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Review On Recent Advances In Soil Liquefaction

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Abstract:
Liquefaction refers to weakening soil's strength and stiffness due to rapid loading, such as earthquake shaking. This process is akin to a solid turning into a liquid under heat or pressure, allowing particles to move more freely, like ice melting or metals softening when heated. Now, it has become a great challenge to avoid liquefaction, and it can be achieved through three factors such as avoiding susceptible liquefaction, building liquefaction-resistant structures, and improving the soil. This article briefly explains the recent advances in measuring liquefaction and how to avoid liquefaction using our modern techniques. The Standard Penetration test, Cone Penetration test, shear wave velocity measurements, cyclic simple shear test, triaxial test, and field liquefaction potential evaluation are the techniques used to determine the liquefaction potential in soil. Ground improvement techniques, such as soil compaction, Vibro compaction, deep soil mixing, and the use of reinforcing materials, show promise in reducing liquefaction risk. Advanced numerical modeling and artificial intelligence applications have also emerged as valuable tools for predicting liquefaction. Seismic design codes and zoning regulations help to design a structure to withstand soil liquefaction. Educating communities about liquefaction risks and promoting construction practices also avoids the risks in seismic-prone regions. Knowledge from these studies provides a foundation for developing more robust infrastructure and designing effective strategies to minimize the impact of liquefaction on communities in seismic-prone regions.

Keywords: *Cone Penetration Test, Cyclic simple shear test, Liquefaction, Numerical modeling, Standard Penetration Test, Triaxial test*

INTRODUCTION

Soil liquefaction, a geotechnical occurrence, occurs when saturated soil loses strength, resembling a liquid due to seismic activity, especially S waves from earthquakes. Seismic waves elevate pore water pressure in the soil, causing collapse if it exceeds the soil's effective stress, leading to fluid-like behavior and reduced strength. This phenomenon poses significant risks to infrastructure and human safety, particularly in areas prone to earthquakes (1-3). The consequences of soil liquefaction can be severe, as evidenced by historical earthquakes such as the Loma Prieta earthquake of 1989, San Francisco earthquake of 1906 (4), 1964 Niigata (5), 1976 Tangshan (6), 1999 Chi–Chi (7) and 2011 Tohoku events have drawn attention from engineers and researchers. While earthquakes are the most common trigger for soil liquefaction, certain construction activities, such as blasting, soil compaction, and vibro flotation, can intentionally induce liquefaction. These practices are sometimes used to improve soil conditions for construction projects, but they can also pose risks if not managed properly.

Granular soils, including gravelly soils and sand-based sludge, are particularly vulnerable to liquefaction due to their loose and porous nature. Seismic shaking causes the water-filled pore size in the soil to break, increasing the pressure between the soil grains. Buildings situated on the soil are consequently less able to withstand them, which may lead to damage or collapse. In addition to causing structural damage, liquefaction can also lead to secondary hazards such as sand blows which are investigated using model testing (8). Liquefaction- induced landslides occur as weakened soil slides downhill, posing threats to life and property. Understanding soil liquefaction is crucial for engineers and urban planners to assess seismic hazards, design resilient structures, and implement effective mitigation measures in earthquake-prone regions. Strategies to reduce the possible effects of liquefaction on society and the built environment are informed by research and continuous monitoring of soil conditions, which aid in identifying places at risk. The primary cause of soil liquefaction is earthquake-induced shaking of loosely packed, water-saturated soils. This shaking causes the soil to behave more fluidly, as seen in Figure 1, by raising pore water pressure and decreasing the effective stress between soil particles. Famous occurrences like the Great East Japan Earthquake in 2011 and the Noto Peninsula Earthquake in 2024 demonstrate the catastrophic effects of these occurrences and emphasize the urgent need for precise forecasting and efficient mitigation techniques (9).

