



Comprehensive Investigation of the Underlying Causes of Soil Liquefaction During Earthquakes

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ABSTRACT

Soil liquefaction is a critical geotechnical hazard that can cause severe damage to infrastructure and compromise the stability of ground foundations during seismic events. This study presents a comprehensive investigation into the primary factors contributing to soil liquefaction during earthquakes. The analysis begins with an overview of the general concept of liquefaction, followed by an in-depth examination of key causes, including the presence of saturated granular soils, high groundwater tables, low-density soil conditions, and the effects of seismic loading such as intensity, duration, and cyclic stress. The research further considers geological and topographical influences, such as soil type, grain characteristics, and ground slope. Emphasis is placed on understanding how these factors interact under earthquake-induced stress to trigger liquefaction. Finally, the study explores modern techniques to reduce the risk of liquefaction, focusing on chemical and mechanical soil stabilization methods, structural mitigation strategies, and the use of specialized equipment. The findings aim to contribute to more resilient geotechnical design and effective risk management in earthquake-prone regions.

Keywords:

Soil Liquefaction, Saturated Soil, Earthquake, Liquefaction Causes.



1. Introduction

Liquefaction may take place in loose soils that are saturated with water, particularly in areas that experience high-magnitude seismic events. This scenario holds particular significance for geotechnical assessments. Cyclic stress ratios play a crucial role in the liquefaction evaluation of water-saturated soils located in earthquake-prone areas. Soil liquefaction is recognized as a primary contributor to considerable damage during seismic events and represents a complex phenomenon that has long captivated the attention of soil mechanics experts. Saturated soils experience elevated pore water pressures, which result in considerable decreases in the shear strength necessary for the soil to endure seismic events [1,2]. When these soils experience earthquakes, they will exhibit significant deformations with nearly no strength, provided that their excessive pore water pressure attains the initial effective stress of the overburden [3,4]. The occurrence of liquefaction is commonly observed in alluvial-filled areas where favorable groundwater conditions are present, particularly as a result of earthquakes caused by monotonic shock loading. The rise in pore water pressure converts the soil into a viscous state, characterized by a lack of cohesion and minimal shear resistance, which ultimately initiates the liquefaction process [5-11]. In general, occurrence of liquefaction is commonly observed in alluvial-filled areas where favorable groundwater conditions are present, particularly as a result of earthquakes caused by monotonic shock loading. The rise in pore water pressure converts the soil into a viscous state, characterized by a lack of cohesion and minimal shear resistance, which ultimately initiates the liquefaction process. Seismic hazards can lead to significant social and economic losses as a result of ground shaking, landslides, structural failures, liquefaction, failures of retaining structures, lifeline hazards, and tsunamis. Among all the processes mentioned, the liquefaction of soil triggered by earthquakes plays a crucial role in the loss of both human lives and infrastructure. In the field of geotechnical engineering, evaluating soil liquefaction caused by earthquakes is a vital undertaking. Earthquakes can result from a variety of triggers, with the most prevalent being the movements of tectonic plates that release energy either within or along significant geological faults [12,13]. In fact, soil liquefaction caused by earthquakes is a destructive occurrence linked to the reduction of soil stiffness due to seismic activity, leading to disastrous transformations of the soil into a liquid-like state. One of the main factors contributing to soil liquefaction in the event of earthquakes is the existence of loose, saturated sandy soils. During seismic activity, pore water pressure quickly accumulates among the soil particles. If the soil lacks sufficient density to withstand this pressure, its structure fails, resulting in an abrupt decrease in shear strength and causing the soil to act more like a liquid than a solid [14]. This occurrence is particularly prevalent in regions characterized by shallow groundwater and inadequate drainage, where water struggles to dissipate during seismic events [15]. Various elements influence both the probability and intensity of liquefaction. These factors encompass the soil type and density, the level of saturation, the depth of the water table, as well as the magnitude and length of the earthquake. Comprehending these parameters is crucial for geotechnical engineers, especially when planning foundations or infrastructure in areas susceptible to earthquakes. Contemporary studies further highlight that liquefaction is not confined to undrained conditions; under specific situations, even drained soils may display liquefaction characteristics as a result of dynamic fluid movement.

2. Literature Review

Comprehending soil liquefaction has been a significant area of interest in the fields of geotechnical and earthquake engineering for many years, particularly in light of the severe consequences witnessed in historical earthquakes globally. Scholars have explored the physical and mechanical



