https://doi.org/10.33261/jaaru. 2022.29.3.001 *Association of Arab Universities Journal of Engineering Sciences (2022)29(3): 01-11*

Association of Arab Universities Journal of Engineering Sciences
مجلة اتحاد الجامعات العربية للدراسات والبحوث الهندسية

كلية الهندسة - جامعة بغداد

جمعية كليات الهندسة اعضاء اتحاد الجامعات العربية

A review of the Performance of Piles in Liquefiable Soil

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Published online: 30 September 2022

Abstract— Extensive damage to the pile-supported bridges and other structures in liquefiable soil has been observed in many earthquakes around the world. Pile foundation failure characteristics can occur during earthquake events in liquefiable soil presented by large displacement, pure bending, maximum shear, and progressive pore water pressure. The occurrence of liquefaction often causes large ground deformations that impose the kinematic (lateral and axial) loads on the pile foundation and reduction in pile capacity to resist the axial and lateral loads (i.e., tip end bearing or lateral subgrade reaction and loss of shaft resistance) that can lead to excessive deformations under static and inertial loads from the superstructure. The design of laterally loaded piles requires estimating the lateral displacement and bending moment under the load concerning desired project criteria, pile geometry and soil conditions. Finally, previous studies showed the performance of pile foundation in liquefiable soil under static axial loading on the pile cap or pile head from the superstructure.In contrast, studies on combined static axial and lateral loadings during earthquake events are limited and contain a suitable analysis method. This paper covered the performance of pile foundations in liquefied soil under different conditions of earthquake events. The analysis process became easier with the debut of powerful computers and simulation tools like finite element software.

Keywords— *Liquefaction. Earthquake event. Failure piles. Lateral response in liquefied soil.*

1. Introduction

Piles are long and slender members inserted into the ground to support heavily loaded structures such as (bridges, buildings, and jetties or oil platforms), where the ground is critically weak to support the structure on its own. Under earthquake events, loose to medium dense saturated sandy soil liquefies and behaves like a solid suspension due to the generation of excess pore water pressure, or the sand soil behaves like" quicksand," which cannot bear any loads. These soils are named "liquefiable deposits," and the phenomenon is named is "liquefaction" [15]. The piles must be designed to resist two parameters: The first one is internal forces from the superstructure. In contrast, the second one is kinematic forces arising from the deformation of the surrounding soil due to the passage of seismic waves [11]. Piles carry both axial and lateral loadings. The lateral loads are due to wave, wind, impact loads, and earthquake, and the lateral load is resisted by soil-pile interaction depending on (pile diameter, pile materials, soil properties, and bed slope of the ground). In contrast, the axial load is transmitted to the soil through the side friction between the soil-pile interface and base resistance offered by the soil bed [43]. The pile performance in liquefied soil is a complex problem due to the effect of the progressive build-up of excess pore water pressure and decrease of stiffness in the saturated soil; this could be attributed to the nonlinearity of soil behaviour during earthquake events (e.g. [**17**, 30, 50, 59, 67, 65, 72, and 78].

Earthquake-induced liquefaction can cause noticeable damage to human lives and buildings. Despite the contribution effort achieved in the mitigation of liquefaction during the last decades, major damage still occurs in seismic areas worldwide. The pile foundations response under combined loadings in liquefied is still not well addressed due to its vast complexity and the main issues that handle a simple answer. Although numerical models offer valuable help in these complex problems, it is important to find pile foundations' main response to simplify the models, saving computation time while keeping them accurate. The paper covers the liquefaction phenomenon in terms of affected factors and failure mechanism foundations during earthquake events. This research revised the literature, including various proceedings papers and journals and thesis (e.g., MSc PhD). The review scope included manuscripts published until the end of 2019.