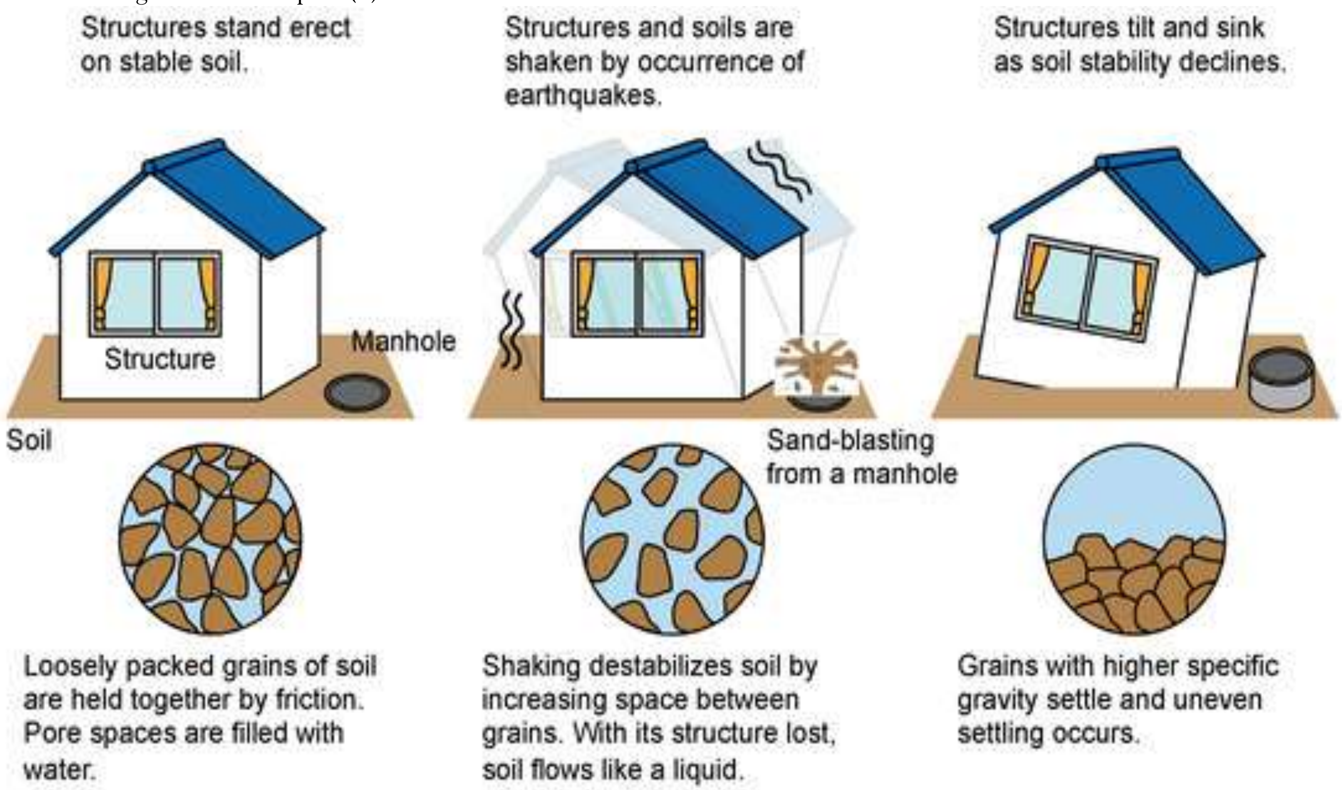

Figure 1. Soil liquefaction behavior during an earthquake.

LESSON LEARNT FROM PAST HISTORY OF LIQUEFACTION

The primary methods to decrease the risk of liquefaction during the construction of new structures which are learnt from the history of liquefaction are:

Avoiding Liquefaction-Prone Soils: This method involves steering clear of building on soils susceptible to liquefaction (10). By assessing soil characteristics, builders can determine if a site is vulnerable to liquefaction and choose a more stable location if needed.

Constructing Liquefaction-Resistant Structures: When building on liquefaction-prone soil is unavoidable, structures can be designed to withstand liquefaction. Engineers achieve this by reinforcing foundations and structural elements to endure potential ground movement and strength loss.

Enhancing Soil Stability: Another approach is to improve soil stability to reduce liquefaction risks. This involves using various techniques like compaction and drainage installation to strengthen the soil's structure and drainage capabilities. By following the aforementioned procedures, engineers can reduce the effect of liquefaction on structures, guaranteeing safer and more resilient building projects.

