Ground Improvement Techniques for Mitigation of Liquefaction Hazards

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ABSTRACT

Generally areas having predominantly sandy deposit with low strength values and high water table condition are prone to liquefaction causing serious threat to safety of structures during earthquakes. The case study presented in this paper relates to a power plant project site in North India where sandy slit in submerged condition with low ‘N’ values is encountered upto depths around 10m. This paper discusses on the susceptibility of soil for liquefaction, selection of appropriate ground improvement technique for mitigation of potential liquefaction hazard and confirmatory field tests conducted post ground improvement to check whether desired degree of ground improvement has been achieved.

1 INTRODUCTION

Liquefaction is defined as the transformation of granular material from a solid to a liquefied state as a consequence of increased pore-water pressure and reduced effective stress due to dynamic loading. During an earthquake the application of cyclic shear stresses induced by the propagation of shear waves causes the loose sand to contract resulting in pore water pressure. The increase in pore water pressure causes an upward flow of water to ground surface in the form of mud sprouts or sand boils. The development of high pore water pressures due to ground shaking and the upward flow of water may turn the sand into an liquefied condition which has been termed as “Liquefaction”. For this state of liquefaction the effective stress is zero and the individual soil particles are released from any confinement as if the soil particles were floating in water.

The impact of liquefaction to structures, utilities and transportation systems are detrimental if suitable risk mitigation measures are not adopted. Several methods that minimize liquefaction effects on structures include: additional ductility to accommodate larger deformations; adjustable supports to allow greater differential settlements; use of end bearing piles or caissons with high lateral capacities; stiffer foundations to span “soft spots”; and tying independent footings together with grade beams.

In-situ ground improvements can also improve performance during cyclic loading, reducing the risk of liquefaction and ground displacement. The ground improvement can be achieved by densification, solidification, dewatering, drainage or sand reinforcement. The implementation of these techniques may result in fully, or partially, eliminating the liquefaction potential, depending on the forces likely to be experienced and amount of deformation that the structure can tolerate. The selection of most appropriate method for a particular purpose will depend on many factors including type of soil, level of improvement needed, the magnitude of improvement attainable by a particular method, required depth and extent of area to be covered. Soil densification is generally considered highly reliable, and the most standard cost effective remedial measure against liquefaction.

The most commonly used ground improvement technique that result in densification are vibro compaction, vibro replacement, dynamic compaction and sand compaction pile. Vibro-compaction provides an economical and effective method to densify deep granular non-cohesives deposits. In vibro-compaction, a vibrating probe (or vibroflot) is repeatedly raised and lowered through the soil, inducing local temporary liquefaction. During liquefaction, the inter-granular particle forces become zero, and gravitational forces rearrange the soil particles into a denser unstrained state, permanently strengthening the soil. During the state of temporary liquefaction, material is fed and compacted into the voids created by the liquefaction, creating densified sand columns. Re-liquefaction of the soil can only occur if subsequent dynamic loading is more
intense than the vibrations induced by the vibro compaction process.

A brief overview of vibro compaction technique is presented before presenting a case study from a recent projection experience.

2. OVERVIEW OF THE VIBRO COMPACTION TECHNIQUE

The essential equipment for this process is a depth vibrator - a long, heavy tube enclosing eccentric weights, driven by an electric motor. The vibrator is connected to a source of electric power and a high-pressure water pump. Extension tubes are added as necessary, depending on the treatment depth, and the whole assemblage is suspended from a crane. With the electric power and water supply switched on, the vibrator is lowered into the ground. The combination of vibration and high-pressure water jetting causes liquefaction of the soils surrounding the vibrator, which assists in the penetration process.

When the required depth is reached, the water pressure is reduced and the vibrator pulled up in short steps. With the inter-particle friction temporarily reduced, the surrounding soil particles then fall back below the vibrator and, subjected to vibratory energy, are rearranged into a denser state. This process is repeated back up to the ground level, leaving on completion, a column of very dense material surrounded by material of enhanced density. The degree of compaction achieved at a particular point depends on the properties of the soil being treated, the amount of time spent at each compaction step and the distance from the vibrator. The spacing of probes is designed to ensure that the zones of influence overlap sufficiently to achieve minimum requirements throughout the treated area. Generally, the effect of the compaction becomes visible at the ground surface in the form of a cone-shaped depression. The depression formed around the vibrator or the extension tubes is continually in-filled with granular materials, which is either imported or obtained from the natural granular deposits at the site. Water required for the penetration and compaction process is obtained either by direct pumping from nearby water source or ground water using well points.