properties of saturated soils subjected to seismic forces to determine the circumstances that increase the likelihood of liquefaction. Throughout the years, a variety of theoretical frameworks, laboratory investigations, and field case analyses have been established to elucidate the triggering mechanisms and impacts of liquefaction. This section intends to summarize the principal discoveries from earlier research, concentrating on the primary elements that lead to liquefaction, its effects on infrastructure, and the strategies suggested for its evaluation and prevention. Cetin et al. [16] studied the soil liquefaction sites following the February 6, 2023, Kahramanmaraş-Türkiye earthquake sequence. The main aim of this research was to explore the incidence and features of soil liquefaction triggered by seismic activity, specifically during the 2023 Türkiye-Kahramanmaraş earthquake sequence. This study sought to record field evidence of liquefaction, which includes surface expressions such as soil ejecta and ground deformations, while also examining the physical and plastic characteristics of the liquefied materials. Furthermore, an additional objective was to assess the susceptibility of fine-grained soils to liquefaction, with a particular focus on clayey and silty-clayey mixtures, which have historically been regarded as less prone to liquefaction. In another study, Santiago et al. [17] investigated the soil liquefaction due to large-magnitude subduction earthquakes. The research successfully established a numerical model that was calibrated utilizing centrifuge test data under free-field conditions. The model demonstrated a strong correlation with the observed results and was employed to perform an extensive parametric study. The results emphasize that the excess pore pressure ratio, shear strain, layer thickness, and CAV are significant indicators of liquefaction triggering during subduction earthquakes. Furthermore, the study resulted in the development of a simplified probabilistic tool that can estimate the probability of full, marginal, or no liquefaction in critical soil layers. This methodology provides a more customized and precise assessment technique for large-magnitude subduction events in comparison to conventional models. Li et al. [18] conducted a study on the effects of a low amount of non-plastic fines on soil liquefaction by dynamic centrifuge modeling. This research seeks to experimentally explore the impact of non-plastic fines on the liquefaction characteristics of sand through dynamic centrifuge testing. The study emphasizes the variations in CPT resistance, shear stiffness, liquefaction resistance, re-consolidation, and surface settlement that occur when minimal quantities of fines are introduced to clean sand. A study by Teixeira [19] focused on mechanisms to explain soil liquefaction triggering, development, and persistence during an earthquake. This research examines the processes that lead to soil liquefaction in the context of earthquakes, emphasizing the roles of pore water pressure, effective stress, and changes in volume in both the initiation and continuation of this phenomenon. Liquefaction takes place at a failure plane where the pore pressure surpasses the effective stress, which usually occurs during the most intense ground shaking. The ongoing nature of liquefaction is associated with soil layers that have low permeability or with the influx of water from springs in the bedrock. The model put forward elucidates the effects observed on the surface and the abrupt occurrences of liquefaction, while also underscoring the necessity for additional experimental verification. Liu et al. [20] examined predicting strain energy causing soil liquefaction. This research seeks to establish a comprehensive method for assessing the potential of soil liquefaction through a strain energy-based framework. A total of 165 sets of cyclic laboratory test data were scrutinized, leading to the proposal of a predictive model utilizing gene expression programming (GEP) to estimate the strain energy necessary for triggering liquefaction. The model's performance was evaluated via sensitivity analysis and validated against results from centrifuge and cyclic tri-axial tests. Following both numerical and experimental validation, the model was juxtaposed with existing strain energy-based methodologies. The results indicate that the GEP-based model provides a high level of accuracy in



forecasting the strain energy threshold for the initiation of liquefaction across diverse loading scenarios. In general, extensive research [21-27], has been conducted on soil liquefaction and its effect on the behavior of structures during earthquakes, and in each of these studies, different factors have been examined.

3. General Concept of Soil Liquefaction

Soil liquefaction refers to a process in which saturated soil experiences a loss of strength and stiffness, resulting in behavior akin to that of a liquid, particularly during seismic events. This phenomenon arises when the pore water pressure within the soil escalates due to dynamic forces, such as the shaking associated with an earthquake, leading to a disconnection among soil particles and a subsequent inability of the soil to bear weight. In fact, liquefaction occurs when loosely arranged, water-saturated sediments located at or near the surface of the ground lose their structural integrity due to intense ground shaking. The occurrence of liquefaction beneath buildings and various structures can lead to significant damage during seismic events. On the other hand, liquefaction refers to a process whereby the strength and rigidity of soil diminish due to seismic activity or other forms of rapid loading. This phenomenon, along with its associated effects, has caused significant destruction during numerous historical earthquakes globally. Liquefaction-related damages have been recognized as one of the major geohazards caused by strong earthquakes [28-30].

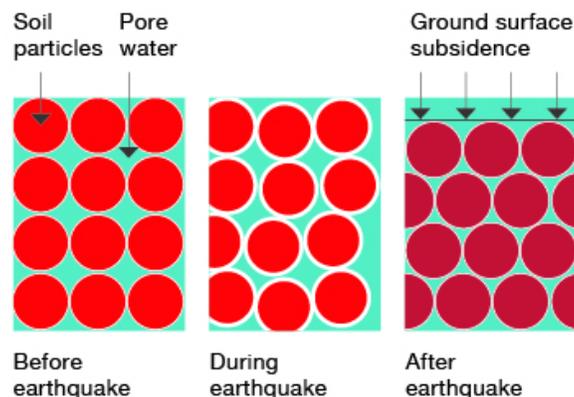


Figure 1: The liquefaction process (taken from MBIE, Planning and Engineering Guidance for Liquefaction Prone Land, 2017)

Damage arises when liquefaction results in unacceptable ground displacements or ground failure. The types of failure encompass flow failure, inertially induced embankment deformation, lateral spread, loss of bearing strength, and ground settlement. Evaluating the displacements caused by these failure types is typically intricate and necessitates the knowledge of geotechnical experts.