MEASURES TO FIND OUT LIQUEFACTION SUSCEPTIBLE SOIL

The majority of liquefaction happens when the groundwater table is less than 10 meters (11). Liquefaction has occasionally been noted in locations where the groundwater depth exceeds 20 meters (12). The probability of soil liquefaction during powerful earthquakes is increased by the presence of several soil types, such as clay, silty, and sandy soil, as well as shallow groundwater (13). During earthquake events, silt and sand, as well as other soils with particle sizes between 0.002 and 2.36 mm, are particularly vulnerable to liquefaction hazards (14). Liquefaction typically transpires when soil lacks cohesion, is loose, and is fully saturated, coupled with the presence of dynamic forces such as earthquakes. Additionally, the critical depth for liquefaction initiation is generally less than 12 meters. Furthermore, liquefaction is expected to transpire if the average shear stress (τ) exceeds a certain threshold (15). During liquefaction, fine particles rise, and coarse settle, implying less severe consequences in sand-gravel mixtures than typical sands (16). The evaluation measured the liquefaction potential using the Idriss and Boulanger Semi-Empirical Method. A corrected Standard Penetration Test (SPT) blow count of less than 14 indicates that the soil strata are susceptible to liquefaction, whilst values greater than 20 are usually regarded as safe. Furthermore, immunity to liquefaction is generally linked to vertical effective stress levels greater than 95 kN/m^2 (17). The sands' resistance to liquefaction rises as their mean particle size and relative density do (18). Results showed that the degree of saturation reduces as the homogeneity coefficient rises. Additionally, it was noted that upon saturation, well-graded sands settle more than equally graded sands (19).

METHODS FOR EVALUATING SOIL LIQUEFACTION POTENTIAL

Main goal of this review is to create more stable and robust classification models using the data and explanatory variables at hand, we try to distinguish between the two main methods of liquefaction susceptibility research. The empirical and deterministic research are referred to as direct and indirect modeling approaches, respectively. The classification goal is the driving force behind this nomenclature Fig.2. In direct models, a separating hyperplane—also called the decision boundary or the limit-state—is explicitly established. The variables of interest can then be indirectly used to infer a liquefaction-triggering mechanism. In contrast, indirect models create useful transformations that infer significant correlations between variables of interest. In addition to formulating the classification problem, indirect models have the advantage of conceptually interpreting the obtained index (20). Remarkably, from a machine learning standpoint, such methods can be regarded as unsupervised learning strategies, in which the development of the classification strategy is independent of the liquefaction identity of the case study under consideration.

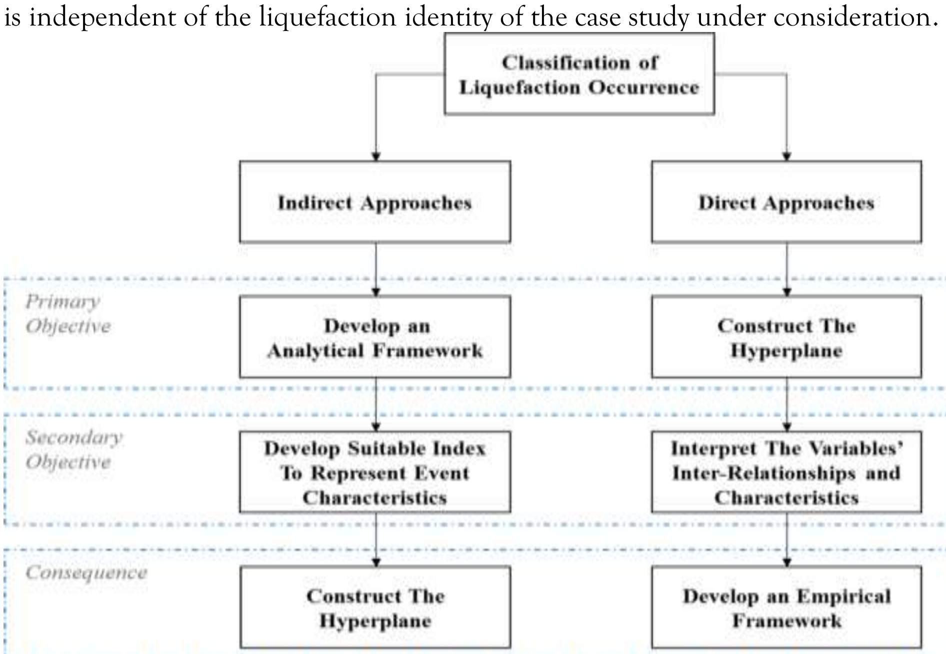

Figure 2. Predicting seismic-induced liquefaction through ensemble learning frameworks

Standard Penetration Test

Soil liquefaction potential is frequently evaluated using the Standard Penetration Test (SPT). A split-barrel sampler is pushed into the earth by a drill rig in an SPT, and the number of blows required to penetrate the sampler to a certain depth is recorded. This test helps assess the danger of liquefaction by providing information on soil density, consistency, and friction angle.