Vibro compaction is suitable for treating sands with a fines content of less than 10 to 15%. Based on various research work carried out, well established guidelines are available to evaluate where vibro techniques could work successfully. It is generally accepted that the Vibro replacement works successfully for grain size range from 0.002 to 0.2mm, whereas vibro compaction could be more appropriate for the grain sizes in the range of 0.2 to 60mm.

3. CASE STUDY FROM A RECENT PROJECT

The site under consideration is for a proposed power plant, in North India where predominantly sandy silt in loose to medium condition was encountered. The Groundwater was encountered at shallower depths of around 1-2m depth below EGL. The borelogs (Fig. 1) can be referred, which shows that the in-situ soil consist of sandy silt / silty sand in the top 1m below the EGL. This was followed by poorly graded fine sands having fines content between 1% and 6% to the final explored depth of around 30m. According to Figure 1 and Annexure E of IS 1893 (Part 1)-2002 which shows the seismic zones and zone factors of important towns, the proposed site falls under Zone –IV having zone factor as 0.24.

Fig. 1: Summary of Borehole Profile Before Ground Improvement

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty fine sand</td>
<td>SM</td>
</tr>
<tr>
<td>Fine sand (SP)</td>
<td>SM</td>
</tr>
<tr>
<td>Sand (SP)</td>
<td>SM</td>
</tr>
<tr>
<td>Silt (CL)</td>
<td>ML</td>
</tr>
<tr>
<td>Clays (MH)</td>
<td>ML</td>
</tr>
<tr>
<td>Water table</td>
<td></td>
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</tbody>
</table>

The primary relevant soil properties for finding the liquefaction susceptibility of soil include grain size, fines content (i.e. amount of silt and/or clay), density, degree of saturation, and age of the deposit. The following indices can be used as a general guide for assessing the liquefiable soils.

- Mean size, $D_{50} = 0.02$ to 1.0 mm
- Fines ($d \leq 0.005$ mm) content < 10%
- Uniformity coefficient ($D_{60}/D_{10}$) < 10
- Relative density $D_r < 75$
- Plasticity index PI < 10

When the above parameters were arrived for the present soil conditions, it clearly indicated the soil at the considered project site was susceptible for liquefaction. Also as per IS:1893 (Part-1):2002, Table 1; liquefaction is likely in fine sands below water table with corrected SPT values less than 15 (for Seismic
Zone Levels III, IV and V). From the above consideration, it can be concluded that soil under consideration is susceptible for liquefaction. However, the depth up to which it is susceptible for liquefaction, generally termed as ‘liquefaction depth’, needed to be ascertained. The Liquefaction assessment as per IS:1893 (Part-1):2002 was carried out for above sub soil profile. According to that, there could be potential for liquefaction of the soils at the site to about 13.0 m depth. The IS Code (Section 6.3.5.2) suggests that specialist literature be referred to for determining the liquefaction susceptibility of a site.

For a better evaluation of the liquefaction potential at the site, a detailed analysis has been done as per standard procedures given in published literature; such as the methodology based on the simplified procedure developed by Seed and Idriss, as described in the NCEER Summary Report (2001) (4). Based on the above literature, detailed liquefaction susceptibility analysis was carried out considering SPT, SCPT and CHST results of the site. It was recommended that an overall depth of liquefaction of about 10.0 m below EGL.

Ground improvement was recommended to be carried out at the site to reduce the liquefaction susceptibility of the ground and thereby improving the bearing capacity of the ground and densifying the strata. The sub soil profile at site shows predominantly poorly graded fine sand, grain size distribution of the soil indicates average size of the particles as 0.2 to 0.5mm and the fines content of the soil was less than 15%. Considering the various aspects stated above, it was concluded that vibro compaction technique to be the appropriate choice of ground improvement.

