A Review on Soil Liquefaction Mitigation Techniques and its Preliminary Selection

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Abstract. Soil liquefaction is a phenomenon where a saturated cohesion-less soil substantially losses its strength as a result of reduction in effective stress and/or increase in the pore water pressure due to sudden change in stress condition, causing soil to behave like a liquid. Liquefaction may cause detrimental effects on infrastructures, loss of life and lifeline systems, which was historically observed in numerous earthquakes with major manifestations in 1964 Niigata, Japan, 1964 Alaska and recently in 2001 Bhuj, India earthquake. In order to mitigate liquefaction effectively, knowledge about prevailing site conditions, subsurface stratification, project constraints, ground water table fluctuation, details of past seismic events etc. and thorough technical knowledge of various liquefaction mitigation techniques is required. This article provides a concise summarization of various soil liquefaction mitigation techniques in current state of practice. Based on the mechanism of soil improvement methods were categorized as (a) hydraulic modification, (b) soil structure densification and (c) reinforcement of soil. Finally, each of the listed methods were evaluated by generating a feasibility index through rated score analysis. This ratings were established on the basis of available literature while considering equal weightages to technology selection parameters. It is intended that the calculated feasibility index will serve geotechnical professionals by eliminating least feasible methods for given site conditions during initial stage of project.

Keywords: Soil Liquefaction; preliminary selection; Feasibility Index

1 Introduction

Soil liquefaction involves loss of strength and stiffness of saturated cohesion-less soils during dynamic loading or sudden change in soil's initial stress condition. Conceptually it can be elucidated from fact that development of pore water pressure reduces effective stress, thereby decreasing shear strength of such soil. Soils having particle size in range of 0.002 to 2.36 mm (silt and sands) are found to be susceptible to this hazard [27]. The devastating effects of soil liquefaction on infrastructure are quite apparent from long prevailing history, i.e. Alaska and Nigata earthquake (1964), El Sentro earthquake (1979), Kobe (1995), to recent ones in Kocaeli (1999) and Bhuj (2001). The manifestations of above natural hazards were observed in manner such as settlement or tilting of building rested on liquefiable soil, rupture and cracking at joints of buried utilities, lateral spreading of slopes and tilting of quay walls. Studies were done to examine liquefaction susceptibility and characteristics of potentially liquefiable soils. In the past simplified procedures and vivid criteria were developed for tests focused at evaluating liquefaction resistance [31]. Researches have analyzed field liquefaction observations from past major earthquake of century to obtain more detailed insights on soil liquefaction [11; 12]. Mitigation of soil liquefaction in an effective way which shall minimize costly repercussions and damages caused by it, is currently sought by researchers and geotechnical professionals.

2 Mitigation of Soil Liquefaction

It is important to identify critical soil properties which directly affects the soil performance in an event of liquefaction. In an elementary study, this properties were found to be drainage characteristics, state of packing and reinforcement compatibility of soil [25; 12]. Several methods and techniques have been developed to improve these properties of soil, few of them are listed as below (see Table 1).

Table 1. Classification of soil liquefaction mitigation techniques

	Mechanism of Improvement		
	Improvement of Drainage Characteristics	**Densification of Soil Structure**	**Reinforcement of Soil Structure**
Techniques	Induced Partial de-saturation [14]	Vibro-compaction [17]	Permeation grouting [9]
	Earthquake PVDs [21]	Vibro-replacement [23]	Deep soil mixing [24]
	Electro-Osmotic Consolidation [10]	Dynamic compaction [16]	Jet Grouting [15]
		Compaction Grouting [3]	Passive Site remediation [7]
		Blasting Compaction [20]	Microbial Induced calcite precipitation [29]

Among this mentioned techniques, few are conventional while others are novel in nature. Geotechnical professionals are expected to select most appropriate ground improvement technology under prevalent site and project-specific conditions for ensuring adequate and cost effective treatment. In absence of such approach remediation may damage structure to an unacceptable state as well as cost high [20]. However, plenty of literature is already available, unraveling working mechanism and design considerations of this methods. But, they are not structurally organized to deliver exact information on feasibility of selecting concerned methods. Although, previous studies [2] have suggested a preliminary selection process of such techniques but, recent researches and developments in soil liquefaction mitigation technology have fetched us with more sustainable and novel methods which, otherwise were absent in foresaid selection process. Thus, in purview of unavailability of such updated selection model this article attempts to address the problem by detailing conventional as well as new methods on the basis of certain critical factors. Additionally a feasibility index is also generated which shall be elaborated in this paper.