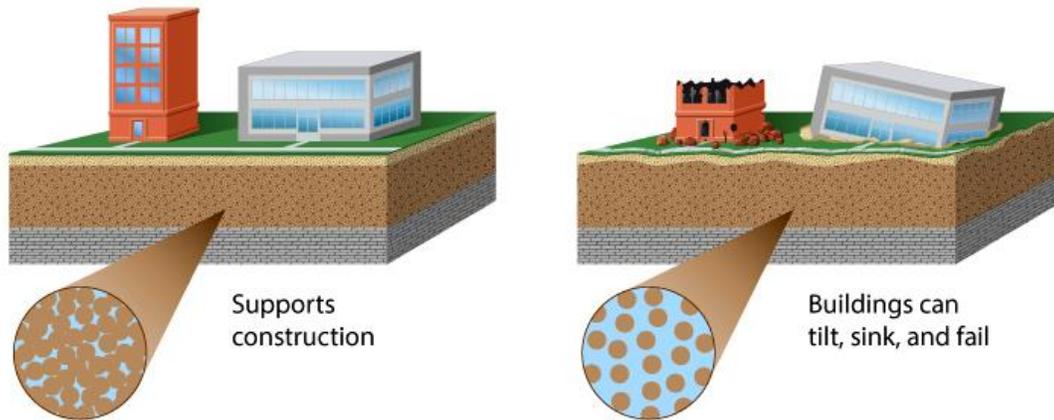


Figure 2: Liquefaction occurs when loose soil, saturated with water, is shaken by an earthquake, causing the soil to behave like a liquid



Figure 3: The collapse of the two-level Cypress Freeway was the most lethal event associated with the 1989 Loma Prieta earthquake. Reclaimed marshland amplified the shaking and soil liquefaction occurred

As a result, liquefaction requires three factors: The first is soil composed of loose, granular sediment often “made” land, such as when marshland is filled with material to create solid ground.

4. Main Causes of Soil Liquefaction During Earthquakes

Soil liquefaction represents a significant geotechnical phenomenon that frequently manifests during intense seismic events, especially in saturated, loose, and cohesionless sandy soils. The fundamental mechanism behind liquefaction is the accumulation of excess pore water pressure resulting from cyclic shear stresses generated by seismic activity. As these stresses escalate, the soil particles are inclined to reorganize into a denser arrangement; however, under undrained conditions, this compaction triggers a swift increase in pore pressure and a corresponding decline in effective stress. When the effective stress nears zero, the soil behaves akin to a liquid, forfeiting its shear strength and stiffness. Various factors, including soil type, relative density, grain size



distribution, saturation level, and the intensity and duration of ground shaking, play a crucial role in determining the vulnerability to liquefaction.

4.1. Presence of Saturated Granular Soils (Sand or Silt)

The presence of saturated granular soils, such as loose sand or silt, is a fundamental condition for the occurrence of soil liquefaction. These types of soils have low cohesion and relatively high permeability, allowing pore water to occupy the spaces between particles. When fully saturated, and especially in loose states, these soils are highly susceptible to a sudden buildup of pore water pressure under cyclic loading, such as earthquake shaking. This buildup can lead to a drastic reduction in effective stress, causing the soil to temporarily behave like a fluid. The grain size, uniformity, and density of the granular material significantly affect its liquefaction potential [31]. Fine, non-cohesive soils—like silty sands and non-plastic silts—are especially susceptible to liquefaction when subjected to seismic loading. These soils, defined by their small particle size and lack of cohesion, demonstrate low shear strength and easily build up excess pore water pressure during cyclic shaking, which greatly diminishes their effective stress [32].

4.2. High Groundwater Table

When the water table is situated near the surface of the ground, saturated soils are more susceptible to a quick increase in pore-water pressure during seismic activity, which greatly diminishes effective stress and can result in liquefaction. Empirical and numerical research, especially in fine sandy soils with shallow groundwater, indicates that excess pore pressure can form rapidly, undermining soil strength and heightening the risk of liquefaction [33].

4.3. Low Soil Density (Loose Compaction)

Loose, uncompacted soils—particularly those that are saturated, low-density sands and silty sands—exhibit a heightened vulnerability to degradation in strength and loss of stiffness when subjected to seismic loading. During cyclic stresses induced by earthquakes, these soils tend to contract instead of dilating, leading to a swift accumulation of excess pore-water pressure in undrained conditions. This increase in pressure diminishes effective stress and shear resistance, ultimately resulting in liquefaction [34].

4.4. Earthquake Intensity and Duration

More intense and prolonged earthquakes greatly increase the likelihood of soil liquefaction. Shaking of higher magnitudes produces greater cyclic shear stresses, and extended ground motions lead to an increased number of loading cycles—both of these elements accelerate the accumulation of excess pore-water pressure, reducing effective stress and instigating liquefaction. In particular, observations from the 2011 Great East Japan Earthquake—characterized by moderate accelerations but over 300 s of shaking—demonstrated substantial liquefaction in Tokyo Bay due to long-duration stress even without extremely strong intensity, highlighting the importance of total shaking duration.

4.5. Low Effective Stress Conditions

Loose soil located close to the surface undergoes minimal effective confining stress, making it considerably more susceptible to liquefaction in the event of seismic activity. This susceptibility arises from the fact that reduced confining stress diminishes the resistance of the soil, necessitating a lower cyclic stress ratio to initiate pore pressure accumulation and subsequent liquefaction.



Laboratory and field studies consistently show that as effective confining pressure increases, the cyclic resistance ratio (CRR) needed for liquefaction also increases—meaning soils at shallow depth (low $\sigma'v$) are more vulnerable under the same seismic loading [35].

4.6. Cyclic Loading from Seismic Vibrations

The repeated application of shear stress during seismic events leads to a gradual accumulation of excess pore water pressure in saturated soils. This accumulation subsequently diminishes the effective stress and shear strength of the soil matrix. As a result, this phenomenon compromises the integrity of the soil structure, rendering it increasingly vulnerable to liquefaction as the soil progressively loses its capacity to bear loads under cyclic loading scenarios.

