UNDERSTANDING LIQUEFACTION

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ABSTRACT

The paper is designed to give a clearer perspective of the Liquefaction Phenomenon including the causative conditions that will trigger liquefaction as well as the soil mechanics principles involved.

An understanding of the Geotechnical environment that could be susceptible to liquefaction including the groundwater influence, granulometry including fines content, Plasticity of the fines (LL & PL) and the triggering Earthquake intensity are discussed.

Much of the work have been gleaned from state of the art papers on soil liquefaction such as the "*Queen Mary Paper" by Seed et al* and references from the USGS website as well as the Authors' own experiences in evaluation of liquefiable ground conditions have been included in this paper.

Significant advances in the body of knowledge and state of practice in liquefaction evaluation have been published in numerous literature and technical papers. This paper in effect is a compilation and summary of the current *State of Practice* in liquefaction evaluation and mitigation.

Essentially this Paper is a Literature Review of Current knowledge about Liquefaction. The figures and entries most of the time have been copied *verbatim* and therefore major credit is due to the sources listed in the references and the authors acknowledge this.

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1.0 Introduction [3]

Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Liquefaction and related phenomena have been responsible for tremendous amounts of damage in historical earthquakes around the world.

Liquefaction occurs in saturated soils, that is, soils in which the space between individual particles is completely filled with water. This water exerts a pressure on the soil particles that influences how tightly the particles themselves are pressed together. Prior to an earthquake, the water pressure is relatively low. However, earthquake shaking can cause the water pressure to increase to the point where the soil particles can readily move with respect to each other.

Liquefaction has been observed in earthquakes for many years. In fact, written records dating back hundreds and even thousands of years describe earthquake effects that are now known to be associated with liquefaction. Nevertheless, liquefaction has been so widespread in a number of recent earthquakes that it is often associated with them.

Because liquefaction only occurs in saturated soil, its effects are most commonly observed in low-lying areas near bodies of water such as rivers, lakes, bays, and oceans. The effects of liquefaction may include major sliding of soil toward the body slumping and of water.

Earthquake shaking often triggers an increase in water pressure, but construction related activities such as blasting and vibratory pile driving can also cause an increase in water pressure.

When liquefaction occurs, the strength of the soil decreases and, the ability of a soil deposit to support foundations for buildings and bridges are reduced as seen in the photo of the overturned apartment complex buildings in Niigata in 1964.

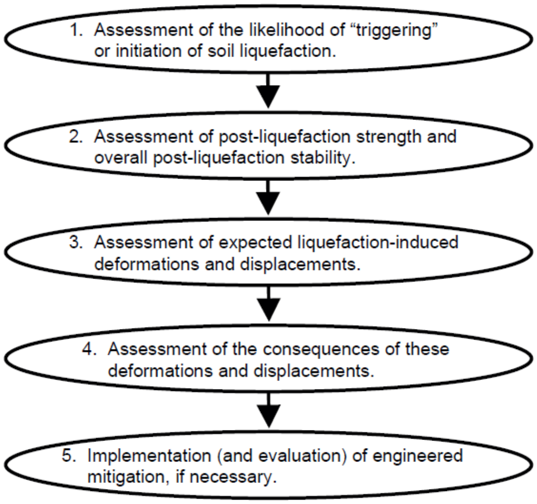
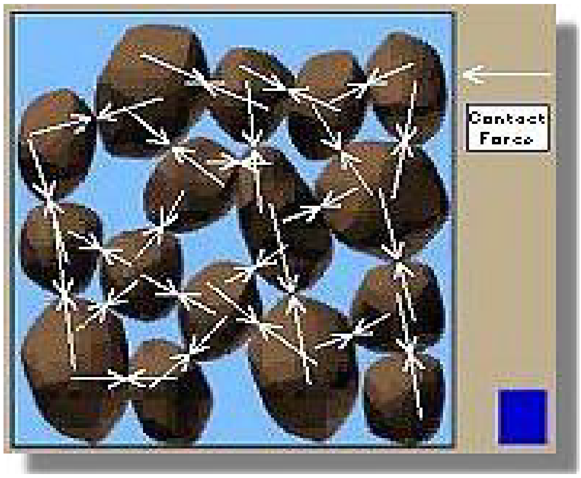


Fig. 1: Key Elements of Soil Liquefaction Engineering

2.0 The Liquefaction Phenomenon

To understand liquefaction, it is important to recognize the conditions that exist in a soil deposit before an earthquake. A soil deposit consists of an assemblage of individual soil particles.

