Guidelines and codes for liquefaction mitigation by ground improvement

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Abstract

Ground improvement has become one of the most effective tools of geotechnical engineering, being adopted for an always larger variety of civil engineering applications. To reduce the role of subjective choices of operators, the use of different techniques tends to be codified by specific guidelines. In the European Union there is an ongoing effort to standardize execution and design within codes continuously reviewed by designated committees. A widespread and systematic standardisation on the ground improvement as a mean to mitigate the effects of liquefaction on buildings and infrastructures is missing. The paper presents and overview of traditional and new ground improvement technologies suitable for this application. The methods are firstly classified by considering their effects on the ground (e.g. densification, stabilization, drainage, desaturation, etc.). Design principles are then outlined for new or pre-existing buildings and infrastructures, considering the ongoing review process of the design Eurocodes.

Keywords: Liquefaction, critical infrastructures, ground improvement, standardisation, Eurocodes.

1. Introduction

Liquefaction is among the most devastating effects induced by earthquakes, being capable of producing severe damages on buildings and infrastructures and thus undermine the whole life of the communities (NASEM, 2016). Despite observations show that compared to ground shaking, landslides and tsunamis, liquefaction is likely to cause less conventional collapse of structures or fatalities (Bird and Bommer, 2004), the economic losses coupled with this phenomenon are typically huge as the restoration of damaged structures is costly and time consuming. A reliable assessment of risk should consider not only the repair cost of the physical goods exposed to this phenomenon (built asset, lifelines, productive units), but also the losses consequent to their reduced functionality, proportional to the time necessary to restore original conditions and to the criticality of the considered structure for the life of the community. Normally, the functions of urban systems are heavily injured by liquefaction and the process to restore original life conditions is long and toilsome in a way that populations are often discouraged to undertake recovery and stimulated to migrate elsewhere.

Dramatic events like those occurred recently in Izmir 1999 (Sancio et al., 2002), Christchurch 2011 (Canterbury Development Corporation, 2014), Tohoku Oki 2011 (Yasuda et al., 2012), Emilia

Romagna 2012 (Fioravante et al., 2013), have demonstrated the gravity of liquefaction phenomena and raised a new awareness in the stakeholders on the need to undertake preventive actions. Strategies to improve the resilience of cities and communities may move both at the political level, i.e. reallocating critical infrastructures in zone not susceptible of liquefaction, or at a technical level reducing the physical vulnerability of structures (Morga et al., 2018).

Ground improvement technology offers a variety of appealing methods to reduce the susceptibility of soil to liquefy and mitigate the above effects. The choice of the most appropriate solution for a specific application implies an innermost knowledge of the techniques and the capability to predict the modification induced on the soil and the performance of the latter when subjected to a seismic excitation. To limit the role of subjective choices of operators and promote a rational use of the technology, there is an ongoing effort of the scientific and technical community to methodise design, execution and control of treatments into guidelines and codes that fix the goals of treatments and set the rules for application. A rational application of ground improvement is vital to mitigate risk and make the asset management sustainable. The present paper deals with the standardisation of ground improvement for liquefaction mitigation. After an overview of the ground improvement techniques available for such use and of the codes proposed in some countries to standardise them, the focus is set on the Eurocodes describing the present situation and possible developments.

2. Ground improvement against liquefaction

The liquefaction occurrence is determined by the combination of seismic shaking, generally affecting large areas around the sources, and local susceptibility dictated by specific geological conditions. The above factors may combine even at very large distances from the epicentre (e.g. Yasuda et al. 2012) producing effects at the ground level that range from large settlements of buildings, tilting of tall and slender structures, sliding induced by lateral spreading, cracks on embankments, interruption of horizontal facilities like electric lines, gas and freshwater networks, sewers etc. (Figure 1).