4.7. Soil Structure and Geological History

Recently deposited or loosely bonded soils, including loose sands and silty sands, frequently demonstrate low cohesion and weak inter particle bonds, making them structurally susceptible to seismic stresses. These types of soils are likely to undergo rapid densification when subjected to cyclic loading, resulting in considerable pore water pressure accumulation and a decrease in effective stress, which may initiate liquefaction during seismic events. The vulnerability of these soils to liquefaction is affected by various factors, including particle size distribution, fines content, and initial density, with loose and inadequately consolidated deposits being especially at risk.

4.8. Topography and Ground Slope

Sloped terrains have a considerable impact on the dynamics of liquefaction during seismic events, as they enhance its effects and elevate the likelihood of lateral spreading and flow failures. The gravitational forces acting on sloped surfaces, coupled with the reduction in soil strength resulting from liquefaction, can result in significant ground displacement, which in turn may lead to slope instability and damage to infrastructure. Consequently, comprehending the impacts of slope is essential for evaluating and mitigating seismic hazards in hilly and mountainous areas.

5. Soil Type and Grain Characteristics

The characteristics of soil type and grain are essential elements that govern the susceptibility to liquefaction. Recent research indicates that clean, poorly graded sands exhibit the greatest potential for liquefaction, particularly when they are loosely packed and saturated. The effect of fines is complex: minimal amounts of non-plastic fines may lead to an increase in pore pressure accumulation, while plastic fines generally enhance soil stability by improving cohesion. The distribution of grain sizes has a significant impact on the behavior of soil when subjected to cyclic loading. Soils that are well-graded, featuring a wider range of particle sizes, enhance particle interlock and mitigate the risk of liquefaction by restricting volumetric contraction and the buildup of pore pressure. In contrast, uniformly graded sands do not possess this interlocking capability, rendering them more susceptible to liquefaction. The shape of grains and their surface roughness play a crucial role in determining liquefaction resistance. Grains that are angular and have a rough texture enhance the frictional resistance among particles, which in turn bolsters the material's ability to withstand cyclic shear stresses. In contrast, grains that are rounded and smooth facilitate a more straightforward rearrangement of particles, which can lead to a quicker generation of pore pressure and an increased likelihood of liquefaction.



6. Soil Saturation and Groundwater Conditions

Soil saturation plays a vital role in determining the likelihood of liquefaction occurring during seismic activities. Soils that are completely saturated, especially sandy and silty sandy types, exhibit a significant vulnerability to liquefaction due to the fact that pore water facilitates the accumulation of excess pore pressure when subjected to cyclic loading. In soils that are unsaturated or only partially saturated, the air present in the pore spaces can compress, leading to a decrease in the rate at which pore pressure rises, thus enhancing resistance to liquefaction. In general, the depth of the groundwater table has a direct impact on the saturation levels of soils, which in turn influences their susceptibility to liquefaction. Soils situated in proximity to shallow water tables are often completely saturated, resulting in conditions that promote the accumulation of pore pressure and the potential for liquefaction during seismic events. In contrast, lower groundwater levels frequently lead to the formation of unsaturated soil zones, thereby diminishing the likelihood of liquefaction as a result of the presence of air in the pore spaces. The variability of groundwater conditions, resulting from seasonal changes or human activities, can impact soil saturation and the potential for liquefaction. Variations in groundwater levels, driven by factors such as rainfall, irrigation, or groundwater extraction, can alter the saturation levels of near-surface soils, thereby influencing their vulnerability to liquefaction over time. This dynamic behavior necessitates diligent monitoring and integration into seismic hazard evaluations. The interaction between soil permeability and drainage properties, along with saturation levels, governs the dissipation of pore pressure during seismic events. Soils characterized by low permeability impede drainage, leading to a swift accumulation of pore water pressure under cyclic loading, which heightens the risk of liquefaction. Conversely, soils that are well-drained can dissipate excess pore pressures more efficiently, thereby enhancing stability in the face of earthquakes. Comprehensive numerical and experimental investigations have improved the comprehension of the influence of saturation and groundwater on liquefaction. High-resolution centrifuge experiments and pore pressure monitoring have shown that fully saturated conditions are essential for liquefaction, and that variations in groundwater levels considerably affect soil behavior during seismic loading.

As a result, conditions of soil saturation and groundwater play a crucial role in determining both the likelihood and intensity of soil liquefaction in the event of earthquakes. Soils that are saturated, particularly those that are loose and sandy, exhibit a heightened vulnerability to liquefaction. This susceptibility arises from the elevation of pore water pressure that occurs during seismic activity, which diminishes the soil's capacity to endure stress. Dwiyantoro et al. [33] studied the influence of Groundwater Table Fluctuation on Liquefaction Potential Analysis Using Cyclic Stress Approach. This study examines the potential for liquefaction in Sleman, Yogyakarta, through the analysis of Standard Penetration Test (SPT) and Cone Penetration Test (CPT) data utilizing a cyclic stress methodology. The investigation emphasizes the impact of varying groundwater table (GWT) depths, specifically those ranging from -8 m to -6 m. To evaluate risk levels, the liquefaction safety factor (FSL), liquefaction potential index (LPI), and liquefaction severity index (LSI) were computed. The findings reveal that shallower groundwater tables correspond to increased values of both LPI and LSI, thereby heightening susceptibility to liquefaction. Notably, soil layers demonstrated liquefaction potential under all GWT conditions, with LPI classifications varying from high to very high at deeper GWT depths (-8 m and -7 m) and reaching very high at the shallowest depth (-6 m). Furthermore, LSI classifications transitioned from low risk at -8 m to low-to-moderate risk at shallower depths, underscoring the considerable effect of groundwater depth on the assessment of liquefaction risk.