If we look closely at these particles, we can see that each particle is in contact with a number of neighboring particles. The weight of the overlying soil particles produce contact forces between the particles - these forces hold individual particles in place and give the soil its strength.



Grain to grain

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However, when ground shaking occurs, these delicate grain to grain contacts are disturbed and the soils grains are dislodged.

This causes a momentary loss of support which transfers the vertical stresses to the porewater. The pore water in turn further increases in pore pressure thus further buoying up the individual soil grains.

Since water has *practically* no shear strength, collapse of the support happens and thus all superimposed structures and the soil itself slumps due to gravity.

Much of the previous knowledge of liquefaction attributes this phenomenon exclusively to Clean Sands. However, current State of the art have established that even fine grained soils and coarser materials such as Gravels will liquefy given the right conditions and the right earthquake characteristics. This paper seeks to update our current understanding based on the current *State of Practice* as gathered from various literatures.

3.0 Types of Liquefaction Related Phenomena

There are several types of liquefaction related Phenomena as Follows (Ref 1.0)

Flow Liquefaction- Flow liquefaction can occur when the shear stress required for static equilibrium of a soil mass (the *static shear stress)* is greater than the shear strength of the soil when it liquefies. Once triggered, the large deformations produced by flow liquefaction are actually driven by static shear stresses. Flow liquefaction produces the most dramatic Effects.

Flow Liquefaction failures are characterized by the sudden nature of their origin, the speed with which they develop and the large distances over which the liquefied materials often move.

Cyclic Mobility- Cyclic mobility in contrast to Flow Liquefaction occurs when the static shear stress is less than the shear strength of the liquefied soil. It is basically driven by both Cyclic and static shear stresses. The deformations produced by cyclic mobility failures develop incrementally during earthquake shaking. A special case of *cyclic mobility* is level ground liquefaction.

Because horizontal shear stresses that could drive lateral deformations do not exist, level ground liquefaction can produce large chaotic movements, known as *ground oscillation* during earthquake shaking but produces little lateral soil movement.

Level Ground failures are caused by the upward flow of water when seismically induced excess pore pressures dissipate. Excessive vertical settlements and consequent flooding of low lying land and the development of sand boils are characteristic of level ground liquefaction.

4.0 Liquefaction Susceptibility [2]

Liquefaction Susceptibility is determined by the grain size, fines content (LL), the presence of groundwater, the static state of stress as well as the characteristics (*amplitude and length of time of propagation)* of the triggering Earthquake Magnitude that could induce adequate ground shaking.

The following are the criteria for identifying possible liquefaction susceptibility:

4.1 Historical criteria

Soils that have liquefied in the past can liquefy and liquefaction can recur in these same soils when soil and groundwater conditions have not changed. Thus, liquefaction case histories in a particular site can be used to identify specific sites or general areas that are susceptible in future earthquakes.

4.2 Geologic Criteria

Soils susceptible to Liquefaction generally are formed within a *narrow* geologic Environment (*Youd). The depositional environment, hydrological environment and age of the deposits all contribute to its liquefaction susceptibility. Geologic processes that sort soil into uniform grain size distribution and deposit them gently in loose states produce soil deposits with high liquefaction susceptibility.*

Consequently, fluvial deposits and colluvial deposits and aeolian deposits when saturated are likely to be susceptible to liquefaction.

4.3 Compositional Criteria

Liquefaction susceptibility is influenced by the compositional characteristics that influence volume change behavior. Compositional characteristics associated with high volume change potential tend to be associated with high liquefaction susceptibility. These characteristics include particle size, shape and gradation and % fines.