3 Site and Project Constraints

The selection of most effective technique for a particular site needs a comprehensive understanding of pivotal factors like site and project specific constraints [2]. Constraints from site condition and geometrics may comprise of limitations imposed by site accessibility, depth of water table, soil type and depth of treatment. While economical aspect, time for remediation, environmental aspect, validation of remediation and ease of operation are included in project specific constraints. It must be noted that parameters like site accessibility, depth of water table, soil type, depth of treatment, environmental aspect, validation of remediation and ease of operation are qualitative in nature whereas economical aspect and time for remediation are quantitative in nature. Both of them are quantified and rated suitably as illustrated hereafter.

4 Quantification of Site and Project Constraints

Site and project constraints identified in previous sections were qualitatively assessed to screen out least appropriate methods [2]. However, in order to arrive at a measurable judgment for technique selection it is necessary to convert all qualitative parameters in a quantifiable sense, so that each technique can be valued comprehensively. Also, this approach may further seek to optimize each constraint to arrive at best method among given choice. To accomplish this a quantified rating score is proposed to be evaluated. This quantified rating is ultimately expected to furnish ‘Feasibility index (F.I.)’.

Initially to begin with, total response scored is calculated by summing up suitability of technique in terms of ‘True’ or ‘False’ for each governing criteria. As linguistic term ‘True’ and ‘False’ are denoted by ‘T’ & ‘F’ respectively and are assumed to fetch numeric value one and zero in succeeding rating analysis. This being divided by maximum possible score yields efficacy scored in percentage. After which conversion of efficacy scored into performance level and further into quantifiable rating is worked out by preset gradation as tabulated below (see Table 2).

Table 2. Gradation and rating scheme for qualitative parameters.

Efficacy Scored (E.S %)	Gradation	Performance Level	Quantified Rating
$\frac{\text{Total Response Score x 100}}{\text{Maximum Score}}$	E.S=0%	*Poor*	*
	0%< E.S ≤ 40%	*Below average*	**
	40% < E.S≤ 60%	*Average*	***
	60%< E.S<100%	*Good*	****
	E.S =100%	*Excellent*	*****

Soil liquefaction mitigation techniques under consideration for above analytic assessment are also tabulated with their respective abbreviation, which shall be used several times in article (see Table 3).

Table 3. Techniques considered for analysis with respective abbreviations.

Abbreviation	Techniques	Abbreviation	Techniques
IPS	Induced Partial Saturation	CG	Compaction Grouting
PVDs	Earthquake Pre-fabricated Vertical Drain	BC	Blasting Compaction
EOC	Electro-osmotic Consolidation	PG	Permeation Grouting
VC	Vibro-compaction	DSM	Deep soil mixing
VR	Vibro-replacement	JG	Jet Grouting
DC	Dynamic Compaction	R&R	Removal & Replacement
MICP	Microbial Induced calcite Precipitation	PSR	Passive Site Remediation

4.1 Quantifying 'Depth of Water Table' effect

Effect of depth of water table refers to suitability of a technique for existing and forecasted water table at that particular site. Fully or partially loose saturated soils generally located at shallow depth i.e. less than 15 m are most susceptible to liquefaction. The high depth of water table in such scenario can critically affect effectiveness of ground improvement technique employed. To ascertain foresaid effectiveness, suitability of considered techniques subjected to possible depths of water table are evaluated on the basis of empirical guidelines from literature by [26], [2], [28], etc. Further this are translated to corresponding quantified rating with methodology proposed in earlier sections.

Table 4. Evaluation of suitability to various depth(s) of water table

Techniques	**Suitability to depth(s) of water table**				**Efficacy Scored (%)**	**Performance Level**	**Quantified Rating (Q.R.^{1})**
	0 to 2m	**2 to 3m**	**3 to 6 m**	**6 to 12m**			
IPS	T	T	T	T	100	*Excellent*	*****
PVDs	T	T	T	T	100	*Excellent*	*****
EOC	T	T	T	T	100	*Excellent*	*****
VC	F	F	F	T	25	*Below average*	**
VR	T	T	T	T	100	*Excellent*	*****
DC	F	F	T	T	50	*Average*	***
CG	T	T	T	T	100	*Excellent*	*****
BC	T	T	T	T	100	*Excellent*	*****
PG	T	T	T	T	100	*Excellent*	*****
DSM	T	T	T	T	100	*Excellent*	*****
JG	T	T	T	T	100	*Excellent*	*****
R&R	F	F	T	T	50	*Average*	***
MICP	T	T	T	T	100	*Excellent*	*****
PSR	T	T	T	T	100	*Excellent*	*****

