A Review on Soil Improvement Techniques to Mitigate Liquefaction

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ABSTRACT:
Liquefaction of soil results when there is hardly any shear strength left in the soil to resist the shear stresses induced when subjected to dynamic loading such as during an earthquake. A proper evaluation of liquefaction vulnerability of a place is of utmost importance before any construction in that particular place to avoid any disaster in the near future. It is therefore necessary to take aid of various soil improvement techniques to resist liquefaction as a part of pre-disaster management to the maximum extent possible. The present study thus purports to review the various soil improvement techniques in a single documentation that can be effectively applied depending upon the site-soil conditions in order to mitigate liquefaction.

Keywords: Earthquake, Soil Liquefaction, Liquefaction Mitigation Techniques

1. INTRODUCTION: LIQUEFACTION

Liquefaction is a phenomenon which is mostly observed in loose, saturated and cohesionless soils when subjected to dynamic forces such as during an earthquake. Liquefaction of soil occurs when shear stress required for equilibrium of a soil mass is greater than the shear strength of the soil in its liquefied state. Soil Liquefaction is associated with pore pressure build-up, which in turn reduces the effective stress and thus decreases the shearing resistance of soil.

The destructive effects due to liquefaction can be remembered from the devastation brought by Good Friday earthquake (M_w = 9.2) in Alaska and Niigata earthquake (M_S = 7.5) in Japan both in the year 1964. Beside, recent earthquakes such as Kobe (1995), Kocaeli (1999), Chi-chi (1999) and Bhuj (2001), the liquefaction were a major cause of damage to civil engineering structures. So a proper study of liquefaction potential of a place has become very important so that such disastrous after-shock effect can be minimized.

2. SOIL IMPROVEMENT TECHNIQUES AGAINST LIQUEFACTION

There are numerous soil improvement techniques that can be applied to mitigate liquefaction of soil which acts as a necessary pre-disaster management technique. With the passage of time more advancement were seen in this particular field and many new soil improvement techniques to check liquefaction has evolved, tried and found effective. The employment of a particular technique depends mainly on type of soil, cost of improvement, feasibility of application of the technique, etc to name a few. The mechanism behind most of these soil improvement techniques are mainly densification, drainage, reinforcement and confinement. The various soil improvement techniques that can be applied to mitigate liquefaction are reviewed below –

1. **Vibratory Methods –** It mainly works based on the principle of densification of the soil mass due to induced vibration on the soil mass along with drainage, reinforcement and confinement to varying extent. There are mainly three vibratory methods. They are –

   i. **Sand Compaction Piles -** This method is generally applied for depths of 3 to 15 m. it uses clean sand as backfill material. Sand Compaction Piles can be completed with or without water jets (i.e. wet or dry method). The use of water jets aid penetration and reduce inter-granular forces, thereby encouraging compaction (Dobson and Slocombe 1982). This method is best suitable for clean granular soils. One drawback is that it seems to be costly if this method is applied for a deep single liquefiable layer as improvement must be carried out for entire depth of insertion. The degree of compaction that Sand Compaction Piles are capable of is highly dependent on; vibrator type and size, penetration spacing, soil type, and compaction procedures.

   ii. **Stone Columns –** Stone Columns or Granular Piles is one of the most effective soil improvement techniques to mitigate soil liquefaction. It uses crushed gravel for the backfill material. Stone Columns improve the ground by compaction of the soil adjacent to it, reinforcing and permit rapid dissipation of earthquake induced pore pressure development by virtue of their high permeability. An additional advantage of using granular piles is that they tend to dilate as they get sheared during an earthquake providing better anchorage. But it also suffers with the same drawback as that of sand compaction piles.

   iii. **Vibro-Concrete Columns –** Here instead of sand and stone, concrete is used. In this method by the help of the vibrator, the concrete is forced into the soil to be treated. After the vibrator is withdrawn concrete is pumped into the void space producing a concrete column. It helps to transfer load to deeper underlying suitable strata and at the same time compacts the surrounding soil layer.