Cone Penetration Test

A geophysical survey method called the Cone Penetration Test (CPT) is used to learn more about the pore pressure, penetration resistance, and stratigraphy of soil. It involves measuring the resistance experienced by driving a cone-shaped penetrometer into the ground. In order to make well-informed decisions during geotechnical evaluations and construction projects, engineers use CPT data analysis to determine the soil's susceptibility to liquefaction (21).

Software for Interpreting CPT data

Cone Penetration Test (CPT) data interpretation and geotechnical design based on CPT results have been made easier in recent years by the development of commercial tools. Two such programs, CPeT-IT (pron. C-petit) and CLiq (pron. slick), were developed in part by the author. These programs provide users with accessibility and are both affordable and easy to use. The website http://www.geologismiki.gr/Products.html offers them for download. Bernard R. et al.'s In Situ Shear Wave Velocity test (22) measures shear wave velocity to determine the stiffness of the soil.

Becker Penetration Test

In North America, its application as an in-situ method for determining the liquefaction potential of gravelly soils has grown. This test functions similarly to a big dynamic penetrometer and includes both pile driving and the Standard Penetration Test (23).

Ground Response Analysis

The study looks into the relationship between ground motion intensity and liquefaction response measures in order to determine how ground motion parameters affect soil liquefaction response. It generates data by applying a wide range of modestly scaled ground motions to 13 distinct deposit models through nonlinear dynamic analysis. The connections between liquefaction response measurements and ground motion intensity measurements are established using this data (24).

Laboratory Tests

Table 1 Name of the Laboratory tests

Name of the Laboratory test	Usage	References
Cyclic Triaxial Test	Dynamic soil property measurements across a broad strain range.	Takeji Kokusho (1980) (25)
Cyclic Simple Shear Test	Assessing the cyclic shear strength of soil samples that have been packed or left undisturbed	Suresh Maurya et.al (2022) (26)
Cyclic Torsional Shear Test	Shear modulus, undrained cyclic strength, and excess pore water pressure following cyclic loading of embankment soils.	Susumu Yasuda and Takafumi Tsuruda (2010) (27)
Dry Funnel Pluviation method followed by gradual saturation.	To investigate the relationship between soil granulometry and saturation level	Bozana Bacic and Ivo Herle (2019) (19)

Numerical Modeling

Numerical modeling is simulating real-world processes via the use of computing methods and mathematical algorithms. It employs mathematical equations to represent the behavior of the system being studied and solves these equations using computers. In geotechnical engineering, numerical modeling is often used to predict soil behavior, analyze structural stability, and assess the effects of natural hazards. The gradual increase in the shear strain amplitude in sand during the post-liquefaction cyclic response is taken into account by the recently created SANISAND-Sf model. This model, along with its predecessor, the DM04 model, was calibrated using undrained cyclic torsional shear tests conducted at LEAP (28).

Constructing Liquefaction – Resistant Structures

To achieve a structure with ductility, large deformation accommodation, and adjustable supports for correcting settlements, along with a foundation design capable of spanning soft spots to minimize liquefaction damage, several key aspects must be considered.

Shallow Foundation Aspects

During earthquakes, isolated shallow foundations may experience difficulties due to the occurrence of differential settlements. However, if there is sufficient depth of non-liquefiable soils beneath the footing, lighter loaded structures can be adequately supported by joining shallow foundations with grade beams and structurally built floor slabs. A tenth of the maximum column load is typically supported by grade beams (29). In areas where uneven permanent ground deformations can occur due to earthquake-induced liquefaction, mat foundations are commonly thought of as a good choice for foundations. This type of foundation is adept at spanning such irregularities when appropriately designed.

Deep Foundation Aspects

Numerous successful case studies have demonstrated that piles are an acceptable foundation solution in liquefiable ground. Nevertheless, there are also cases when piles have lost support due to inadequate resistance to the additional loads from liquefied soil. Designing piles in liquefiable soils demands careful assessment of both pile behavior and their implications on supported structures (30). Pile foundations are highly effective under earthquake loads and are frequently employed in seismically active regions due to their robust performance. Additionally, pile caps are commonly interconnected with grade beams and structurally designed floor slabs to enhance stability and distribute loads efficiently.

Use of Rubble brick earth Drains

The efficacy of using rubble brick for earthquake drains in mitigating liquefaction effects. Results demonstrate reduced settlement of foundations compared to unimproved, liquefiable ground. Valuable insights into excess pore pressure variation below foundations are provided, highlighting the effectiveness of the rubble brick drains (31).