7. Techniques for Reducing the Risk of Soil Liquefaction

Mitigating the risk of soil liquefaction is an essential component of geotechnical engineering, particularly in areas prone to seismic activity. Liquefaction can result in significant ground deformation, structural collapse, and damage to infrastructure during seismic events. Consequently, a range of ground improvement methods has been devised and implemented to alleviate this risk by improving the strength, density, and drainage capabilities of vulnerable soils. These methods differ in terms of complexity, cost, and appropriateness based on soil characteristics, project specifications, and levels of seismic risk. It is crucial to comprehend the various liquefaction mitigation strategies to choose the most effective and feasible solution for a specific location. In other hand, mitigating soil liquefaction has emerged as a vital factor for construction and mining endeavors in regions prone to seismic activity. The loss of strength in saturated soil during earthquakes can lead to catastrophic outcomes for both structures and infrastructure. This occurrence, in which solid ground temporarily acts like a liquid, presents considerable challenges for engineers and project managers in at-risk areas. In general, soil liquefaction mitigation strategies can be classified into various categories, each tailored to specific applications and advantages based on project needs and site characteristics. These techniques are designed to either decrease the probability of liquefaction happening or lessen its impact on structures. Choosing the right method is contingent upon several factors, including soil conditions, project budget, available machinery, environmental factors, and the importance of the structure that requires protection. Ground densification techniques function by enhancing the density of vulnerable soils, which consequently diminishes their propensity to liquefy. These methods encompass vibro-compaction, dynamic compaction, and compaction grouting. Vibro-compaction entails the insertion of a vibrating probe into the earth to reorganize soil particles into a more compact arrangement. Dynamic compaction employs heavy weights that are dropped from a height to compress loose soils. Compaction grouting involves the injection of rigid grout into the soil to displace and compact the adjacent materials. An alternative method focuses on improving drainage, which aids in alleviating excess pore water pressure during seismic occurrences. Strategies encompass the installation of stone columns, prefabricated vertical drains, and horizontal drainage layers. These measures create channels for water to exit, thereby averting the accumulation of pressure that can result in liquefaction. This strategy is especially beneficial in regions where densification techniques may be unfeasible due to site limitations or the presence of existing structures. To reduce the risk of soil liquefaction, various techniques can be utilized, which can be generally classified into densification, drainage, grouting, and reinforcement. The objective of these methods is to either enhance the density of the soil, facilitate drainage to lower pore water pressure, fortify the soil matrix, or bolster the soil structure, thereby minimizing the likelihood of liquefaction occurring during seismic activities.

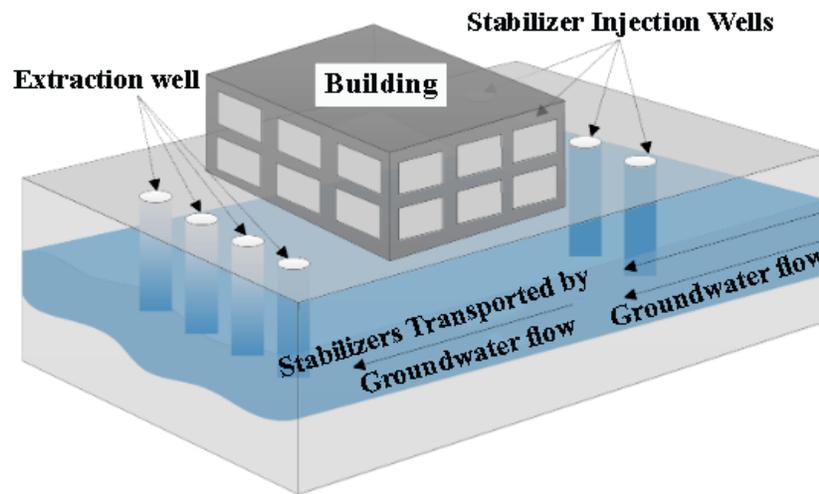


Figure 4: Concept for passive site stabilization [36,37]

7.1. Chemical and Mechanical Stabilization Solutions

Chemical soil stabilization techniques such as cement, lime, and fly ash are widely utilized for the enhancement of inadequate subgrades. While the initial affordability of these chemicals may be appealing, various other considerations essential for effective installation such as soil compatibility, curing duration, and the requirement for specialized equipment are frequently neglected. Additionally, there are significant repercussions for breaches of environmental regulations and uncertainties regarding the long-term efficacy of these methods. Tensar multi-axial geogrids represent the pinnacle of innovation within the industry. They improve the performance of substandard soils by interlocking with unbound aggregate materials. As the granular substances pass through the openings of the geogrid, they experience lateral restraint and achieve a greater level of confinement. This more rigid, stabilized layer mitigates rutting, enhances bearing capacity, and boosts traffic capacity. Mitigating soil liquefaction via chemical stabilization entails the application of binding agents that enhance the integrity of the soil structure. This method converts loose, vulnerable soils into more cohesive substances that are resistant to liquefaction. Typical techniques encompass deep soil mixing, jet grouting, and permeation grouting utilizing materials like cement, lime, or various chemical compounds. Jet grouting employs high-pressure jets to erode soil while concurrently mixing it with grout, resulting in the formation of cylindrical columns of stabilized material. This technique is adaptable and can be utilized in locations with restricted access or where it is essential to minimize vibration. Mechanical stabilization techniques encompass the implementation of stone columns, aggregate piers, or various other rigid inclusions that enhance the soil matrix. These components not only facilitate drainage pathways but also establish a composite ground system characterized by enhanced strength and stiffness. The rigid inclusions assist in load distribution and alleviate stress on liquefiable soils, thereby minimizing both settlement and lateral spreading.