2. **Deep Dynamic Compaction** – In this method heavy weight (9,000 – 27,000 kg) is allowed to fall repeatedly from a height of about 15-40 m in order to densify the soil mass for cohesionless soils. It is an economic site improvement technique to resist liquefaction which can be used to treat a range of porous soil types. It is effective upto a depth of about 10 m under ideal conditions when a 'working mat' of dry granular soil is used on the surface (Hayden and Baez 1994). This method is not recommendable for a depth greater than 10 m or to improve the soil condition under already existing structures. It will be mainly useful for the improvement of soil conditions of cohesionless deposits before any construction. It results in minimizing the void spaces and in the process dissipates the pore pressure beforehand increasing the effective stress over the liquefiable layer.

3. **Compaction Grouting –** Compaction Grouting is mainly a densification technique for loose soils (Moseley and Kirsch 2004). In this method a grout rod is drilled to the maximum depth of improvement, then a slow slump grout is injected under pressure and the development of a growth bulb slowly densify the soil. The grout rod is then gradually moved up and the above process is repeated until the entire target layer is treated. Compaction Grouting is not applicable for a depth less than 6 m due to lack of confining pressure. The technique is ideal for remediating or preventing structural settlements and for site improvement of loose soil strata. This method is cost effective and efficient for soils containing deep isolated liquefiable layers as the grout can be injected at the target layers without having to treat the entire soil column (Idriss and Boulanger 2008). The cost of this technique is dependent on the depth and spacing needed to achieve the required

densification. Besides, during the grouting operation the structure may remain occupied and in-service causing minimal disturbances. Also compaction grouting offers minimal risk of catastrophic failure while re-leveling structures or remediating sinkhole conditions. But one of its important disadvantages is mainly damage to underground utilities such as pipelines, vaults, etc.

4. **Permeation Grouting –** This method is also known as chemical grouting. In this method materials are injected into the pore spaces of a loose soil, thereby cementing the particles together by combination of cohesive and adhesive forces and in the process filling the void spaces (Idriss and Boulanger 2008). Grouting materials can consist of wide range of substances from chemical grouts to micro-fine cement with admixtures. The grouting material is forced into the soil under pressure and permeates out radially into the pore spaces of the soil. This method is useful when the disturbance of the in-situ soil is not at all desirable (Thevanayagam and Jia 2003).

5. **Jet Grouting –** This method uses the mechanism of replacement and/or confinement to mitigate liquefaction. A drill rod, with high pressure port/ports, is advanced to maximum depth of improvement. Then high velocity jets of air, water and grout first erodes and then mixes the soil as the drill rod is rotated and lifted. The result is a soil-crete column through the entire target layer. Jet Grouting can be used to make in-ground shear walls by overlapping columns, or as an underpinning technique. In order to mitigate liquefaction overlapping shear walls can be employed through this technique in a pattern to confine the soil or to improve entire blocks of liquefiable material within a target layer. Different Jet Grouting techniques are available which can be applied depending upon the site-specific soil conditions and project requirements, such as single, double and triple fluid systems, as well as Super Jet and X-Jet grouting arrangements (Burke 2004).

6. **Deep Soil Mixing –** It consists of an auger, or row of overlapping augers, being rotated to the target depth, which is followed by pumping of cement through the tip of the augers, while the augers being rotated and lifted. This causes the cement and soil to mix, producing a soil-crete column or row of columns (Idriss and Boulanger 2008). The columns can be arranged into many different patterns which are dependent on the extent of reinforcement necessary. Deep Soil Mixing is applicable for depth of over 30 m and can be used with fine grained material.

7. **Deep Blasting –** It is a method of densification that uses explosive charges to destroy the existing soil structure and rearrange particles in a more compact state (Narin van Court and Mitchell 1995). The use of blasting was used to densify soils to depths of 40 m as documented by Solymar (1984). Successful densification must be confirmed with post-blasting in-situ testing and surveys to confirm settlements. The effectiveness of blasting could be an issue at shallow depth or for sands with fine content greater than 15-20% (Idriss and Boulanger 2008).

8. **Earthquake Drains** – Earthquake Drains have been used to provide drainage of excess pore water pressure and to reduce total settlements in liquefied soil layers (Chang et al. 2004). It generally consists of 75-100 diameter corrugated pipe with open slots, covered with filter fabric. The open slots help to dissipate excess pore water pressure while the filter fabric prevents the fines from entering and clogging the slots. The drains can be installed using casing and conventional drilling techniques, or a modified vibrating mandrel (Chang et al. 2004). Generally Earthquake Drains can be installed upto depths of about 25 m. The effectiveness of a drainage system depends on the soil characteristics

(cyclic resistance, compressibility, hydraulic conductivity and layer thickness); the characteristics of earthquake shaking (intensity and duration of shaking); and the drain characteristics (radius, spacing, and hydraulic resistance).