4.2 Quantifying Economic Consideration

Economical consideration reflects cost per cubic meter of using technique in field conditions excluding mobilization cost & labor charges, which may vary regionally The economical aspect plays a key role in selection of any soil improvement technique. It is always desirable to select remediation technique having least cost of treatment from available choices. To achieve same, the quantified rating for all considered techniques are directly extracted on the basis of devised scheme for cost levels (see Table 5). In proposed scheme of rating, the treatment cost per cubic meter are segregated on five cost levels, which are established from cost analysis referenced from [28]. It must also be noted that least treatment cost range is being attributed to excellent qualitative level as well as maximum corresponding rating. This is done to assure that techniques with least cost of treatment are rated as best.

Table 5. Devised scheme of rating techniques on economical aspect

Treatment cost per m^3 ($\$/m^3$)	Qualitative Level	Quantified Rating (4)
0 to 20	*Excellent*	*****
20 to 50	*Good*	****
50 to 100	*Average*	***
100 to 200	*Below average*	**
More than 200	*Poor*	*

In the proposed scheme, evaluation is done by entering response as ‘T’ i.e. true corresponding to that cost group and finally converted into corresponding quantified rating.

Table 6. Evaluation of quantified rating for cost of remediation

Techniques	Treatment cost per cu. meter ($\$/m^3$)					Performance Level	Quantified Rating (Q.R.[4])
	0 to 20	20 to 50	50 to 100	100 to 200	more than 200		
IPS	T					*Excellent*	*****
PVDs	T					*Excellent*	*****
EOC		T				*Good*	****
VC	T					*Excellent*	*****
VR		T				*Good*	****
DC	T					*Excellent*	*****
CG					T	*Poor*	*
BC			T			*Average*	***
PG					T	*Poor*	*
DSM				T		*Below average*	**
JG					T	*Poor*	*
R&R		T				*Good*	****
MICP	T					*Excellent*	*****
PSR				T		*Below average*	**

As far as quantification of remaining constraints is concerned instead of lump sum evaluation, they have been simply elaborated on respective governing premise required for consequent establishment of ratings (i.e. **Q.R**^{2}, **Q.R**^{3}, etc.)

4.3 Quantifying Suitability to Soil Type

Soil type relates compatibility of a technique with soil present at site. Amongst different soil types, slightly cohesive and loose cohesion-less soils which may be partially or fully saturated are mostly prone to liquefaction in seismic event. However, each liquefaction mitigation technique has its own suitable soil type where it functions effectively. The effectiveness of remedial technique corresponding to medium and highly liquefiable soil types i.e. (GM - Silty Gravel; SP - Poorly graded sand; SW-Well graded sand SM- silty sand; SC - clayey sand; ML - silt) [2] are ascertained on basis of literature sourced from [18; 17; 4; 12].

4.4 Quantifying Suitability to Depth of Treatment

Depth of treatment refers to practical applicability of a particular technique for given liquefiable layer of soil, where treatment has to be implemented. The overburden depth below which soil is likely to liquefy was roughly estimated to be around 25 m [31]. This provides limit to the possible depth of treatment and its further split into depths (0 to 3 m; 3 to 6 m; 6 to 12 m; 12 to 25 m; more than 25 m) where liquefaction is expected to occur. The techniques employed for liquefaction mitigation may express their working limitations for particular depths of treatment and henceforth their suitability is evaluated to screen out best among them. The background for such evaluation is attributed to work of [6; 22; 28].

4.5 Quantifying Time of Remediation

Time for remediation expresses amount of time required by a particular technique to remediate one cubic meter of soil. Time constraints are important from project execution point of view as it is seen that time directly relates to cost of project. It is always intended to select technique consuming lowest time to remediate any problematic construction activity. To achieve same for mitigation of soil liquefaction, the quantified rating for all considered techniques are directly extracted on the basis of devised scheme for time duration levels (see Table 7). In proposed scheme of rating, time required to remediate per cubic meter are split on five duration levels, this levels are setup from past empirical findings of [1; 7; 8; 28].

