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Critical Review on the Parameters Influencing Liquefaction of Soils

Rupam Saikia[1], Malaya Chetia[2]

Under Graduate Student, Civil Engineering Dept, Assam Engineering College, Guwahati, Assam, India[1]

Assistant Professor, Civil Engineering Dept, Assam Engineering College, Guwahati, Assam, India[2]

Abstract **— Liquefaction of soils is associated with the loss of shear strength due to an increase in pore water pressure. It causes extensive damages to buildings and infrastructures during earthquakes. It is important to know the parameters influencing liquefaction of soil in order to understand the liquefaction phenomenon clearly. Past studies clearly indicate that there are different parameters that would influence the liquefaction of soils. Therefore, the present study purports to critically review the findings reported in the literature to reveal the influence of different parameters on liquefaction of soils. The critical evaluation brings out the anomalies associated with the influence of some of the parameters on the liquefaction. The study also indicates the need of further experimental investigations regarding few factors' influence on liquefaction of soil.**

Keywords **— Earthquake, Soil, Liquefaction, Parameters, Influence, Critical review.**

I. Introduction

Liquefaction is the phenomenon which is observed when there is loss of strength in saturated and cohesion-less soils because of increased pore water pressure and hence reduced effective stresses due to dynamic loading. As a result of liquefaction the soil merely behaves like a fluid mass with hardly any shear strength, which can lead to serious damage of structures constructed in such soils. Liquefaction induced ground failures include loss of bearing strength, lateral spreading, and flow failures, which may cause many engineering problems such as foundation failures, damage to utilities, slope failures, land slides, and large displacements of earth dams [4]. The study of liquefaction susceptibility of a seismically active region or site is necessary before any construction to avoid serious hazards due to earthquake which otherwise may end up to disaster. Therein lays the importance of study of factors influencing liquefaction of soil which can give a clear knowledge of what causes liquefaction and how a soil would behave due to liquefaction.

Many researchers have noted that there are different parameters that would influence liquefaction. It is essential for the modelers and engineers dealing with liquefaction to fully appraise these parametric influences. There are various conflicting observations and anomalies related to some of the parameters influencing liquefaction, which requires a systematic understanding. With this objective, the present study purports to critically review the influence of different parameters on liquefaction. The critical evaluation highlights the anomalies associated with the influence of some of the parameters on liquefaction. However, further experimental investigations are required to quantify soil-specific parametric influence on liquefaction.

II. Theoretical Background

Soil is basically an assemblage of many soil particles or soil grains which stay in contact with each other. The contact forces produced by the weight of the overlying particles hold individual soil grains in its place and provide strength. As a result of cyclic loading the loose and saturated sand grains break down and the loosely-packed individual soil particles try to move into a denser configuration. However, there is not enough time for the pore-water of the soil to be squeezed out in case of earthquake loading. Instead, the water is trapped and prevents the soil particles from moving closer together. Thus, there is an increase in pore water pressure which reduces the contact forces between the individual soil particles causing a loss of strength that leads to liquefaction of soil.

III. Factors Influencing Liquefaction of Soil

The various factors which influence liquefaction of soil are stated below.

1. *Grain-size Distribution and Soil Types:* Liquefaction is most commonly observed in shallow, loose, saturated cohesionless soils subjected to strong ground motions such as during earthquakes. The type of soil most susceptible to liquefaction is one in which the resistance to deformation is mobilized by friction between particles. If other factors such as grain shape, uniformity coefficient and relative density are equal, the frictional resistance of cohesionless soil decreases as the grain size of soils becomes smaller.