For many years, only sands were thought to liquefy. Finer grained soils were considered incapable of generating the high pore pressures commonly associated with liquefaction and coarser grained soils were considered too permeable to sustain any generated pore pressure long enough for liquefaction to develop.

However, present day experience on recent liquefaction events, suggest otherwise. More recently, the bounds on the gradation criteria for liquefaction susceptibility have *broadened.*

The most important work was done by a team headed by R.B. Seed (Ref 2.0) in their seminal paper delivered at the *HMS Queen Mary,* on April 30, 2003.

Although previous work have been done by the Chinese in 1979, the *Queen Mary Paper* further moved it several notches to reflect current recorded liquefaction events.

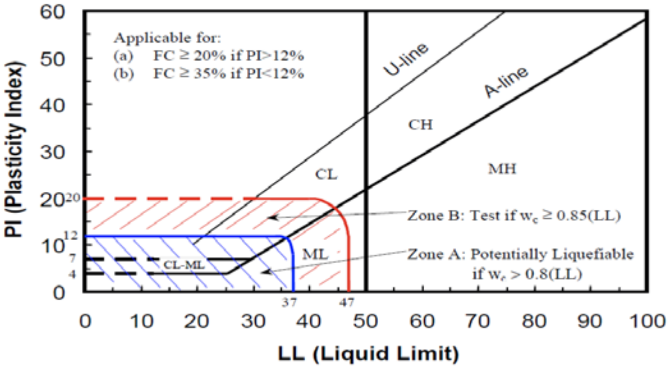

Fig 4: Recommendations Regarding Assessment of "Liquefiable" Soil Types

State Criteria

Even if the preceding criteria are all met, it still may or may not be susceptible to liquefaction. Liquefaction susceptibility also depends on initial state of the soil (i.e. its stress and density characteristics at the time of the earthquake).

Since the tendency to generate excess pore pressure of a particular soil is strongly influenced by density and initial stress conditions, liquefaction susceptibility depends strongly on the initial state of the soil.

5.0 Initiation of Liquefaction

Procedures to determine the initiation of liquefaction have now been updated beyond the understanding before the publication of the *Queen Mary Paper.*

5.1 Cyclic Stress Approach

Research on the on the advances of present day knowledge on Liquefaction was started by H.B. Seed and continued and refined by the son, R. B. Seed, initially leading to the determination of the loading conditions that could trigger liquefaction. This loading was described in terms of cyclic shear stresses and liquefaction potential was evaluated on the basis of the amplitude and the number of cycles of earthquake induced shear stresses.

The improvements came in a more reliable prediction of the non-linear mass participation factor rd as well as the reduction in the peak cyclic stress ratio (CSR).

This general approach came to be known as the "Cyclic *Stress Approach"* as expounded by *Seed,* the elder.

$$CSR_{peak} = \left(\frac{a_{\max}}{g}\right) \cdot \left(\frac{\sigma_v}{\sigma'_v}\right) \cdot (r_d) \qquad \text{(Eq. 1)}$$

where

a_{max} = the peak horizontal ground surface acceleration,

g = the acceleration of gravity,

σ_v = total vertical stress,

σ'_v = effective vertical stress, and

r_d = the nonlinear shear mass participation factor.

This CSR has since been modified by R. B.Seed et al as follows:

$$\mathrm{CSR}_{\mathrm{eq}} = (0.65) \cdot \mathrm{CSR}_{\mathrm{peak}} \qquad \text{(Eq. 3)}$$

d < 65 ft:

$$r_d(d, M_w, a_{\max}, V^*_{s,40'}) = \frac{\left[1 + \dfrac{-23.013 - 2.949 \cdot a_{\max} + 0.999 \cdot M_w + 0.016 \cdot V^*_{s,40'}}{16.258 + 0.201 \cdot e^{0.104 \cdot (-d + 0.0785 \cdot V^*_{s,40'} + 24.888)}}\right]}{\left[1 + \dfrac{-23.013 - 2.949 \cdot a_{\max} + 0.999 \cdot M_w + 0.016 \cdot V^*_{s,40'}}{16.258 + 0.201 \cdot e^{0.104 \cdot (0.0785 \cdot V^*_{s,40'} + 24.888)}}\right]} \pm \sigma_{\varepsilon_{r_d}} \qquad \textbf{(Eq 2)}$$

d ≥ 65 ft:

$$r_d(d, M_w, a_{\max}, V^*_{s,40'}) = \frac{\left[1 + \dfrac{-23.013 - 2.949 \cdot a_{\max} + 0.999 \cdot M_w + 0.016 \cdot V^*_{s,40'}}{16.258 + 0.201 \cdot e^{0.104 \cdot (-65 + 0.0785 \cdot V^*_{s,40'} + 24.888)}}\right]}{\left[1 + \dfrac{-23.013 - 2.949 \cdot a_{\max} + 0.999 \cdot M_w + 0.016 \cdot V^*_{s,40'}}{16.258 + 0.201 \cdot e^{0.104 \cdot (0.0785 \cdot V^*_{s,40'} + 24.888)}}\right]} - 0.0014 \cdot (d - 65) \pm \sigma_{\varepsilon_{r_d}}$$

where

$\sigma_{\varepsilon_{r_d}}(d) = d^{0.850} \cdot 0.0072$ [for d < 40 ft], and $\sigma_{\varepsilon_{r_d}}(d) = 40^{0.850} \cdot 0.0072$ [for d ≥ 40 ft]

Recommended NOMOGRAPH for Probabilistic SPT based Liquefaction Triggering Correlation for Clean Sands [3]