Table 7. Devised scheme of rating techniques for time of remediation

Time of remediation per m^3 (Days/m^3)	**Performance Level**	**Quantified Rating**
0 to 5	*Excellent*	*****
5 to 10	*Good*	****
10 to 20	*Average*	***
20 to 50	*Below average*	**
More than 50	*Poor*	*

It must also be noted that least treatment time range is being considered as excellent qualitative level and is followed same by corresponding quantified rating. This ensures that techniques with least duration of treatment are graded as best. In the proposed scheme, evaluation is done by entering response as ‘T’ i.e. true if technique furnishes that particular duration level, which is then finally reformed to corresponding quantified rating.

4.6 Quantifying Site Accessibility

Site accessibility includes dimensional freedom to work i.e. available headroom and planar space at site, as well as troubles caused by remote location and terrain profile of working site. Site accessibility factor is generally an intuitively important issue in construction industry. This cannot be ignored considering mitigation of soil liquefaction is bound to face variety of construction constraints [19]. The selection of particular technique for given liquefiable soil is effectively aided if we evaluate its suitability to anticipated site accessibility factors. To accomplish this each technique is analyzed in terms of suitability with respect to site accessibility constraints defined as Low Headroom ; clearances; Low working planar space; Near-by Infrastructure Lifelines; All ground Profiles; Remote location of Site.

4.7 Quantifying Suitability to Environmental Considerations

Environmental impact represents effect of using particular technique, to nearby environment in terms of sustainability i.e., disturbance to nearby structures, lifelines, health of concerned manpower employed, effect on ecosystem involved etc. The environmental concern of selecting certain mitigation technique cannot be disregarded in era of sustainable development. Each method may have their own environmental impact [13], which is proposed to be assessed by calculating suitability to environment on five identified parameters. Agreement to these parameters such as No Disturbance to nearby Structure; No Disruption of Ecosystem; No waste/spoils generation; Promotes Sustainability is recorded as True and False as mentioned earlier. The technique selection considering environmental valuation is surely expected to inspire confidence in governmental agencies, non-profit organizations and environmental regulatory etc. clientele.

4.8 Quantifying Suitability to Ease of Operation , Validation of Remediation

Ease of operation is defined as ease with which technique can be actually used in the field considering skills and expertise of manpower employed as well as technological limitations in remediation of geotechnical problem. Validation of remediation reflects add-on facilitation to supervising authority (Quality Assurance personnel) for maintaining quality control by sampling and real-time monitoring of ongoing remediation process. Specifically this can be ascertained by evaluating suitability of technique in regard to No Specialized Manpower requirement; No Advanced Technological Requirement; Supports Sampling & Quality Control; Real-Time Monitoring in terms of true and false. However evaluation on such parameters must be backed up by extensive case studies, which was available for routine methods from [28].

5 Formation of Decision Matrix

After performing explicit quantification of all sites and project constraints, a decision matrix for all considered techniques is formed. Concept of weighted rating was added to the decision matrix to obtain feasibility index. The feasibility index so calculated, attempts to summarize efficacy of applying any particular technique in possible liquefaction mitigation scenario and helps to zero down to most appropriate technique. Higher value of feasibility index suggests more suitable technique. This feasibility index is based on weightage schemes (see Table 8) devised to cover various levels of expectations from technique selection authority. The levels of expectations mentioned below, query selector how important is that technology selection parameter in selection process and are weighed accordingly.

Table 8. Proposed scheme of weights for levels of expectation & Feasibility Index

Levels of Expectation	Weightage	Feasibility Index
Extremely Important	1	$\dfrac{\mathbf{Q.R^1 \times Weightage^1 + \ldots\ldots + Q.\ R^n \times Weightage^n}}{\mathbf{n}}$
Highly Important	0.8	
Moderately Important	0.6	
Less Important	0.4	(Note: ‘n’ express expandable nature of index which is meant for inclusion of more parameters in future, for current study ‘n’ is limited to 8)
Not Important	0.2	

6 Case Study

To demonstrate effectiveness of proposed evaluation, a case study has been incorporated from literature [2]. The problem is defined as follows:

- **Location** : Liquefied natural gas plant in Delta, British Columbia, Canada
- **Type of Structure** : Shallow reinforced concrete raft foundation
- **Performance Objective**: To densify the foundation soil and to minimize the liquefaction induced settlement in soils below the foundation.
- **Depth of liquefiable layer** : 22 m
- **Depth of water table** : 1 to 2 m below G.L
- **Area to be remediated** : 12 x 12 m^2 in foot print of Foundation
- **Project Constraints**: (I) 2 m of headroom clearance available for construction, (II) potential damage to the existing settlement sensitive utilities near construction site (III) an accelerated construction schedule, (IV) adjacent existing utilities that are sensitive to ground movement and disturbance.