Tsuchida (1970) [44] summarized the results of sieve analyses performed on a number of alluvial and diluvial soils that were known to have liquefied or not to have liquefied during earthquakes. He proposed ranges of grain size curves separating liquefiable and non-liquefiable soils. Soils with a higher percentage of gravels tend to mobilize higher strength during shearing, and to dissipate excess pore pressures more rapidly than sands. However, there are case histories indicating that liquefaction has occurred in loose gravelly soils [36, 22, 3] during severe ground shaking or when the gravel layer is confined by an impervious layer. Ishihara (1985) [22] stated that clay-size or silt-size materials having a low plasticity index value will exhibit physical characteristics resembling those of cohesionless soils, and thus have a high degree of potential for liquefaction. Walker and Steward (1989) [46], based on their extensive dynamic tests on silts, have also concluded that non-plastic and low plasticity silts, despite having their grain size distribution curves outside of Tsuchida's boundaries for soils susceptible to liquefaction, have a potential for liquefaction similar to that of sands and that increased plasticity will reduce the level of pore pressure response in silts. This reduction, however, is not significant enough to resist liquefaction for soils with plasticity indices of 5% or less.

2. *Fine Contents and Plasticity:* The effects of fine contents and plasticity on liquefaction or shear strength of sandy soils have been investigated extensively [22, 17, 43, 12, 34, 42, 19, 33, 9]. However, confusion still exists about the effect of fines on soil liquefaction: fines within soil structure may either increase or decrease the liquefaction resistance of sandy soils. For example, as per Seed et al. (1985) [38] empirical correlations from in-situ studies show that the presence of fines increases liquefaction resistance. Besides several studies such as by Fei (1991); Chang et al. (1982); Dezfulian (1984); Vaid (1994); Amini and Qi (2000) [13, 8, 10, 45, 1, 16, 26, 49, 21] have also shown that liquefaction resistance of a silty soil increased as the fine content increased, whereas Finn et al. (1994), Lade and Yamamuro (1997), and Zlatovic and Ishihara (1997) [16, 26, 51] reported that liquefaction resistance decreased as the fine content increased. Andrianopoulos et al. (2001) [2] have shown that the presence of fines is beneficial at relatively small effective stresses, i.e. the stresses prevailing at the liquefiable layers in-situ. Furthermore they have shown that the effect is reversed at relatively large effective stresses, i.e. the stresses usually considered in the laboratory tests. Bouferra and Shahrour (2004) [5] also showed that the liquefaction resistance of sand containing clay decreased as the clay content increased up to 15%. They insisted that small amounts of clay contents within sand matrix decreased the dilation of an entire specimen. But Liang et al. (2000) [28] in their studies on effect of clay particle content (up to 9%) on liquefaction of soil has shown that the clay particle content is not in a linear relationship with the liquefaction resistant capacity. They have also shown that the cyclic shear strength of medium sand is higher than that of fine sand having same clay particle content. This finding proves that the coarse particle take an important part in sand to resist liquefaction. Law and Ling (1992) [27] and Koester (1994) [24] noted that when the void ratio of a specimen is constant, the liquefaction resistance of silty sands initially decreased, but then after a certain fine content it increased with increasing fine content. Published research results regarding the effect of plasticity on the fines used for evaluations on liquefaction resistance seem also contradictory. As per Koester (1994) [24], the plasticity index, PI of the fines is less important than the fines content (f %) in estimating liquefaction resistance, contrary to Prakash et al. (1999) [32] who claims that fines with high plasticity fundamentally change the mechanism of excess pore pressure build-up. Recently studies were carried out by Park and Kim (2013) [31] on effect of low fraction of plastic fines when mixed with clean sand. In their study, clean sand was mixed with 10% plastic fines having different plasticity indexes (PIs), and the effect on liquefaction resistance was evaluated in terms of cyclic stress ratio. Four types of fines were used to simulate different fines: silt (PI = 8%), kaolinite (PI = 18%), bentonite and silt mixture (PI = 50%), bentonite (PI = 377%). A series of undrained cyclic triaxial tests were carried out on loose, medium, and dense specimens that were reconstituted in the laboratory by the under-compaction method. The

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results showed that liquefaction resistance tended to decrease as the PI of 10% fines in the specimens increased. Liquefaction resistance of loose specimens was marginally influenced by the plasticity of fines. However, in the case of dense specimens, liquefaction resistance decreased up to 40% as the PI of 10% fines increased. It was shown that even though a low fraction of plastic fines was included within sand matrix, it still had a significant effect on the liquefaction resistance of sandy soils.