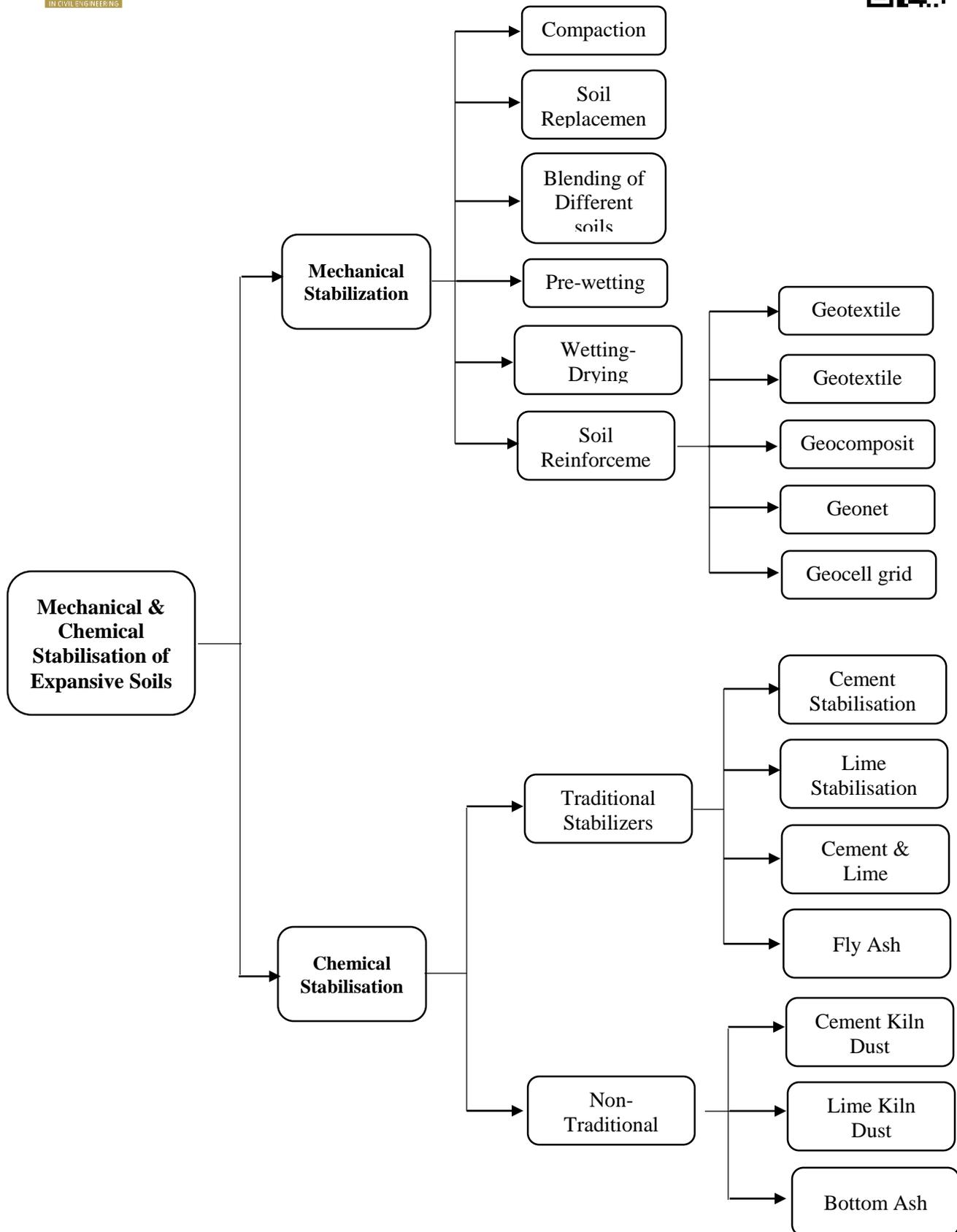


Figure 5: Mechanical and Chemical Stabilizations methods of expansive soils



7.2. Structural Approaches to Managing Liquefaction Risk

Mitigating soil liquefaction can also be approached through structural design techniques that allow for potential ground movement instead of attempting to prevent liquefaction itself. These methods are especially beneficial when it is impractical or financially unfeasible to treat the entire site. Structural solutions emphasize the design of foundations and structures capable of enduring the impacts of liquefaction without experiencing catastrophic failure. Deep foundation systems, including piles that are driven into stable soil layers beneath liquefiable zones, effectively transfer structural loads to competent soil or rock. These foundations completely avoid the problematic soils, thereby guaranteeing stability even in the event of liquefaction in adjacent areas. A variety of pile types may be employed, such as driven piles, drilled shafts, and micropiles, based on site conditions and structural needs. Modifications in structural design can also assist in alleviating the impacts of liquefaction. This encompasses the creation of flexible utility connections that are capable of adapting to ground movement, the integration of features that tolerate settlement, and the application of seismic isolation systems. In regions that are seismically active, building codes frequently contain particular stipulations for the design of structures situated in areas susceptible to liquefaction. As a result, structural methods for mitigating liquefaction risk mainly focus on improving soil strength and drainage capabilities, as well as designing buildings to endure possible ground shifts and settling. This encompasses strategies such as soil enhancement, fortifying foundations, and integrating adaptable design features to respond to seismic events.

