground motion and many other factors.

There are a number of ways liquefaction can affect a building and its connecting infrastructure, including:

- Reduced bearing capacity due to the associated reduction in soil strength;
- Subsidence associated with shear deformation, cyclic ratcheting, lateral spreading and ground re-levelling, and reconsolidation;
- Surface ejection of soil and water (sand boils) from beneath or around foundations;
- Heave of ground bearing floor slabs and buoyancy of buried pipes, tanks, chambers and basements;
- Horizontal displacement and stretching of the footprint and foundation with lateral spreading;
- Kinematic bending of piles with horizontal ground displacements; and
- Pile down-drag (negative skin friction) caused by ground subsidence.

The degree to which these effects relate to a particular site and structure, depends on the site specific ground conditions and the details of the structural system. Detailed discussion on the effects of liquefaction on buildings is given in Module 4.

3 GROUND IMPROVEMENT PRINCIPLES

The Guidelines discuss five principal methods employed to improve the ground and increase its resistance to liquefaction: replacement, densification, solidification, reinforcement, and drainage. Ground improvement methods normally utilise one or a combination of these mechanisms to improve the ground's resistance to liquefaction and improve seismic performance. A secondary mechanism of some techniques is the potential improvement of the soil's resistance to liquefaction triggering by an increase in the lateral stress within the soil and thus changing its initial state. This mechanism cannot be easily verified in the field and may not greatly reduce the effects of liquefaction should it be triggered. Until further research gives a better understanding of its effectiveness at mitigating liquefaction and ways to confidently verify that the increase in lateral stress is achieved in the field, this mechanism should not be depended on in design.

4 SEISMIC RESPONSE OF BUILDINGS SUPPORTED ON IMPROVED GROUND

Ground improvement can greatly increase the stiffness of the soil profile. It is well understood that the stiffness of the soil has a marked effect on seismic ground motions at the surface. Stiffening the soil can amplify accelerations at the surface but decrease displacements. In many cases, ground improvement will not fully eliminate the effects of liquefaction. Settlement of buildings with shallow foundations supported on improved ground will result from shear and volumetric changes within the improved zone and in the soils surrounding or underlying the improved zone. The prevalent mode of deformation depends on the ground improvement method adopted, its size and stiffness; the size, weight and stiffness of the structure (and the distribution of weight and stiffness) and the extent of the liquefiable soil beneath the improved zone.

Except for methods that completely solidify or replace the liquefiable soils with stiff (cemented) low permeability materials, subsidence can develop from shear deformation in the improved ground under loading from the building. This is often more pronounced at the perimeter of structures, particularly for tall and heavy structures that can exert large loads on perimeter foundations. The magnitude of subsidence can be exacerbated by softening of the improved soils with cyclic shearing, the associated development of excess pore water pressure and the migration of excess pore water pressures from the surrounding liquefied soil into the improved zone. Reconsolidation of soils in the improved zone as excess pore-pressures dissipate will cause additional subsidence. Lattice and columnar reinforcement elements can be subjected to considerable bending, shear and axial stresses. With partial depth of improvement, settlement and tilting of the improved ground overall can develop from shear induced deformation in the liquefied soil beneath the improved zone, reconsolidation of the liquefied soils as pore water pressures dissipate and ratcheting effects during earthquakes, similar to the mechanisms of settlement for shallow foundations on liquefaction prone sites as described in Module 4. Ground improvement in areas of lateral spreading can experience large compression and tension stresses from dynamic and kinematic forces imposed on it by the surrounding spreading ground. This can cause horizontal displacement, stretching and shear deformation of the zone of ground improvement.

5 PERFORMANCE REQUIREMENTS

The general philosophy for the design of ground improvement is to eliminate liquefaction and lateral spreading or mitigate their effects to the extent needed to meet the design performance criteria for the structure. In this context, the effectiveness of ground improvement should be assessed within the performance-based design framework by estimating the reduction of effects of liquefaction in relation to a no-improvement case, and by assessing the seismic response in relation to specific performance objectives for earthquake loads associated with different return periods. Qualitative effects of ground improvement on the dynamic response of foundation soils, structure and soil-structure system should be also considered in this evaluation. Such relatively rigorous performance requirements imply the need for adequate standards for design, construction control and verification of the effectiveness of ground improvement.

Performance criteria for the acceptable damage, settlement and differential settlement for each damage state should be developed collaboratively between the owner/developer, structural engineer and geotechnical specialist to get an overall system that meets regulatory (minimum) requirements and the expectations of the owner/developer.