SOIL IMPROVEMENT TECHNIQUES

Different soil improvement techniques and its methods are mentioned in table 2.

Table 2. Soil improvement techniques and its methods

Category	Method
Consolidation	Prefabricated vertical drains and surcharge
Densification	Vibro compaction and dynamic compaction by falling weight impact
Deep soil mixing	Wet and Dry mixing methods
Grouting	Permeation grouting and jet grouting
Load reduction	Geofoam, foamed concrete and lightweight fill

Load Transfer	Column Supported Embankment
Reinforcement	Stone columns

The soil improvement techniques are each tailored to specific soil conditions and engineering needs. Compaction Pile is ideal for granular and clean soils, while Deep Dynamic Compaction effectively addresses cohesion less soil. Deep Blasting proves beneficial for loose soil, while Permeation Grouting fills pore spaces in loose soil. Jet Grouting serves as an underpinning technique, and Deep Soil Mixing densifies soil to considerable depths. Earthquake Drains and Dewatering play pivotal roles in managing water and settlements. Removal and Replacement replace liquefiable soil with compacted fill, while Grand Flex Mole Technology employs chemical grouting. Induced Partial Saturation targets existing structures for enhancement. These methods collectively offer versatile solutions for soil stabilization and structural support, contributing significantly to geotechnical engineering practices (32). Soil Improvement using Industrial Waste is specifically tailored for sandy soils, utilizing industrial waste as a resource (33). All soft or loose inorganic soils, including sand, silt, clays, and others, can be stabilized by adding cement, lime, or asphalt using a dedicated in-place mixer or a spinning auger. These methods provide innovative approaches to soil improvement, offering sustainable solutions while enhancing soil properties for various engineering applications.

Table 3 Classification of soil liquefaction mitigation techniques.

	Enhancement of Drainage Properties	Densification of the Structure of Soils	Strengthening of the Soil Structure
Techniques (Punit Bhanwar and Trudeep Dave, 2021) (34)	Partial De-Saturation Induced	Vibro-Compaction	The process of grouting Penetration
	Earthquake PVDs	Vibro-replacement	Deep Soil mixing
	Electro-osmotic consolidation	Dynamic Compaction	Jet Grouting
		Compaction Grouting	Passive Site Remediation
		Blasting Compaction	Microbially-induced precipitation of calcite

CONCLUSION

Understanding the mechanisms of soil liquefaction and conducting appropriate tests are essential for mitigating the risks associated with this phenomenon. Liquefaction primarily affects sandy and silty soils of low plasticity, which can lose their strength when subjected to seismic activity. Engineers can prevent liquefaction's negative effects on infrastructure and the environment by being aware of the elements that lead to it. Liquefaction risk is most prominent in soils with particle sizes ranging from 0.002 to 2.36 mm, particularly silt and sand. The severity of liquefaction is influenced by factors such as groundwater depth and seismic activity. Thus, to reduce the risks of liquefaction, precise evaluation techniques and a comprehensive knowledge of soil characteristics are crucial. Tools such as software for interpreting Cone Penetration Test (CPT) data are valuable in these assessments. Understanding the dynamics of soil behaviour during earthquakes is crucial for risk management and the development of resilient infrastructure in earthquake-prone regions.

A crucial factor in foundation design is soil liquefaction, which can place large lateral loads on pile foundations. Piles that penetrate weak, possibly liquefiable soil layers to reach stronger strata must withstand bending moments brought on by lateral soil movements as well as horizontal loads from the superstructure. To ensure adequate resistance, piles may need to be designed with larger dimensions or increased reinforcement to withstand these additional forces during a seismic event. Effective soil improvement methods, such as sand compaction and stone columns or granular piles, have been identified as efficient and cost-effective solutions for enhancing soil shear resistance against liquefaction triggered by earthquakes. Additionally, the use of industrial waste in soil improvement has proven to be a cost-effective alternative. Emerging technologies, such as Admixture Stabilization and Grand Flex Mole Technology, show promise but have not yet gained widespread adoption. Furthermore, innovations in numerical modeling for simulating potential liquefaction scenarios are being explored to enhance disaster response planning and improve resilience.

Author Contributions

Authors contributed equally to conceptualization, data analysis, and manuscript writing for this study.

Conflict of Interest

The authors have no competing interests (financial or otherwise) to declare.

Ethics Approval

Not Applicable.

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