The phenomenon affects saturated loose sandy soils shaked by sufficiently intense earthquakes. The contractive tendency of cyclically loaded granular materials and the difficulty of the water to seep in the short time generate a growth of pore pressures that reduces the normal force among the grain contacts. Ultimately, when the latter is nullified, the frictional resistance disappears, and the soil behaves like a liquid losing its bearing capacity. Ground improvement acts on the predisposing factors, aiming to reduce the tendency of soil to contract or to release the build-up of water pressure. These results can be obtained with various methods, grouped in Table 1 depending on the effects produced on soil or water and on their applicability to new and/or existing structures. The list includes traditional techniques for which a long and well-established practice exists, and new technologies tested at the prototype scale but not fully proved on site.

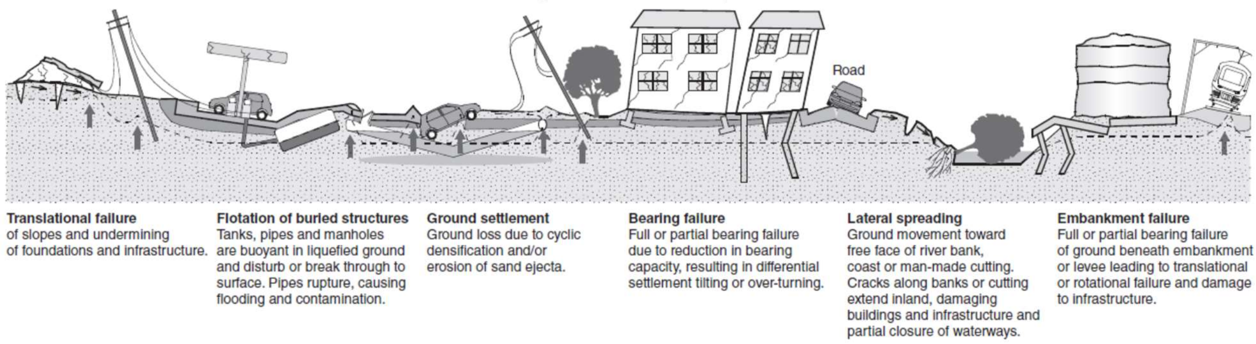

Figure 1. Effects of liquefaction on buildings and infrastructures (adapted from Mian et al., 2013).

Table 1. List of ground improvement techniques for liquefaction mitigation (European execution standards are indicated where available).

Principle	Applicability	Techniques
Densification	New structures	• Impact compaction • Deep dynamic compaction • Vibratory shallow compaction • Vibro-compaction (EN14731) • Blasting
	Also existing structures	• Compaction grouting • Foam injection
Soil fabric solidification	New/existing structures	• Permeation grouting (EN12715) • Resin injection • Nanosilicate injection • Bio-grouting • Electro-chemical stabilisation
Modification of soil composition	New structures	• Dynamic replacement • Dense gravel replacement • Stabilised soil replacement • Mixing with hydraulic binders (e.g. cement, lime) • Mixing with finer materials
Drainage/Desaturation	New/existing structures	• Earthquake drains • Gravity drains (EN 15237) • Vacuum-pump drains • Dewatering • Desaturation
Reinforcement	New structures	• Deep Soil Mixing (EN 14679) • Stone Columns – Vibro-replacement • Sand Columns • Jet Grouting (EN 12716) • Secant piles

The principle of the first category of methods is to reduce the tendency of soil to contract by densification, without changing its original composition. On granular materials alternate deviatoric loading is generally more effective than static compression, and thus dynamic actions (vibration, impact or blasting) are adopted. On the other hand, these techniques induce vibration and stress regimes intolerable by existing structures and are thus applied only to improve soil before the construction of new structures. Compaction applied by injecting thick grout mixes (cement, sand and bentonite assorted with variable proportion) or by bi-component expanding polyurethane foams has been recently applied for the rehabilitations of existing structures.