It is often not economic, nor required in a regulatory sense, to completely eliminate liquefaction beneath buildings with ground improvement. Apart from methods that completely solidify or replace all liquefiable soils with non-liquefiable material, excess pore water pressures can develop within the zone of improvement. The frequency of earthquake at which these aspects start to have a significant effect on the amenity of the structure should be discussed and agreed with the owner/developer. Consideration should be given to the resilience of the ground treatment and the overall response should be ductile. The weight and stiffness of the structure and its foundations; the type, extent, and stiffness of the ground improvement; the ground conditions, characteristics of earthquake shaking and the extent of liquefaction triggered in an earthquake, all affect seismic performance. In assessing seismic performance and resilience, the uncertainties in these parameters and the interaction between the superstructure, connecting infrastructure, foundation, improved ground and native soil need to be considered holistically. The high degree of uncertainty in many of the parameters affecting seismic response implies the need to assess the sensitivity of the system response to each parameter and apply an appropriate level of redundancy in the design. Sensitivity assessment should be undertaken as part of any ground improvement design and discussed within the foundation options and design reports.

Improved structural measures can be incorporated to reduce damage susceptibility due to liquefaction, improve resilience and reduce or eliminate the need for ground improvement. These can comprise:

- Use of robust mats or a stiff grid of intersecting ground beams instead of stand-alone footings.
- Making above ground structural elements or connections between structures flexible and ductile to cope with total and differential settlements or lateral spread.
- Constructing foundation systems that seismically isolate the building from the ground and allow it to be re-levelled.
- Pile foundations to competent ground that is not underlain by liquefiable soils to prevent bearing failure and mitigate settlement and uplift (buoyancy).

- Control of ground deformation and structural performance by structural measures (rigidity of the structure, rigid rafts, sheet piles to confine liquefiable material, geogrids, base isolation of structures).

6 DESIGN OF GROUND IMPROVEMENT

Engineering assessment, consideration and design process for ground improvement can be summarised as follows:

- Determine performance requirements for the building and its foundation system (refer to the NZ Building Code, NZS1170, Module 1 and Module 4 and NZSEE Assessment and Improvement of the Structural Performance of Buildings in Earthquakes).
- Assess site conditions, ground conditions and geohazards including seismicity and susceptibility to liquefaction and lateral spreading (refer to Modules 1, 2 and 3). Where existing geotechnical information is insufficient, a geotechnical investigation should be carried out (refer to Module 2).
- Assess if liquefaction will be triggered, severity of liquefaction and the free field effects of liquefaction at the site (refer to Module 3).
- Assess the lateral spreading hazard at the site and the potential for differential lateral displacement across the building footprint.
- Assess the effects of liquefaction on the structure (with shallow or pile foundations and no ground improvement) and compare with the performance criteria. Consider whether there are readily available structural options to reduce susceptibility to damage from liquefaction. Where reasonable structural options alone are not sufficient to satisfy the performance requirements, consider ground improvement options.
- Select suitable methods for ground improvement.
- Design the extent (depth and size in plan) of improvement needed to meet design objectives. Consider soil-ground improvement-structure interaction. Early engagement between the structural and geotechnical engineers, and where practicable constructors, will enable a more efficient and holistic assessment of ground improvement and foundation options (also refer to Module 4).
- Design the size and arrangement of the ground improvement; determine material requirements, e.g. unconfined compressive strength of soil-cement mixture.
- The usual goal of ground improvement is to eliminate liquefaction. However ground improvement does not necessarily need to eliminate liquefaction within the improved zone but should control and mitigate the effects of liquefaction, and meet the performance criteria.
- Determine quality control (QC) and quality assurance (QA) requirements. In many cases a ground improvement trial will be required to confirm design assumptions and QA methods and optimise the design.

Full depth improvement is unlikely to be economic for sites underlain by deep liquefiable deposits and partial depth improvement can often give acceptable performance by reducing the magnitude of settlement. Assessment of nearly 60,000 lightweight single family dwellings in Christchurch following the Canterbury Earthquake Sequence clearly showed that less structural damage occurred in liquefaction prone areas containing an intact relatively stiff non-liquefying crust that was at least 3 m thick. From case history studies, Hausler and Sitar (2001) noted that one of the reasons why unacceptable performance was noted in the majority of ground improvement cases they investigated was due to inadequate remediation zone depth. Centrifuge studies on this topic (Liu and Dorby, 1997; Hausler 2002) came to a similar conclusion. Figure 1 shows the plot of normalised foundation settlement (i.e. foundation settlement divided by the total thickness of liquefiable layer) vs normalised improvement depth (i.e. thickness of improved soil divided by the total thickness of liquefiable layer) from case studies and centrifuge tests. The case studies and centrifuge tests indicate a marked increase in settlement for treatment depths that are less than 50% of the thickness of the liquefiable layer.

The required lateral distance or width of soil improvement outside the perimeter of the structure is determined by the zone that controls the stability and deformation of the structure, even if liquefaction occurs over a wide area.