2. Liquefaction

The liquefaction phenomenon was firstly studied in 1964 after the earthquake in Niigata, Japan. The liquefiable soil can be defined as the loss in shear resistance during monotonic, cyclic, or shacking loading and flows in a manner resembling a liquid. The soil liquefaction is defined as transforming a solid-state to a liquid state due to pore pressure increased, and effective stress is reduced [75]. It can be shown many characteristics when evaluating the liquefaction phenomena :

•Seismic conditions: included the magnitude, intensity, and duration of the earthquake motions. The intensity and magnitude depend on the propagation of a shear wave through the soil skeleton and the hypocentral distance.

•Geological and geotechnical conditions: involve river channels, wind deposits, alluvial soils, and poorly compacted fill. Hence, the liquefaction potential will be induced due to the low permeability of poorly graded sand.

On the other hand, the uniformity coefficient increases the probability of liquefaction when its value is equal to 2 or higher. Other criteria, the saturated soils can be classified with a plastic index (PI) less than 12 and liquid limit (LL) less than 37 as potentially liquefiable, provided that the natural moisture content of the soil is greater than 80% of the liquid limit 0.8 LL. Finally, the phreatic surface, confining pressure, and shear stress there is another important consideration for the development of pore water pressure and the occurrence of liquefaction phenomenon [23, and 44]. Also, this section describes a review of different parameters that affect the characteristics behaviour of liquefied soil. In recent years, soil liquefaction has been identified as a significant concern in geotechnical engineering in designing and constructing buildings or bridges.

It could be noted that the resistance of sands to liquefaction vary over a range of parameters, for instance: confining pressure (e.g. [29, and 55]), initial relative density (e.g. [26, 60, 63, and 71]), presence of static shear stress (e.g. [37, 54, 70, and 77]), specimen preparation method (e.g. [38]) and shaking characteristics such as many cycles and intensity of the shaking.

Al-busoda [4] studied the liquefaction potential of Baghdad city in Iraq by taking (7) sites. The factor of safety variation with depth, settlement, and lateral spreading due to liquefaction was studied. The author showed the acceleration has a significant effect on the soil liquefaction susceptibility; on the other hand, the magnitude is minimal. The procedure by NCEER 1997 was more suitable to estimate the liquefaction susceptibility of Baghdad soil, and a new chart was developed, as shown in **Fig. 1**. This chart is related to the factor of safety versus liquefaction and the corrected number of blows of SPT. It is vital to investigate the various parameters controlling earthquake events.

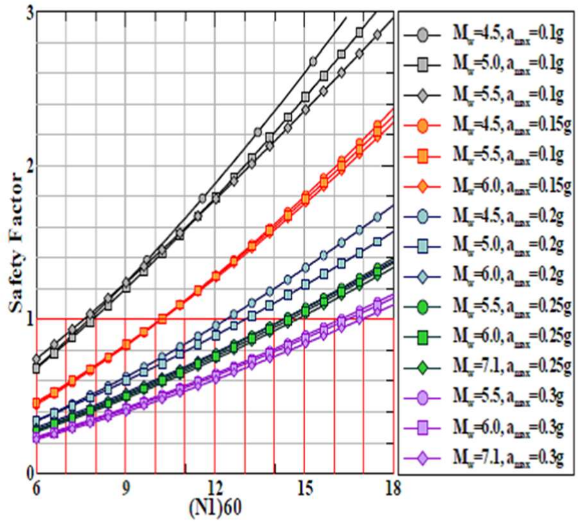


Figure 1: Proposal chart for assessing liquefaction of Baghdad soil, [4]