3. Such contradictions could be partially related to the basis for comparison of liquefaction resistance such as (global or total) void ratio, skeleton void ratio, and relative density [35, 39, 25] have shown that the liquefaction resistance of silty sands is closely related to its skeleton void ratio. Polito and Martin (2001) [33] have found that the liquefaction resistance of silty sands is more dependent on the relative density of sand-silt mixtures than other terms. Based on most of the available studies, Carraro et al. (2003) [6] concluded that (1) the increase of non-plastic fines increases the liquefaction resistance of silty sand if the relative density is used as the basis for comparison, and (2) at the same void ratio, increase of non-plastic fines results in lower liquefaction resistance.

4. *Relative Density*: For a given soil, initial void ratio or relative density is one of the most important factors controlling liquefaction. Liquefaction occurs principally in saturated clean sands and silty sands having a relative density less than 50% [18]. For dense sands, however, their tendency to dilate during cyclic shearing will generate negative pore water pressures and increase their resistance to shear stress. The lower limit of relative density beyond which liquefaction will not occur is about 75% [18]. Although cyclic mobility (temporary loss of strength) can occur at relative densities up to 100%, it is thought that negligible distortions occur in this range at least prior to any drainage or pore-water redistribution [7]. Thus though it is unsure about the upper limit of relative density beyond which liquefaction would not occur but the denser a soil or greater is the relative density, the lower is its tendency toward volume contraction during shearing; the lower is the pore pressure which will be generated; hence, more unlikely to liquefy.

5. *Earthquake Loading Characteristics:* The vulnerability of any cohesionless soil to liquefaction during an earthquake depends on the magnitude and number of cycles of stresses or strains induced in it by the earthquake shaking. These in turn are related to the intensity, predominant frequency, and duration of ground shaking. Ishihara, Tatsuoka and Yasuda (1975) [21] noted that ground motion inputs in which the maximum peak occurs early are less critical than input records for which the peaks are more uniformly distributed (i.e., vibratory as opposed to shock loadings).

6. *Vertical Effective Stress and Overconsolidation:* It is well known that an increase in the effective vertical stress increases the bearing capacity and shear strength of soil, and thereby increases the shear stress required to cause liquefaction and decreases the potential for liquefaction. A number of investigators have observed that saturated sands located deeper than 15 to 18 m are not likely to liquefy [18]. These depths are in general agreement with Kishida (1969) [23] who states that a saturated sandy soil is not liquefiable if the value of the effective overburden pressure exceeds 190 kN/m^2. Both theory and experimental data show that for a given soil, a higher overconsolidation ratio leads to higher lateral earth pressure at rest and thereby increases the shear stress ratio required to cause liquefaction [18]. Although there is a trend towards reduced liquefaction potential at higher stresses, the observed field cases are very limited and cannot be expected to apply in all situations.

7. *Age and Origin of the Soil:* Natural deposits of alluvial and fluvial origins generally have soil grains in the state of loose packing. These deposits are young, weak and free from added strength due to cementation and EB 07-039 Page 27 of 62 aging. Youd and Hoose (1977) [50] stated that, as a rule of thumb, alluvial deposits older than late Pleistocene (10,000- 130,000 years) are unlikely to liquefy except under severe earthquake loading conditions, while late Holocene deposits (1,000 years or less) are most likely to liquefy, and earlier Holocene (1,000-10,000 years) deposits are moderately liquefiable. Thus the tendency of a soil deposit to liquefy decreases with passage of time which is believed due to some form of cementation or welding, which may occur at contact point between sand particles and as being associated with secondary compression of the soil.