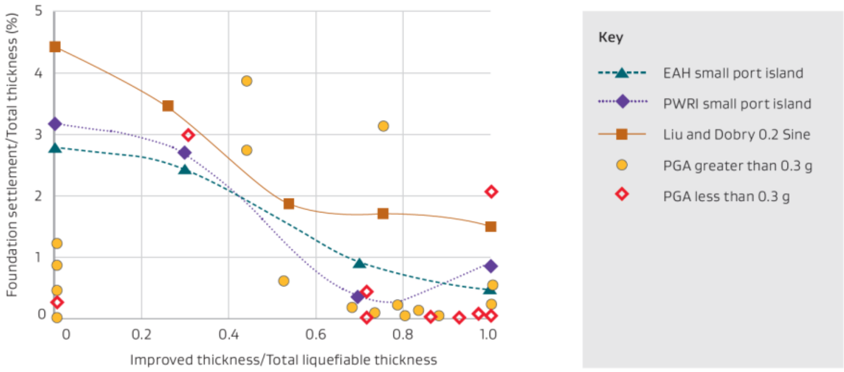

Figure 1: Normalised building settlement vs normalised improvement depth (Liu and Dorby 1997, Hausler 2001, 2002)

Factors that need to be considered when determining the lateral extent of improvement include:

- stresses applied to the improved ground by the building during earthquake shaking. Compressional and shear stresses near the edge of structures can fluctuate greatly and may have a larger zone of influence compared to static stresses, especially for tall and slender structures.
- strength and stiffness of the improved ground and the potential for a reduction in strength and stiffness due to excess pore pressures generated in the surrounding liquefied soil migrating laterally into the improved zone during and after shaking.

Model tests and analysis of ground improved by densification over the full depth of liquefiable soils indicate that in the soils bounded by the square ABCD (Figure 2), the pore water pressure ratio, r_u is often greater than 0.5 (Iai et al, 1988).

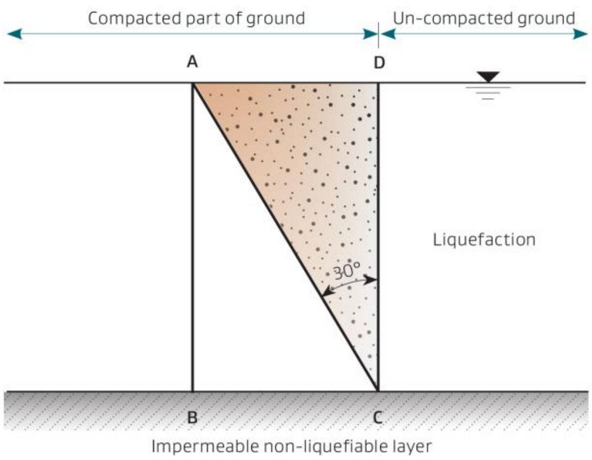

Figure 2: Area of softening in ground improved by densification (ACD) due to pore water pressure migration (after Iai et al, 1988)

The triangular area ACD exhibits particularly unstable behaviour and hence, this part should be treated as liquefied in the design of ground improvement that utilises densification techniques. As a result, it is common practice to continue densification improvement to a distance of at least half of the depth of the improved zone from the edge of the structure.

It is sometimes not possible to extend improvement the recommended distance beyond a structure because of the presence of other structures, property boundaries, or utilities. In these cases, it may be possible to cantilever the foundation over the area of ground improvement affected by lateral migration of pore water pressure. Lattice ground improvement structures and other ground improvement methods that solidify or constrain the lateral deformation of soil beneath the foundation typically do not need to extend far beyond the foot print of the building.

Damage to structures may be especially severe where they are subjected to lateral spreading in conjunction with liquefaction. Strategies to mitigate lateral spreading and its effects at building sites include:

- Construction of structural walls separate from the building. These could be soldier pile walls tied back to anchor piles that cantilever from non-liquefiable soils or caissons founded on non-liquefiable ground.
- Using a buttress of ground improvement on the down slope side of the building but separate from the building foundations. This is may be desirable for piled structures in laterally spreading zones as the greater stiffness and strength of the improved soils could place larger kinematic loads on the piles and increase structural inertia.
- Improving the ground under the structure to mitigate lateral spreading as well as provide a suitable platform for the building.
- A combination of these treatments except that ground improvement should extend under the entire footprint of the building or not at all to avoid high contrasts in stiffness beneath the building that could cause differential subsidence and increase torsional response.

The Guidelines give design recommendations for the following ground improvement methods: replacement, densification (dynamic compaction, vibro-compaction, stone columns, compaction piles, compaction grouting, resin injection), solidification (soil mixing, jet grouting, permeation grouting), reinforcement (lattice intersecting walls, grid of stiff vertical columns) and drainage.

7 QUALITY CONTROL

The Guidelines give recommendations on design verification, quality control and quality assurance procedures, and emphasise the importance of interaction between structural and geotechnical designers. Where the structural and the geotechnical designers work together, the integration of structural and geotechnical design solutions to meet the performance requirements for the building in mitigating the effects of liquefaction and lateral spreading normally results in the most cost-effective design outcomes. The interaction between the structural and the geotechnical designers should also continue through the construction phase, as some adjustments to the structural design may be required depending on the achieved level of ground improvement.

8 CONCLUSION

The national ground improvement design guidelines -Module 5 have been prepared and issued for public comment. The Guidelines identify the key issues that need to be addressed in the design and construction of ground improvement to mitigate the effects of liquefaction, cyclic softening and lateral spreading effects on buildings and provide a consistent framework for resolving these issues through design and construction in New Zealand.

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