The second category includes methods aimed at freezing the original soil fabric, reduce the grain mobility and the tendency to deform and contract during shaking. This goal is accomplished by injecting grout of different compositions. Groutability, i.e. the ability of the soil to be penetrated at relatively large distance by seeping material is the key factor of this technique and motivates the use of more effective (and costly) materials like resins or nanosilicates. Some of them reduce the mobility of sand by bonding the grain contacts, while others fill the soil pores reducing the space for volume contraction. Planting colonies of bacteria (bio-grout) or dissolving metal ions (electro-chemical stabilisation) within the soil pores to solidify the grain contacts represent two of the newest frontiers of ground improvement.

The modification of soil composition, giving heterogeneous grain size distribution or including plastic material in the pores, to reduce the tendency of the shaked soil to contract is the principle of the third category of Table 1. This idea can be conveniently applied, but only to improve soil at relatively shallow depths.

Drainage techniques avoid the water pressure build up during earthquakes. This result can be reached in different ways, i.e. lowering permanently the water table position (dewatering), speeding up the capacity of soil to exhaust excess pore pressure by favouring seepage (earthquake drains), or adsorbing pressure in previously injected/created air bubbles. In all cases, volume contraction produced by shaking is allowed, but frictional resistance is preserved and triggering of liquefaction inhibited.

The reinforcement of soil with rigid inclusions is a well-established methodology, already adopted for several geotechnical applications. For the present specific purpose, the principle is to stiffen the liquefiable deposit limiting soil deformation of the soil entrained between reinforcement and inhibiting triggering of liquefaction. Often lattice structures are created with the idea of forming more rigid structures and limit to the propagation of excess pore pressures. In the case of stone columns, the reinforcing function is coupled with densification of the surrounding soil produced during installation and drainage of pore water.

3. Design principles and standardisation outside Europe

The most suitable technique among the above presented ones should be selected considering the best compromise of effectiveness, technical feasibility, costs and environmental sustainability. A significant effort to standardize design procedures has been made in countries that have suffered severe liquefaction (e.g. Han, 2015; JGS, 1998; Kirsch and Bell, 2012). The complexity of standardization in Japan is depicted in Figure 2 that reports the specifications adopted in Japan by institutions responsible for different infrastructures (JGS, 2011). It is immediate to see that the codes differ from each other, being criteria based on safety factor F_L, liquefaction potential index PL or limit SPT blow counts alternatively adopted. Once limits are exceeded, remediation criteria are required by the promoting institutions. An attempt to unify the approach to liquefaction mitigation in US is proposed in SCEC (1999). Here a procedure is introduced to quantify hazard and implement ground improvement techniques for mitigation. According to this procedure, mitigation projects should contain the following documents:

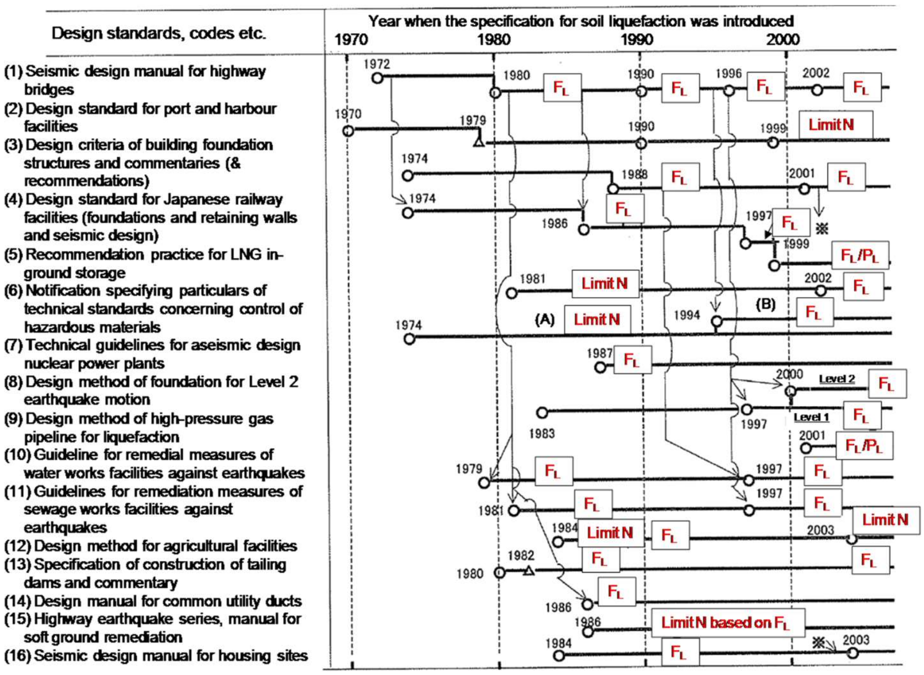

Figure 2. Specifications for countermeasures against liquefaction in Japanese design standards and codes for infrastructures (JGS, 2011).

1. Project description;
2. Description of the geologic and geotechnical conditions at the site;
3. Evaluation of the site-specific liquefaction hazard;
4. Recommendations for appropriate mitigation measures;
5. Logs of field explorations (SPT and CPT);
6. Description of laboratory tests on soil samples and summary of test results;
7. A summary of the assumptions used in analysis
8. Calculation and results.

Following the same strategy, a more detailed approach has been recently developed by the New Zealand Geotechnical Society (NZGS, 2017). According to this guideline, analyses should be aimed at progressively evaluating the liquefaction susceptibility of the subsoil, triggering caused by likely events and effects on the structures. Assessment is thus articulated with the following subsequent steps:

1. Determine performance requirements for the building and foundation system;
2. Assess site seismicity, local seismic response and susceptibility to liquefaction/lateral spreading based on geotechnical investigation;
3. Assess severity and free field effects of liquefaction at the site considering lateral spreading hazard and potential for differential lateral displacement across the building footprint;
4. Assess the effects of liquefaction on the structure and compare them with the performance criteria.
5. Consider structural options to reduce susceptibility to damage from liquefaction or, where they are not sufficient, consider ground improvement options;
6. Select suitable methods for ground improvement;
7. Design the extent (depth and size in plan) of improvement needed to meet design objectives considering soil-ground improvement-structure interaction;
8. Design the size and arrangement of the ground improvement determining material requirements where necessary;
9. Determine quality control (QC) and quality assurance (QA) requirements.

Despite this document does not enter in the details of the analysis for each ground improvement technique, it certainly represents the most complete and up to date methodology for the design of ground improvement to mitigate liquefaction. The effectiveness of the ground improvement techniques is checked against quantitative acceptance criteria based on the performance requirements of the buildings, identifying in this way the relevant ground properties to be modified.

4. Ground improvement and liquefaction in Eurocodes

In the European Union, the topic of ground improvement is treated by two different types of standards:

- "Execution of Special Geotechnical Works" produced by Technical Committee CEN TC 288
- Geotechnical Design Eurocode 7 (EN 1997), drafted by Sub-Committee CEN TC250/SC7

The execution standards provide definitions and rules to contractors in order to obtain safe and reliable products. They define construction procedures including testing, control methods and required material properties. Execution standards are available for the following techniques:

- Grouting (EN12715)
- Deep Mixing (EN 14679)
- Ground Treatment by Deep Vibration (EN14731)
- Jet Grouting (EN 12716)
- Vertical drainage (EN 15237)

Indication on design is briefly recalled in the execution standards, but the topic is thoroughly covered by the codes for design EC7. Its current version contains a very brief chapter (5.5) on ground improvement and reinforcement and provides only generic principles. The need for a more extended and specific chapter on ground improvement has thus been recognized by the Sub-Committee CEN TC250/SC7 and a new version is foreseen in the revised geotechnical design Eurocode, expected in 2020. The debate on this new edition started in 2012, when the SC7 created a specific working group on Ground Improvement (Evolution Group EG14). This Evolution Group has issued its final report on December 2015, providing a draft of the forthcoming chapter on Ground Improvement to be developed by the Project Team who has now the responsibility of writing the new chapter on Ground Improvement Design.

