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A Discussion of Liquefaction Mitigation Methods

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Abstract - *Loose sandy deposits sometimes change to liquid state during rapid vibrations. This is called LIQUEFACTION and poses a serious problem. When the sandy soils liquefy, structures built on them are seriously affected; for example, heavy structures settle and light buried structures heave. Reliable remediation with respect to liquefaction is necessary in geotechnical engineering practice. The various methodologies for the assessment of liquefaction potential and remedial measures to mitigate liquefaction are based on continuous research and decades of experience in design and construction of structures. This paper reviews the different methods available for soil improvement and aspects of liquefaction resistant structures.*

Key Words: Liquefaction, Mitigation, Sandy soils, Soil Improvement, Grouting

1. INTRODUCTION

When subjected to strong vibrations, saturated sandy soils may suddenly change into muddy water and start flowing. This phenomenon is called “liquefaction”. It is a process where the strength and stiffness of soil are reduced, which changes the soil to liquid state due to rapid loading like an earthquake shaking, blasting etc.

When liquefaction occurs the strength of the soil reduces and the ability of the soil deposit to support foundations for structures like buildings and bridges decreases. Liquefied soil also applies higher pressure on retaining walls that cause them to tilt or slide. This movement can cause damage to structures on the ground surface. During liquefaction the water pressure in the soil increases and this may cause landslides and also collapse of dams.

2. LIQUEFACTION PHENOMENON

It is important to understand the conditions that exist in a soil deposit before the application of rapid loading to understand liquefaction phenomenon. A soil deposit comprises of an assembly of individual soil particles, each particle being in contact with the neighboring particles. The overlying soil weight causes contact forces between the particles. Thus, the weight of the overlying soils is transmitted through these contacts. These contact forces hold the individual particles in place and allow the shear resistance of soil to support a structure on the ground surface.

The strong vibrations produced during rapid loading like those produced during an earthquake, blasting etc. cause shear stresses, and the soil structure deforms resulting in decrease of contacts between the particles. As the soil arrangement changes, the loosely packed soil particles try to move into a denser configuration. But, during this rapid loading, there is not sufficient time for the water in the pores to be squeezed out. Instead, the water is “trapped” and inhibits the soil particles from moving closer together. Thus, the pore water pressure rises, contact forces between the individual soil particles decreases. Then the weight of the overlying structures which was originally supported in a vertical direction through the contact points is instead transmitted through pore water. The decrease of contact between the soil particles results in reduction of shear resistance of the soil, thereby softening and weakening the soil deposit.

If the pore water pressure becomes too high, the soil particles lose connection with each other. The soil will then have very little strength, and will behave similar to a liquid with the unit weight of the saturated soil – hence the name “liquefaction”.

3. LIQUEFACTION OF SANDS

Taking the cohesion intercept as zero, the shear strength of sandy soils as given by Mohr – Coulomb equation is,

$$S = \bar{\sigma} \tan\phi' \qquad (1)$$

Where, S = shear strength

$\bar{\sigma}$ = effective stress

ϕ' = Angle of shearing resistance in terms of effective stress.

Consider a sand deposit at a depth z from the ground surface with the water table at the ground surface, the effective stress is given as $\bar{\sigma} = \gamma_{sat} \mathbf{x}\, z - \gamma_w \mathbf{x}\, z$

$= \gamma' \mathbf{x}\, z$

Where, γ_{sat} = saturated unit weight of the sand deposit
γ_w = unit weight of water
γ' = submerged unit weight of the sand deposit

Thus (1) becomes, $S = \gamma' \mathbf{x}\, z\, \mathbf{x} \tan\phi'$

If the sand deposit is shaken due to an earthquake or other oscillatory loads, extra pore water pressure (u’) builds up and the shear strength equation becomes

$$S = (\gamma' \mathbf{x}\, z - u') \text{ x } \tan\phi'$$

As the excess pore water pressure increases, the shear strength decreases. In extreme case, when the pore water pressure increases so high that the soil looses all its shear strength, then

$$\gamma' \mathbf{x}\, z - u' = 0$$

4. HOW TO REDUCE LIQUEFACTION HAZARDS

Primary options to decrease liquefaction hazards when designing and constructing new structures like buildings, bridges, tunnels, roads etc. are:

4.1 Soil Improvement Techniques

Mitigation of liquefaction hazards by soil improvement includes improving the strength, density so that soil skeleton will not collapse under rapid loading and/or improving the drainage characteristics of soils. This can be done by various soil improvement techniques.