7.3. Specialized Equipment for Implementation

The execution of these mitigation strategies necessitates specialized equipment and expertise. In the case of ground improvement techniques that utilize grouting, it is crucial to have high-performance grout mixing plants and pumping systems. These systems are required to provide accurately mixed grout at regulated rates and pressures to attain the intended soil enhancement. In fact, when devising ground stabilization initiatives aimed at mitigating unstable soil conditions, various practical factors can significantly contribute to the successful execution of the project. It is essential to assess these elements during the planning stage to determine the most suitable methods and equipment tailored to the unique requirements of the project. Site investigation represents a critical initial phase in any ground improvement endeavor. A comprehensive geotechnical evaluation aids in determining the nature and extent of problematic soils, enabling engineers to choose the most suitable mitigation approach. This investigation must encompass soil borings, standard penetration tests, cone penetration tests, and laboratory analyses of soil samples. The information gathered offers vital insights into soil type, density, groundwater conditions, and various other elements that affect liquefaction vulnerability and treatment alternatives.

The selection of equipment must take into account not only the technical specifications of the selected mitigation approach but also logistical considerations, including site accessibility, power supply, and environmental limitations. In the case of remote locations or projects with restricted infrastructure, utilizing self-sufficient, modular equipment presents considerable benefits. Systems that are capable of being moved in standard shipping containers or on flatbed trucks offer adaptability for deployment in difficult environments.

Financial factors play a crucial role in determining the choice of mitigation strategies. Although the upfront construction expenses are significant, the assessment must also take into account life-cycle costs, which encompass possible damages from future seismic occurrences. Often, the expenditure on ground enhancement constitutes a minor portion of the overall project budget, yet it offers considerable risk mitigation and possible savings in structural design.



8. Conclusion

Reducing the likelihood of soil liquefaction is a crucial aspect of geotechnical engineering, especially in regions susceptible to seismic events. Liquefaction can lead to considerable ground deformation, structural failure, and infrastructure damage during earthquakes. As a result, various ground enhancement techniques have been developed and applied to mitigate this risk by enhancing the strength, density, and drainage properties of at-risk soils. Mitigating soil liquefaction is a vital component of geotechnical engineering, particularly in areas prone to seismic activity. By comprehending the processes involved in liquefaction and applying suitable countermeasures, engineers can greatly diminish the risks posed to buildings and infrastructure. The array of techniques at their disposal ranging from ground densification and improved drainage to chemical stabilization and structural interventions offers diverse solutions for tackling liquefaction issues across different site conditions and project scenarios. Choosing a suitable mitigation strategy necessitates a thorough evaluation of site-specific elements, project needs, and practical limitations. Comprehensive site assessment, appropriate equipment choice, and quality assurance during the execution phase are crucial for achieving successful results. By incorporating these factors into project planning and implementation, engineers can proficiently address liquefaction risks and guarantee the durability of constructed infrastructure.

9. References

- 1- Atigh, E., Byrne, P.M., 2003. Flow liquefaction failure of submarine slopes due to monotonic loadings- an effective stress approach. *Submarine Mass Movements and Their Consequences*. Springer, Netherlands.
- 2- Cai, Y.Q., Guo, L., Jardine, R.J., Yang, Z.X., Wang, J., 2017. Stress-strain response of soft clay to traffic loading. *Geotechnique*. 67 (5), 446–451.
- 3- Bray, J.D., Sancio, R.B., 2006. Assessment of the Liquefaction Susceptibility of Fine-Grained Soils. *J. Geotech. Geoenviron. Eng.* 132 (9), 1165–1177.
- 4- Asadi, M.S., Orense, R.P., Asadi, M.B., Pender, M.J., 2019. Postliquefaction behavior of natural pumiceous sands. *Soil Dyn. Earthq. Eng.* 118, 65–74.
- 5- Firoozi AA, Firoozi AA, Baghini MS (2016) A Review of Clayey Soils. *Asian J Appl Sci* 4.
- 6- Firoozi AA, Firoozi AA, Baghini MS (2017a) A review of physical and chemical clayey. *J Civ Eng Urban* 6:64–71.
- 7- Firoozi AA, Olgun CG, Firoozi AA, Baghini MS (2017b) Fundamentals of soil stabilization. *Int J Geo Eng* 8:26.
- 8- Mollamahmutoglu M, Kayabali K, Beyaz T (1999) Kolay E (2003) Liquefaction-related building damage in Adapazari during the Turkey earthquake of August 17. *Eng Geol* 67:297–307.
- 9- Sladen J, D'hollander R, Krahn J (1985) The liquefaction of sands, a collapse surface approach. *Canad Geotech J* 22:564–578.
- 10- Yilmaz I, Bagci A (2006) Soil liquefaction susceptibility and hazard mapping in the residential area of Ku'tahya (Turkey). *Environ Geol* 49:708–719.
- 11- Youd TL, Idriss IM (2001) Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. *J Geotech Geoenviron Eng* 127:297–313.
- 12- Kanamori, H. The energy release in great earthquakes. *J. Geophys. Res.* 1977, 82, 2981–2987.
- 13- Calais, E.; Camelbeeck, T.; Stein, S.; Liu, M.; Craig, T.J. A new paradigm for large earthquakes in stable continental plate interiors. *Geophys. Res. Lett.* 2016, 43, 10–621.