The discussion on Ground Improvement Design Rules has been very lively from the beginning, and still is, starting from the definition of the term "Ground Improvement" and proceeding with the interaction between technological issues and design principles and/or methods. However, bearing in mind that the new code has yet to be written, it seems useful to report the main indication provided by the Evolution Group EG14 who has stated that the design of ground improvement can be undertaken by two possible methods (Figure 3):

a) Diffused Ground Improvement
b) Discrete Ground Improvement

Diffused Ground Improvement design is applicable when the behaviour of the improved ground can be modelled by conventional soil or rock models. In this case the designer should evaluate the change of ground properties (i.e. cohesion, friction angle, permeability, etc.) and consequently define "Improved Characteristic Values". Design rules for foundations, retaining structures, embankments, slopes etc. are then applied according to the relevant sections of the Eurocode. The Improved Characteristic Values may be evaluated using testing, empirical methods, comparable experience or analytical/numerical modelling. Discrete Ground Improvement design can be applied when ground improvement relies on inclusions, i.e. discrete elements created in the ground, physically disconnected from any structure, provided with prescribed geometry and mechanical properties. The overall performance of the improved ground is calculated by considering separately the characteristics of the inclusions and their interaction with the soil/rock. In such a case, design rules for foundations, retaining structures, embankments, slopes etc. are applied according to the relevant sections of the Eurocode. In the present version of Eurocode 7 (ENV 1997) it is generally stated that the "effectiveness of the ground improvement shall be checked against the acceptance criteria by determining the induced changes in the appropriate ground properties".

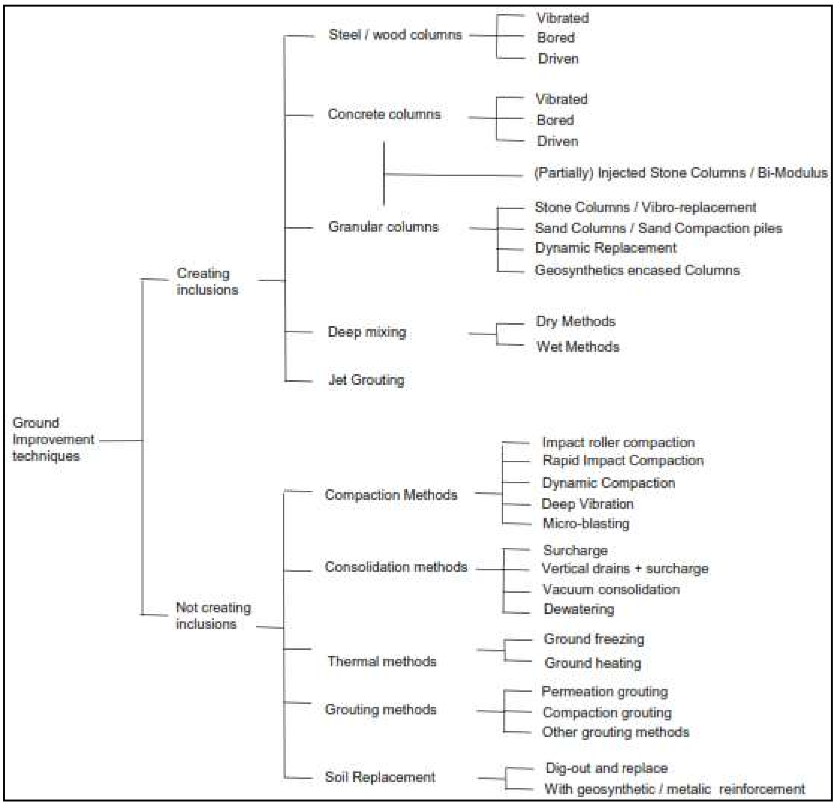

Figure 3. Ground improvement techniques defined by the evolution group EG14.