During analysis, either equal weightage can be assigned to each critical parameter or moderated as per project requirements (see table 8). After extraction of corresponding weightages (see table 9) they are fed into decision matrix to evaluate feasibility index of techniques under consideration for that particular site (see table 10).

Table 9. Extracted weightages from problem definition

Selection Parameter	**Level of Expectation**	**Weighs**
Depth of Water table - ***Q.R***$^{(1)}$	Extremely Important	1
Soil type - ***Q.R***$^{(2)}$	Moderately Important	0.6
Depth of Treatment - ***Q.R***$^{(3)}$	Extremely Important	1
Economic consideration -***Q.R***$^{(4)}$	Highly Important	0.8
Time of remediation - ***Q.R***$^{(5)}$	Extremely Important	1
Site Accessibility - ***Q.R***$^{(6)}$	Extremely Important	1
Environmental aspect - ***Q.R***$^{(7)}$	Extremely Important	1
Ease of operation & Performance Validation **-** ***Q.R***$^{(8)}$	Moderately Important	0.6

Table 10. Summarization of rated analysis and evaluation of feasibility Index

Quantified Performance Rating	**Decision Matrix for Soil Liquefaction Mitigation Techniques**													
	IPS	**PVDs**	**EOC**	**VC**	**VR**	**DC**	**CG**	**BC**	**PG**	**DSM**	**JG**	**R&R**	**MICP**	**PSR**
Q.R$^{(1)}$	*5*	*5*	*5*	*2*	*5*	*3*	*5*	*5*	*5*	*5*	*5*	*3*	*5*	*5*
Weigh	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Q.R$^{(2)}$	*5*	*5*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*4*	*5*	*5*
Weigh	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
Q.R$^{(3)}$	*4*	*4*	*2*	*4*	*5*	*4*	*4*	*3*	*5*	*4*	*5*	*2*	*5*	*5*
Weigh	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Q.R$^{(4)}$	*5*	*5*	*4*	*5*	*4*	*5*	*1*	*3*	*1*	*2*	*1*	*4*	*5*	*2*
Weigh	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8
Q.R$^{(5)}$	*5*	*1*	*2*	*3*	*5*	*1*	*1*	*5*	*4*	*4*	*3*	*5*	*5*	*1*
Weigh	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Q.R$^{(6)}$	*4*	*2*	*4*	*2*	*2*	*2*	*4*	*2*	*4*	*2*	*4*	*2*	*5*	*2*
Weigh	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Q.R$^{(7)}$	*5*	*5*	*4*	*2*	*1*	*2*	*4*	*1*	*4*	*4*	*3*	*1*	*2*	*5*
Weigh	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Q.R$^{(8)}$	*2*	*4*	*3*	*5*	*4*	*5*	*4*	*2*	*4*	*3*	*3*	*5*	*3*	*4*
Weigh	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6
Feasibility Index	**3.9**	**3.3**	**3.05**	**2.8**	**3.25**	**2.675**	**2.95**	**2.75**	**3.45**	**3.1**	**3.125**	**2.7**	**3.85**	**3.125**

7 Concluding Remarks

It can be observed from the decision matrix that IPS, MICP and PG can be prioritized as recommended technique for site remediation. Authors of the said literature [2] recommended permeation grouting (PG) technique for the above mentioned site conditions. However, it should be noted that IPS and MICP are very novel techniques still under research and field scale application is still underway. Hence, it can be concluded that the proposed evaluation approach can be applied at site by judicious weighing of critical parameters before finalizing a particular technique. The proposed selection method can be sought as preliminary guidance to geotechnical professionals and researchers for screening out least appropriate technique for mitigation of soil liquefaction. However, a more rigorous approach is recommended to further optimize the selection process.

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