From the literature reviews and field tests include [20, 19, 16, and 67], the liquefaction is analyzed by many factors such as (particle size, grain composition, relative density, fines content, drainage condition, effective vertical stress and over consolidation, the thickness of the sand layer, degree of saturation, depth of sand layer, groundwater table, seismic strain history, epicentral distance, and magnitude, duration of earthquakes) (e.g. [69, and 61]). Liquefiable soil is commonly addressed with large earthquake events. The earthquakes of **Niigata** in 1964, **Alaska** in 1964, **Kobe** in 1995, and **Kocaeli/ Duzce** in 1999 have illustrated the significance and extent of damages caused by soil liquefaction. Various bridges and buildings collapsed by liquefaction events [49]. Liquefaction is sometimes coupled with sand boiling after an earthquake or during shaking, the excess pore pressure dissipates by an upward flow of pore pressure, and the hydraulic gradient reaches the critical value, and effective vertical stress will reach zero. In this case, water velocity will be sufficient to carry sand particles to the surface. **Fig. 2** shows a sand boil after the liquefaction-Liquefaction-induced boiling has ceased [64]. Many studies were carried out to present liquefaction and lateral spreading of soil, as shown in **Fig. 3** (e.g. [40, 45, 56 and 22]).

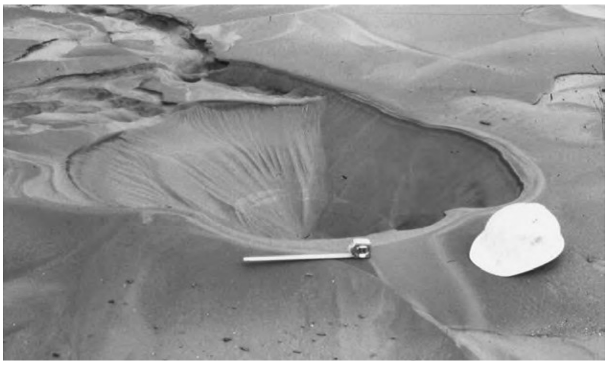


Figure 2: Sand boils after liquefaction-induced boiling from the 1989 Loma Prieta, C000alifornia earthquake has ceased [61]

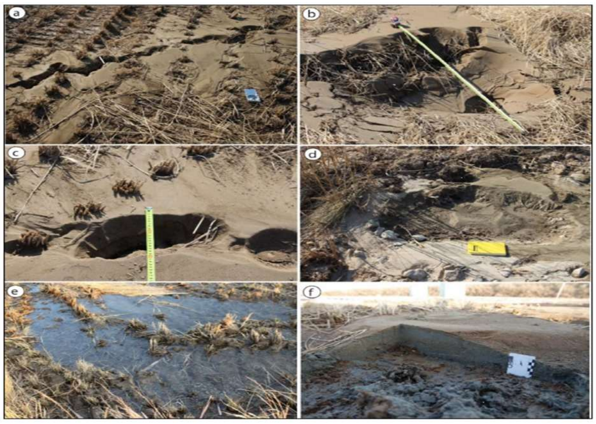
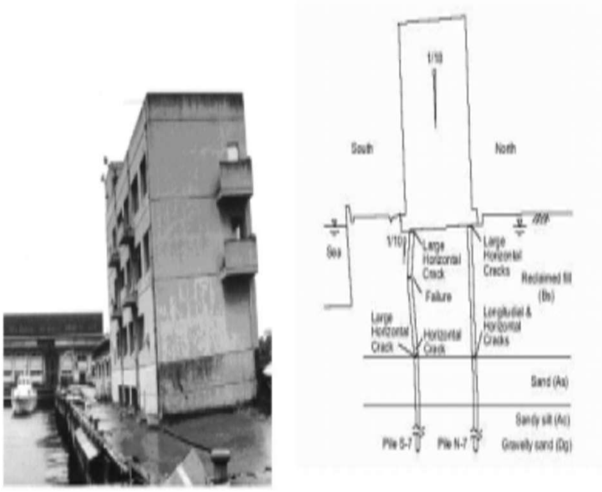


Figure 3: Field evidence of liquefaction occurred during the Pohang earthquake (a) linear chain of sand boils observed around the epicentral area, (b,d) isolated sand boils of larger than 1m in diameter observed in a rice farm and dry river bed ejecting fine sand/silty sand and coarse sand, (c) field photos showing isolated/ lenticular sand boil craters, (e) waterlogging in the rice farms immediately after an earthquake, (f) section of the sand boils where the soil samples were taken for grain size analysis [56]