- *Vibroflotation* method compacts loose sandy soils by inserting a horizontally vibrating vibroflot in the subsoil profile, while jetting water from the bottom end of the vibroflot. The vibrations cause the grain structure to collapse, thereby densifying the soil surrounding the vibroflot. Vibroreplacement is a combination of vibroflotation with a gravel backfill resulting in stone columns, which not only increases the amount of densification but provides a degree of reinforcement and also is an effective means of drainage.

- *Dynamic compaction*: Densification by dynamic compaction is performed by dropping a heavy weight of steel or concrete from heights of 30 to 100 ft. Local liquefaction can be initiated under the drop point making it easier for the sand grains to densify. When the excess pore water pressure from the dynamic loading dissipates, excess densification occurs.

- *Stone columns:* These are columns of gravel constructed in the ground. Stone columns can be constructed by vibroflotation method. They can also be installed with a help of a steel casing and a drop hammer wherein the steel casing is driven into the soil and gravel is filled in from the top and tamped with a drop hammer. The steel casing is successively withdrawn.

- *Compaction piles:* Installing compaction piles is a very effective way of improving soil. Compaction piles are usually made of prestressed concrete or timber. Installation of compaction piles both densifies and reinforces the soil. The piles are usually driven to a depth of 60ft.

- *Deep soil mixing:* This technique improves the soil characteristics by mechanically mixing it with cementitious binder slurry. A column is constructed in the soil with the help of a powerful drill that pumps and mixes the binder slurry into the soil as it advances.

- *Compaction grouting:* Compaction grouting is a technique where slow flowing water/sand/cement/bentonite/clay mix is injected under pressure into the granular soil. The grout forms a bulb that displaces and hence densifies the surrounding soil. Compaction grouting is a suitable choice if the foundation of a standing structure needs improvement, as the grout could be injected into the soil at an inclined angle to reach below the building.

- *Permeation grouting:* This method involves the injection of a low-viscosity fluid into the soil with the intention of filling the voids and waterproofing the un-compacted soil with the injected fluid. This method locally solidifies the soil, thus reducing the risks of compaction and liquefaction.

- *Jet grouting:* In this method, the soil is injected with a mixed fluid at a high pressure in the form of jets such that it replaces the existing soil with the fluid mixture in drill holes at the susceptible site. The jet columns thus formed help to underpinning the structure, offering bearing support and decreasing settlements of the structure

- *Passive site stabilization:* This is a non-destructive mitigation technique where stabilizing material like colloidal silica is slowly injected into the prone area. Injection wells at the edge of the site are used for the injection of the stabilizing material which gets distributed into the liquefiable layer due to the pre-existing groundwater flow. The colloidal silica which is nontoxic, chemically and biologically inert forms a permanent gel that binds the soil particles, increasing the strength and deformation resistance of the soil.

- *Microbial Geotechnology* is the use of microbiological methods to soil to mend the mechanical properties of soil and make it meet constructional and environmental purposes. Three main applications of microbial geotechnology which uses microorganisms to treat soil are biocementation, bioclogging and biogas. Biocementation is the building of particle-binding materials so that shear strength of soil can be improved. Bioclogging is the production of pore-filling materials so that porosity and hydraulic conductivity of soil is reduced. Biogas is a process to generate tiny gas bubbles in otherwise saturated soil to increase the liquefaction resistance of sand or to reduce permeability. Compared to chemical grouting, which is usually costly and toxic for environment, biocementation, bioclogging, or biogas are cost effective and have a lower environmental impact. As microbial processes are more complicated, these applications are soil specific and site environment specific.

- *Induced partial saturation* technique involves injection of a chemical solution that introduces gas bubbles in the pores of the fully saturated sands susceptible to liquefaction. This reduces the degree of saturation of the soil, increases the compressibility of pore water and shear strength of the soil, preventing the occurrence of liquefaction.

- *Drainage techniques:* Liquefaction hazards can be reduced by increasing the drainage ability of the soil. If the pore water in the soil can drain easily, the build-up of excess pore water pressure will be reduced. Drainage techniques include installation of drains of gravel, sand, synthetic materials and earthquake drains. Synthetic weak drains can be installed at various angles, in contrast to gravel, sand and earthquake drains that are usually installed vertically. Drainage techniques are often used in combination with other types of soil improvement techniques for more effective liquefaction hazard reduction.