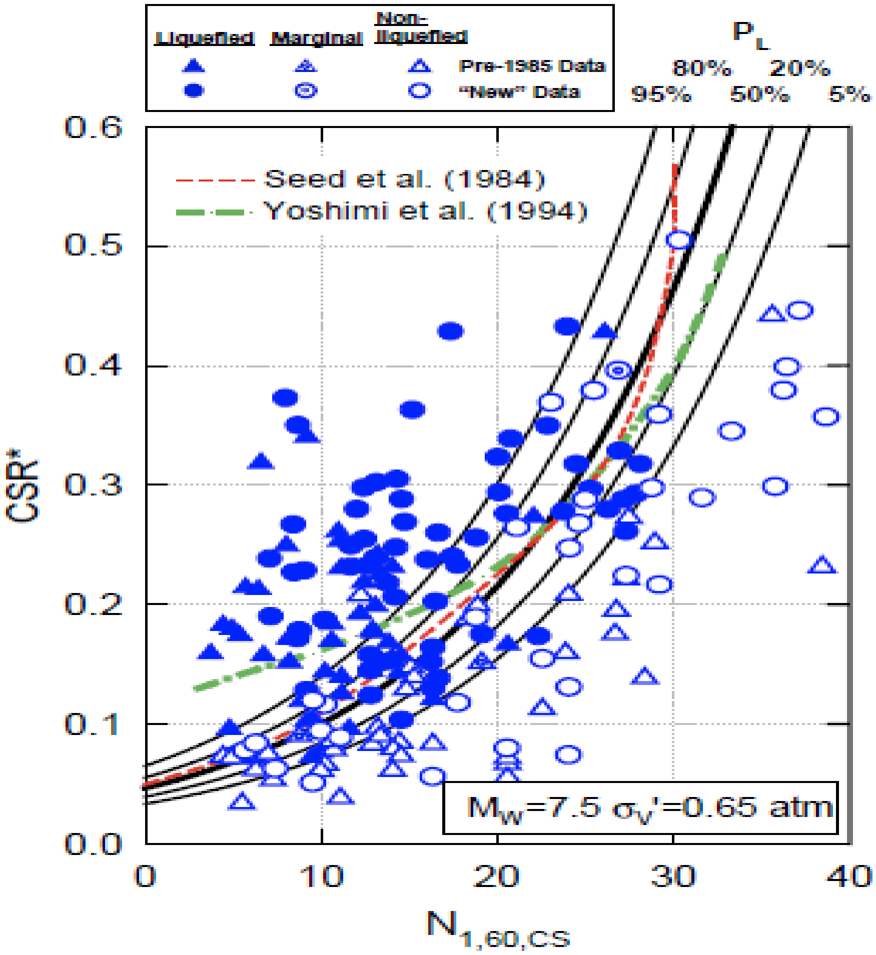

Fig. 10: Recommended Probabilistic SPT-Based Liquefaction Triggering Correlation (for M_w=7.5 and σ_v'=0.65 atm), and the Relationship for "Clean Sands" Proposed by Seed et al. (1984)

Seed et al. (2003)

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[3] Probabilistic Approaches taking into account various acceleration values and Fines content have been evolved in the Virginia Tech Spreadsheet implementation by *Gutierrez et al.*

6.0 Effects of Liquefaction

Liquefaction can induce landslides or collapse of structures, including horizontal infrastructures.

Sand boils can be induced when the excess pore water pressure dissipates by exiting into the ground surface bringing with it fine sand particles much like an erupting volcano.

Ground motion characteristics are also altered after liquefaction when originally stiff soils are altered by positive excess pore pressures. A liquefiable soil that is relatively stiff before may be much softer at the end of liquefaction. Thus, the amplitude and frequency of the soils may change considerably.

This can cause increase in Ground motion and can produce large displacements.

Damage to horizontal and vertical structures can occur depending on the type of liquefaction whether *Cyclic Mobility* or *Flow liquefaction*.

Dams and slopes are very vulnerable to flow liquefaction because the static stress is highly influenced by gravity forces and large lateral spreading occurs.

Cyclic mobility on the other hand occurs mostly on level ground with very little or no lateral spreading. The main effects are on vertical structures which can settle significantly or tilt and collapse when loads are imbalanced or where the soil stratification is uneven.

7.0 Liquefaction Mitigation Methods

A lot of mitigation techniques are currently available which have been used as ground improvement methods to improve strength or reduce deformations. While not covered in this paper, the methods are enumerated for Brevity as this may not be covered in this Paper.

DENSIFICATION METHODS:

- Vibroflotation
- Vibro Rod
- Dynamic Compaction
- Blasting (Camouflet)
- Compaction Grouting

GROUTING TECHNIQUES

- Permeation Grouting
- Intrusion Grouting
- Soil Mixing
- Jet Grouting

DRAINAGE TECHNIQUES

- Stone Columns[4]
- Rammed Aggregate Piers ®
- Prefabricated Vertical Drains PVD's

8.0 Closure

The author's hope that a clearer understanding of the liquefaction phenomenon has been presented to the local Engineering community. Most of the contents of this paper have been directly extracted from the listed references as well as the Author's own experiences in the evaluation of liquefaction problems.

It is suggested that further readings by the Professional are needed in order to achieve a full understanding of the liquefaction phenomenon. This is something which cannot be achieved within the limitations of time and space for this paper.

References

1) Kramer, S. "*Geotechnical Earthquake Engineering* "Prentice Hall, New Jersey 1995.
2) Seed, et al. "*Recent Advances in Liquefaction Engineering: A Unified and Consistent Framework*" 26th annual ASCE Los Angeles Geotechnical Spring Convention.
3) University of Washington Liquefaction Website http://www.ce.washington.edu/~liquefaction/html/main.html
4) USGS Liquefaction Website- http://earthquake.usgs.gov/learn/faq/?categoryID=8&faqID=40
5) Lade et al "*Physics and Mechanics of Soil Liquefaction" A.A. Balkema, Rotterdam 1998.*

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[4] In the case of *Rammed Aggregate Piers ®*, the drainage is greatly facilitated by prestressing and lateral compaction due to the method of installation. Thus, time to $\boldsymbol{U}_{90}$ is greatly speeded up, sometimes to weeks instead of months.