8. *Seismic Strain History:* It has been demonstrated from laboratory test results that the prior seismic strain

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history can significantly affect the resistance of soils to liquefaction [15, 37, 41]. Low levels of prior seismic strain history, as a result of a series of previous shakings producing low levels of excess pore pressure, can significantly increase soil resistance to pore pressure buildup during subsequent cyclic loading. This increased resistance may result from uniform densification of the soil or from better interlocking of the particles in the original structure due to elimination of small local instabilities at the contact points without any general structural rearrangement taking place. Large strains, however, associated with large pore pressure generation and conditions of full liquefaction can develop weak zones in the soil due to uneven densification and redistribution of water content [30, 47] and thus lower the resistance of the soil to pore pressure generation during subsequent cyclic loading.

9. *Degree of Saturation:* There are very few studies on the liquefaction potential of partially saturated sands. Sherif et al. (1977) [40] have shown that the liquefaction resistance for soils increases with decreasing degree of saturation and sand samples with low degree of saturation can liquefy only under severe and long duration of earthquake shaking.

10. *Thickness of Sand Layer:* In order to induce extensive damage at level ground surface from liquefaction, the liquefied soil layer must be thick enough so that the resulting uplift pressure and amount of water expelled from the liquefied layer can result in ground rupture such as sand boiling and fissuring [22, 11]. If the liquefied sand layer is thin and buried within a soil profile, the presence of a non-liquefiable surface layer may prevent the effects of the at-depth liquefaction from reaching the surface. Ishihara (1985) [22] has set up a criterion to stipulate a threshold value for the thickness of a non-liquefiable surface layer to avoid ground damage due to liquefaction. Although this is believed to be speculative and should not be used for design purposes, it provides initial guidance in this matter for sites having a buried liquefiable sand layer with a standard penetration resistance of less than 10 blows per foot (0.3 m). It should also be noted that even though the thickness of a non-liquefiable surface layer exceeds the threshold thickness, the ground surface may still experience some settlement which may be undesirable for certain settlement-sensitive structures. Moreover, this finding is based on just three case histories, may need to be modified as more data become available.

11. *Drainage Conditions:* The rate at which pore water pressure is permitted to dissipate from within a soil body has a major influence upon whether or not liquefaction can occur, particularly under cyclic loading [48]. Since the rate of pore pressure dissipation is known to be a function of the square of the longest drainage path, the detailed geometry of the soil profile is important. A study of the interrelationships between different layer compressibilities and permeabilities on the occurrence of liquefaction has been presented by Yoshimi and Kuwabara (1973) [49]. This analytical study, based upon solutions to the Terzaghi one-dimensional consolidation problem, illustrates that liquefaction will propagate easily from a lower liquefied layer to an overlying permeability than the initially liquefied striation.

A useful tool for investigating the influence of drainage on potentially liquefiable soil strata is discussed by Seed, Martin and Lysmer (1975) [29]. Effective stress computer codes provide a numerical solution of the diffusion equation with a pore pressure generating term included to represent the earthquake-generated pore-pressure increases. It is possible to investigate the influence of length of drainage path, stratification, water table and saturation level variations, different permeabilities, compressibilities, densities and other conditions on liquefaction of soil.

12. *Indirect Factors:* There is a family of soil parameters which, while not related to the liquefaction process directly, do influence the liquefaction potential. These are the response parameters which dictate how a soil will respond to applied stress. For example, since volumetric changes and, hence, liquefaction potential can be related to the distortional strain levels which a soil undergoes [29], the shear stiffness or modulus of rigidity of a soil under a specific load level is of particular concern. Earthquake motions can be either amplified or attenuated, depending upon characteristics of the soil profile (and its interaction with the frequency content of the disturbing earthquake) which, in turn, depend upon the values of the stiffness and damping parameters involved. Since many treatments of earthquake-induced liquefaction deal with vertically transmitted horizontal shear waves, one approach to analysis requires only a value for the shear modulus, G, together with a damping coefficient, to account for the energy absorption of the soil. Extensive experimental works dealing with these two parameters have been

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carried out by Hardin and Drnevich (1970) [20]. These studies permit characterizing the shear response parameters of soil in terms of the basic soil index properties and the existing stress and strain states.