- 14- Shelley, E. O., Mussio, V., Rodríguez, M., & Chang, J. G. A. (2015). Evaluation of soil liquefaction from surface analysis. *Geofísica internacional*, 54(1), 95-109.
- 15- Ben-Zeev, S., Goren, L., Toussaint, R., & Aharonov, E. (2023). Drainage explains soil liquefaction beyond the earthquake near-field. *Nature communications*, 14(1), 5791.
- 16- Cetin, K. O., Soylemez, B., Guzel, H., & Cakir, E. (2025). Soil liquefaction sites following the February 6, 2023, Kahramanmaraş-Türkiye earthquake sequence. *Bulletin of Earthquake Engineering*, 23(3), 921-944.
- 17- Santiago, Y., Ledezma, C., & Tiznado, J. C. (2025). Assessing soil liquefaction due to large-magnitude subduction earthquakes. *Soil Dynamics and Earthquake Engineering*, 188, 109069.
- 18- Li, Z., Escoffier, S., & Audrain, P. (2025). Study on the effects of a low amount of non-plastic fines on soil liquefaction by dynamic centrifuge modeling. *Soil Dynamics and Earthquake Engineering*, 195, 109400.
- 19- Teixeira, F. (2024). Mechanisms to explain soil liquefaction triggering, development, and persistence during an earthquake. *Earthquake Science*, 37(6), 558-573.
- 20- Liu, Y., Javdanian, H., & Tahmasb, A. (2024). Predicting strain energy causing soil liquefaction. *Transportation Geotechnics*, 49, 101419.
- 21- Mele, L., Lirer, S., & Flora, A. (2024). Induced partial saturation: from mechanical principles to engineering design of an innovative and eco-friendly countermeasure against earthquake-induced soil liquefaction. *Geosciences*, 14(6), 140.
- 22- Lee, H. H., Hsu, C. F., Chao, S. J., & Chi, C. C. (2022). A Study on the Reasons for No Soil Liquefaction Occurring in the Lanyang Plain in a Strong Earthquake Area. *Sustainability*, 14(14), 8244.
- 23- Hu, J., Tan, Y., & Zou, W. (2021). Key factors influencing earthquake-induced liquefaction and their direct and mediation effects. *Plos one*, 16(2), e0246387.
- 24- Wu, Y. T. (2022). Changes in soil conditions before and after earthquakes at a repetitive soil liquefaction site in Taiwan. *Geophysics*, 87(3), B179-B191.
- 25- Fatima, T., Sadique, M. R., & Alam, A. A. (2023). A review on impacts and mitigation of liquefaction of soil around the tunnels. *Journal of Failure Analysis and Prevention*, 23(5), 1822-1840.
- 26- Ghanizadeh, A. R., Aziminejad, A., Asteris, P. G., & Armaghani, D. J. (2023). Soft computing to predict earthquake-induced soil liquefaction via CPT results. *Infrastructures*, 8(8), 125.
- 27- Zhang, J., & Wang, Y. (2021). An ensemble method to improve prediction of earthquake-induced soil liquefaction: a multi-dataset study. *Neural Computing and Applications*, 33(5), 1533-1546.
- 28- Idriss IM, Boulanger RW. *Soil liquefaction during earthquakes*. Richmond, CA: Earthquake Engineering Research Institute; 2008.
- 29- Tuttle M, Law KT, Seeber L, Jacob K. Liquefaction and ground failure induced by the 1988 Saguenay, Quebec, earthquake. *Can Geotech J* 1990;27(5):580–9.
- 30- Mollamahmutoglu M, Kayabali K, Beyaz T, Kolay E. Liquefaction-related building damage in Adapazari during the Turkey earthquake of August 17, 1999. *Eng Geol* 2003;67:297–307.
- 31- Liu, Y., Javdanian, H., & Tahmasb, A. (2024). Predicting strain energy causing soil liquefaction. *Transportation Geotechnics*, 49, 101419.
- 32- Dang, Q. H., Reiffsteck, P., Vu, M. N., Nguyen-Sy, T., & Pham, V. H. (2024). Effect of plastic fine content on the static liquefaction potential of sandy soil. *Applied Sciences*, 14(13), 5881.
- 33- Aini, I., Wilopo, W., & Fathani, T. F. (2024). The Correlation Of Liquefaction With Excess Pore Water Pressure In Langkat, North Sumatra. *GEOMATE Journal*, 26(114), 117-125.



- 34- Kumar, D., & Kumari, S. (2024). Assessment of liquefaction susceptibility of fine-grained soil based on soil classification. *Indian Geotechnical Journal*, 54(4), 1366-1380.
- 35- National Academies of Sciences, Engineering, and Medicine. (2021). State of the art and practice in the assessment of earthquake-induced soil liquefaction and its consequences (D. Tramontina & R. Boulanger, Eds.). The National Academies Press. <https://doi.org/10.17226/23474>.
- 36- Gallagher, P.M.; Pamuk, A.; Abdoun, T. Stabilization of Liquefiable Soils Using Colloidal Silica Grout. *J. Mater. Civ. Eng.* 2007, 19, 33–40.
- 37- Gallagher, P.M.; Mitchell, J.K. Influence of colloidal silica grout on liquefaction potential and cyclic undrained behavior of loose sand. *Soil Dyn. Earthq. Eng.* 2002, 22, 1017–1026.