Although very general, this statement requires to implement a design method for structures likely to undergo ground improvement, to identify weak relevant properties of the soil to be modified by ground improvement, to fix acceptance criteria and appropriate experimental methodologies to assess the quality of execution and the performance of improved soil. While the performance requirements for foundations are generally defined in terms of ULS and SLS in section 6.2 of the Eurocode 7, the assessment of performance against liquefaction is only recalled for the SLS of spread foundations (section.6.6.4 Vibration analyses) and in the ULS of earth retaining structures (section 9.7).

Specific liquefaction analyses are dealt in section 4 (Requirements for siting and for foundation soils) and in Annex B (Empirical charts for simplified liquefaction analysis) of the Eurocode 8 part 5. Assessment is aimed at evaluating susceptibility of the considered subsoil and triggering caused by the earthquake. Susceptibility is defined considering the simultaneous existence of the following conditions:

- saturated sandy soils at depths greater than 15 m from ground surface, peak ground acceleration a_g higher than 0.15g and at least one of the following conditions:

- the sands have a clay content lower than 20% with plasticity index PI > 10;

- the sands have a silt content lower than 35% and a normalised SPT blow count value N1(60) < 20;

- sands are clean and have normalised SPT blow count value N1(60) < 30.

Once susceptibility is ensured, triggering is evaluated by comparing the cyclic stress ratio induced by earthquakes with the cyclic resistance ratio. The former is expressed by the following formula:

$$CSR = \frac{\tau}{\sigma'_{vo}} = 0.65 \cdot \frac{a_g}{g} \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \qquad (1)$$

where a_g is the peak ground acceleration evaluated considering the seismic hazard and local site conditions, σ_{vo} and σ'_{vo} are respectively the total and effective overburden pressure. The cyclic resistance ratio CRR is evaluated with empirical charts illustrating field correlation with different types of in situ measurements (Figure 4 shows an example extracted from the Annex B).

This assessment is carried out for depths lower than 20 m and the response is considered negative if CSR>0.8*CRR, i.e. assuming a safety coefficient equal to 1.25.

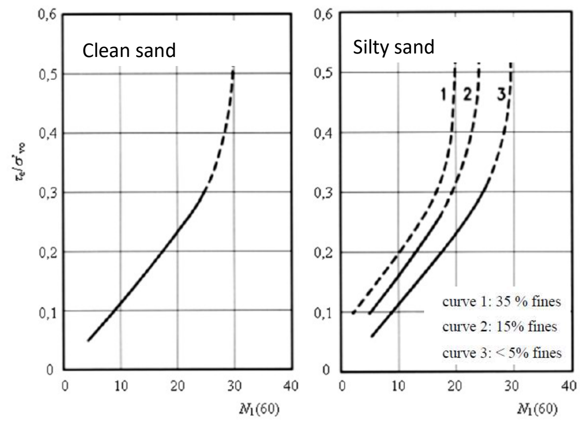

Figure 4. CRR as function of N1 (60) for MS=7,5 earthquakes (modified from EC8 part 5).

Then in chapter 4.1.4 (potentially liquefiable soils) it is stated that "if soils are found to be susceptible to liquefaction and the ensuing effects are deemed capable of affecting the load bearing capacity or the stability of the foundations, measures such as ground improvement and piling shall be taken to ensure foundation stability". It is also specified that "ground improvement against liquefaction should either compact the soil… or use drainage to reduce the excess pore-water pressure generated by ground shaking".

It is noted that the above criterion quantifies the triggering of liquefaction but does not consider extent and depth of the liquefiable layer that would certainly play a predominant role on determining different effects at the ground level and on the upper structures. Additionally, general requirements are given for ground improvement without referring them to the performance of structures.

For this and other limitations, EC8 is undergoing a thorough revision, as all the design Eurocodes are, and it is hoped that some specific guidelines on the use of ground improvement against liquefaction will be incorporated in the revised edition.

5. Acknowledgement

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