9. **Dewatering –** This method is also based on the principle of drainage. Liquefaction can be avoided to an extent if pore pressure build-up can be checked and this is achieved through this method by dewatering i.e. nothing but draining out of water. The use of this technique is very expensive as continuous pumping is necessary and at the same time it is also difficult to maintain the pump in a working condition for a long period of time. Gillette and Bliss (1997) concluded that this alternative was unsuitable for a permanent solution because of the high cost of operation and the possibility of perched water above the target drawdown elevation. Besides this method will also fail in mitigating liquefaction when permanent and continuous recharge condition exists.

10. **Removal and Replacement –** It is the most direct method of soil improvement against liquefaction i.e. to remove the liquefiable soil and replace it as a compacted fill. This method is one of the most reliable of all the methods which can be applied to mitigate soil liquefaction. But unfortunately, this method is often too expensive except at shallow depths (Idriss and Boulanger 2008). This method becomes inapplicable and difficult if the water table lies at shallow depth.

11. **Grand Flex Mole Technology -** It is a newly developed chemical grouting technique developed in Japan by H. Ishii et al. (2012). It can provide necessary reinforcement to the soil more efficiently and easily beneath an already existing structure without the requirement of additional vertical shafts like that of normal chemical grouting technique. This particular advantage of this method makes it most applicable to mitigate liquefaction in an already developed region with lack of forehand application of soil improvement techniques. It has also proved to be cost-effective for depths greater than 3m than conventional permeation grouting.

12. **Induced Partial Saturation –** It is a new liquefaction mitigation measure (Bayat et al. 2009) which will be cost-effective and practical solution for new as well as existing structures. It improves earthquake induced liquefaction resistance of loose sands by introducing some amount of air or gas in the voids of the sand. Two different methods explored to introduce air or gas; one is through generation of hydrogen and oxygen gases in the sand through electrolysis and the other through air entrapment in the voids by draining and reintroducing water in the fully saturated sand. Uniform cyclic simple shear tests performed, using a shaking table, on air or gas entrapped specimens demonstrated that its presence reduces the pore pressure build-up significantly, thus preventing liquefaction of soil.

Lastly, a summary of the advantages and disadvantages of the above methods along with the principle of working behind them is given in Table 1.

Table 1 Summary of advantage and disadvantage of some methods

Method	Advantage	Drawback	Principle
Vibratory Methods	Stone columns tend to dilate as they get sheared during an earthquake providing better anchorage	Costly if a deep single liquefiable layer need to be treated	Densification
Deep Dynamic	Economic site improvement	Existing structures acts as a	Densification

Compaction	technique for a range of porous soil types	hindrance	
Permeation Grouting, Compaction Grouting, Jet Grouting	Deep isolated liquefiable layers can be treated	Underground utilities such as pipelines may prove to be a hindrance	Compaction and Densification
Deep Blasting	No appreciable advantage	Requires environmental clearance	Re-arrangement of particles and densification
Earthquake drains	Effective dissipation of pore pressure	Difficulty in treating a single liquefiable layer	Drainage
Dewatering	Effective as a primary step in water-logged areas	Costly as continuous pumping is necessary	Drainage
Removal and Replacement	Reliable measure as tendency of liquefaction is eliminated	Costly method to be practiced	Replacement

CONCLUSION

Earthquake induced liquefaction has gradually become a cause of serious concern with the expansion of habitation. Application of proper soil improvement technique can help in increasing the shearing resistance of soil against liquefaction. Among them from the review study it has been found that use of sand compaction and stone columns or granular piles are both efficient and cost effective. Some other techniques prove to be more efficient to mitigate liquefaction in comparison to these two techniques but are too expensive. Newly developed Grand Flex Mole Technology is seen to be another useful soil mitigation technique though it is yet to become popular. Besides all this innovation of newer methods for determination of liquefaction potential of a place as a part of disaster response is sought for along with proper numerical modeling to simulate situation of potential liquefaction under dynamic loading.

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