4. SUGGESTED VIBRO COMPACTION SCHEME

It is understood from various literatures that the loose sand deposits needs to be densified to achieve a relative density of 70% to cater the above stated project requirements. It was recommended to extend the ground improvement beyond lateral area corresponding to an angle of 30 deg against the vertical axis from the foundation periphery. This was required as the pore water pressures are transmitted from the liquefied area into the improved area of the ground. Vibro Compaction for the purpose was proposed to an average depth of 10m below existing ground level. Spacing of 3m x 3m was adopted which was predetermined based on the field trials on different spacing. The improvement was proposed to be verified using pre and post Cone Penetration Tests (CPTs). The results were analyzed using Schmertmann’s correlation between Relative Density (Rd, %) and Cone Penetration Resistance (Qc, Mpa) and achieving of 70% relative density is to be confirmed for post compaction test results.

5. PRE CONE PENETRATION TEST RESULTS

2 pre CPTs (Pre CPT 1 & 2) were performed at the trial location. The CPT test results were consistent with the stratigraphy observed in the bore holes, which indicate the soils to be sandy silt / silty sand with Qc values ranging between 2 MPa and 4 MPa to about 1m depth. This was followed by loose to medium dense Fine Sands with Qc values ranging between 2 MPa and 10 MPa to about 10m depth. The pre CPT results can be seen in Figure 2. The Qc values obtained by pre CPT results were plotted and Qc values corresponding to 70% and 80 % relative density (using Schmertmann’s correlations) were also superimposed. It can be observed that the pre compaction Qc values correspond to a Relative Density (Rd) of 30% to 60% (excluding some high values) and generally are below the Qc values corresponding to 70% and 80 % relative density.

6. EXECUTION OF VIBRO COMPACTION WORKS

Vibro Compaction works were carried out up to a depth of 10m in 3m grid spacings for each area. The crater formed during vibro compaction was filled using the sand-available material at site (Fig. 3). For the present area, the consumption of backfill material (sand) was 10 to 14%, which clearly indicates that significant densification has taken place. Also the ground level in compacted area went below by 1m clearly showing the achieving of ground improvement.
7. POST CONE PENETRATION TEST RESULTS
After 7 days from the completion of vibro compaction at Pre CPT-1 & 2, post CPT tests i.e., Post CPT-1 & 2 were conducted at the Pre CPT locations respectively. The post CPT results are illustrated in Figure 4. The results indicate that the post compaction cone tip resistance (Qc) values improved to 7MPa to 18MPa in the top 10m. The Qc values obtained by post CPT results corresponding to various depths are plotted.

The results have been analyzed using Schmertmann’s correlation between Relative Density (Rd, %) and Cone Penetration Resistance (Qc, Mpa). The post compaction Relative Density (Rd) has been estimated to be more than 70%, which satisfies the project requirements.

![Fig. 4: Cone Penetration Resistance Vs Depth from Post CPT Tests](image)

8. RECONFIRMATION BY SPT TESTS
Various standard approaches like Schmertmann’s, Robertson and Campanella are available for qc-Rd correlation. But different correlations yield different results and will not converge to a single relative density value. Hence it was decided to reconfirm the achieved ground improvement by carrying out boreholes in the improved ground. The SPT tests were proposed to be carried out in these boreholes and it was suggested to check with the earlier SPT values obtained in the boreholes in the respective areas. The attached Figure 5 shows the sub soil profile with ‘N’ values in the improved ground. Comparing these profiles with the ‘N’ values obtained in unimproved ground, it can be concluded that the ‘N’ values have remarkably improved and desired ground improvement has been achieved.

9. NOTATIONS
Qc – Cone resistance
N – Standard Penetration resistance
Rd – Relative density
SPT – Standard Penetration Test
SCPT – Static Cone Penetration Test
CHST – Cross Hole seismic Test
EGL – Existing Ground Level

CONCLUSIONS
The susceptibility of liquefaction hazard for a given site to be clearly established based on the standard approaches.

Prior to determining a course of action for the remediation of liquefiable soils, it is important to arrive at the exact depth upto which the soil is susceptible for liquefaction.

Vibro compaction is a suitable compaction technique to mitigate the liquefaction potential and can be successfully implemented. The target Relative Density of 70% was achieved using a grid spacing of 3m c/c in square pattern for the project under consideration.

In-situ field tests should be performed both prior to and following implementation of the remediation methods to measure the degree of improvement that has been obtained.

REFERENCES
Barbara S Moffat and Bellevue W A . Soil Remediation Techniques for Reduction of Earthquake Induced Liquefaction.