IV. Differences and Contradictions Regarding Few Factors Influencing Liquefaction of Soil

1. From literature survey different conclusions were observed on the influence of fine content on liquefaction of soil. Extensive research on this very field has already been done but still a general agreement on the effect of fine content on the liquefaction potential of a soil is not reached. Fei (1991); Chang et al. (1982); Dezfulian (1984); Vaid (1994) and Amini and Qi (2000) [12, 8, 43, 1] have shown that liquefaction resistance of a silty soil increased as the fine content increased, whereas Finn et al. (1994), Lade and Yamamuro (1997), Zlatovic and Ishihara (1997) and Park and Kim (2013) [16, 25, 51, 32] reported that the liquefaction resistance decreased as the fine content increased. This contradiction in evaluations has to be concluded with a specific conclusion such that the effect of fine content on liquefaction of soil can be properly ascertained.

2. As per Shen et al. (1977) and Kuerbis et al. (1988) [39, 25], the liquefaction resistance of silty sands is closely related to its skeleton void ratio. While as per Polito and Martin (2001) [33] the liquefaction resistance of silty sands is more dependent on the relative density of sand-silt mixtures than other terms. Based on most of the available studies, Carraro et al. (2003) [6] concluded that (1) the increase of non-plastic fines increases the liquefaction resistance of silty sand if the relative density is used as the basis for comparison, and (2) at the same void ratio, increase of non-plastic fines results in lower liquefaction resistance. Thus unless the proper basis is set aside it will be difficult to come to a sole conclusion which can be only possible with further research.

3. Walker and Steward (1989) [45], based on their extensive dynamic tests on silts, have concluded that non-plastic and low plasticity silts, despite having their grain size distribution curves outside of Tsuchida's boundaries for soils susceptible to liquefaction, have a potential for liquefaction similar to that of sands and that increased plasticity will reduce the level of pore pressure response in silts. Thus Tsuchida's curve has failed to agree under this situation.

4. Published research results regarding the effect of plasticity on the fines used for evaluations on liquefaction resistance seems contradictory. As per Koester (1994) [24], the plasticity index, PI of the fines is less important than the fines content (f %) in estimating liquefaction resistance, contrary to Prakash et al. (1999) [32] who claim that fines with high plasticity fundamentally change the mechanism of excess pore pressure build-up.

5. The effect of clay content in liquefaction resistance of soil also suffers different conclusions. Bouferra and Shahrour (2004) [5] have shown from cyclic triaxial test using sand containing up to 15% clay that the liquefaction resistance decreased as the clay content increased. They insisted that small amounts of clay contents within sand matrix decreased the dilation of an entire specimen. But Liang et al. (2000) [27]in their studies on effect of clay particle content on liquefaction of soil have shown that the clay particle content is not in a linear relationship with the liquefaction resistant capacity but with a minimum value at percentage of clay, P_c = 9%. Besides they have also shown that the cyclic shear strength of medium sand is higher than that of fine sand of same clay particle content, which proves that coarse particle takes an important part in sand to resist liquefaction.

V. Conclusion

This study presents a comprehensive review of different parameters that influence liquefaction of soil, which is essential for the unambiguous understanding of liquefaction of soil. This critical review highlights the anomalies associated with the influence of some of the key parameters on liquefaction of soil. The review highlights that inspite of the recent advances in the field of Geotechnical Engineering and widening of the discipline some conclusions on some important aspects still remained inconclusive and equivocal. Such equivocal results were seen in the evaluation of few factors influencing liquefaction of soil, which is an important aspect in order to understand liquefaction of soil better. Such contradictions can be only solved to a definite conclusion by further research into these specific fields. The research work can be made effective by combined efforts of past researchers on this fields and facilitation of research works into grass-root level may also help to achieve the same. Liquefaction of soil due to earthquake is one of the primary causes responsible for loss of life and property in the earthquake prone zones of the world. Thus

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proper evaluation of liquefaction potential in a region is necessary which can be made possible only by proper insight into factors which influence liquefaction of soil.

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