4.2 Build Liquefaction Resistant Structures

If it is essential to construct on liquefaction prone soil due of space constraints, favorable locations, or other causes, make the construction liquefaction resistant by designing the foundation components to resist the effects of liquefaction.

The structure should possess ductility to accommodate significant deformations, adjustable supports for the rectification of differential settlements and foundation design that spans over soft spots to decrease the extent of damage the structure may undergo in case of liquefaction. To achieve these qualities the different aspects to be considered are:

- *Shallow foundation aspects:* All the foundation components in a shallow foundation should be tied together, making the foundation move or settle uniformly. This decreases the amount of shear forces induced in the structural elements resting upon the foundation. A stiff foundation mat is a suitable kind of foundation, as it can pass on the loads from locally liquefied zones to adjacent stronger ground. Buried utilities, such as sewage and water pipes, should have ductile connections to the structure to put up with the large movements and settlements that can happen due to liquefaction.

- *Deep foundation Aspects:* Liquefaction produces large lateral loads on pile foundations. Piles driven through a weak, potentially liquefiable soil strata to stronger strata, have to bear vertical loads and bending moments induced by lateral movements if the weak strata liquefy. Necessary resistance can be accomplished by piles of larger dimensions and/or more reinforcement. The connection between the pile and the pile cap should be ductile enough to allow some rotation without failure of the connection. The ability of the cap to resist the overturning moments from the super-structure by developing vertical loads in the piles is lost if the pile connection fails.

4.3 Avoid liquefaction Susceptible Soils

Construction on liquefaction susceptible soils should be avoided. There are various criteria to determine the liquefaction susceptibility of a soil. Relating the soil at a specific building site to these criteria, one can check if the soil is prone to liquefaction. The different criteria are as follows:

- *Historical Criteria:* Observations from previous earthquakes offer abundant information about the liquefaction susceptibility of certain types of soils and sites. Soils that have liquefied earlier can liquefy again in future earthquakes. Data in the form of maps of regions where liquefaction has occurred previously and/or is expected to occur in the future is available. Many local government bodies have prepared maps of sensitive areas prone to liquefaction.

- *Geological Criteria:* The type of geological course that formed a soil deposit has a strong effect on its liquefaction susceptibility. Saturated alluvial soils, colluvial deposits, aeolian deposits are liquefaction susceptible. These processes sort particles into uniform grain sizes and deposit them in a loose state that tends to densify under vibrations. This tendency for densification may increase pore water pressure and decrease the strength. Artificial soil deposits, especially those created by the process of hydraulic filling, are susceptible to liquefaction.

- *Compositional Criteria:* Uniformly graded soils are more prone to liquefaction than soils with a different range of particle sizes. When the soils have a wide range of particle sizes, the small particles tend to fill in the voids between the bigger particles, thus reducing the tendency for densification and pore water pressure buildup when shaken. Also, the friction between the angular particles is higher than those between the rounded particles; hence a soil deposit with angular particles is normally stronger and less susceptible to liquefaction. Liquefaction susceptibility depends on the soil type. Sensitive clayey soils, exhibit strain-softening behavior similar to that of liquefied soil, but do not liquefy in the same way as sandy soils are.

- *State Criteria:* The initial "state" of a soil is described by its denseness and effective stress at the time it is subjected to swift loading. Looser soils are more inclined to liquefaction than dense soils, at a given effective stress level. Also, soils at high effective stresses are generally more susceptible to liquefaction than soils at low effective stresses, at a given density.

5. CONCLUSIONS

Soil Improvement methods are most commonly employed to reduce or eliminate the effects of liquefaction. Most of these techniques have advanced over the years, typically by trial and error. Though widely used, the traditional mitigation methods have limitations like environmental impact, disturbance to existing structures when subjected to vibrations and deformations, size of the area to be treated etc.

Lately, new concepts like passive site remediation, microbial geotechnology, induced partial saturation have been proposed. New methods of liquefaction mitigation such as colloidal silica grouting, bentonite suspension grouting, biocementation, air injection, biogas, and mitigation using geomaterials have been developed based on these concepts.

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