The tendency of structure to settlements begins after liquefaction and sinking of soil deposits remain liquefied. Other parameters that affect liquefaction, such as cohesion-less soils (SP), particle size, gradation, drainage length, surcharge loads, and vibration characteristics (acceleration and frequency that have a dominant effect), the acceleration has more significant effect to increasing the chance of liquefaction. Liquefaction usually occurs after a certain number of vibration cycles are repeated [8]. During the earthquake shaking event, the soil liquefaction has a catastrophic impact on the structure, pipeline, bridges, and other ground facilities. These impacts have been seen in **Fig. (4. a)** that demonstrates the collapse of a building with 38 piles of support located at 6m from the quay wall on reclaimed land in the Higashinada-Ku area of Kobe city. It should be noted, the quay wall was displaced by 2 m towards the sea, and the building tilted by about 3 degrees. The damage pattern is shown in **Fig. (4. B)** suggested that the building supported on the piles rotated during the earthquake eve [13]. (**Fig. 5)** shows the damage caused by liquefaction in the 1999 **Kocaeli** earthquake [6]. Several cases of failure and damage of piles during earthquake events have been noted by researchers [58, and 53]. Finally, the liquefaction process is uncontrolled, dangerous and essential during earthquake events when the soil loses its shear strength and stiffness [6, 57, and 32].



(a) Failure pattern of a pile-supported building, photo courtesy K. Tokimatsu

(b) Damage pattern of the piles supporting the building

Figure 4: The collapse of a building supported on 38 piles in the Higashinada-Ku area of Kobe City [13]

Figure 5: an example of Liquefaction Damage [6]

Meymand [58**]** studied the response of piles to liquefaction. The cracks on the piles were observed at the top (at the point of the maximum moment) and the interface zones between soft and hard soil layers, as shown in **Fig. 6 and 7,** resultant in failure at these connections between pile cap and pile.

Figure 6: pile cap and failed pile supporting the Higashi-Kobe ferry pier [58]

Figure 7: Failed piles and pile cap supporting the Higashi-Kobe ferry pier [58]

Guan et al. [32] studied the damage of the piles during the Hokkaido Nansei-Oki earthquake of 7.8 Mw on pile foundation-supported silo. The silo suffered intensive damage with (1/20) tilting and (90) cm differential settlements with 45 cm lateral displacement, as shown in **Fig. 8**. The author also defines the pile failure into two types: shear or bending, shear with large shear deformation, another bending failure extent at of depth of 1 to 3 m below the pile head. (**Fig. 9)** shows the damage to a pile under a building in Niigata caused by ground displacement [76**]**.

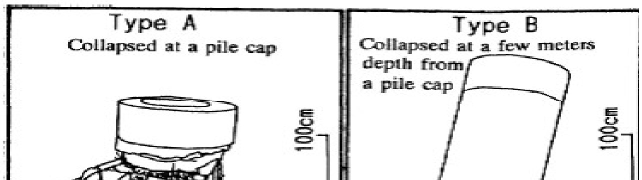


Figure 8: Failure patterns of damaged pile heads [32]

Figure 9: Pile damage at two lateral ground displacement during the 1964 Niigata earthquake [32]

Finally, the building design code about liquefaction soil is not adequate and must be improved or revised from previous research. If this is not done, some area suffers a loss of life and property. We should study new phenomena, which is precisely the intent of our work [7, and 35].

3. Failure Mechanisms of Piles in Liquefiable Soil

This section describes the failure mechanisms of pile foundation in liquefiable soils, as shown in Table. 1 and Fig. 10. Wang et al. [73] discussed an alternative mechanism of pile failure in liquefiable soil based on buckling failure formulated by examining fifteen case histories of pile foundation performance during past earthquakes and verified using dynamic centrifuge modelling. The author stated that during earthquake-induced liquefaction, the soil surrounding the pile loses its effective confining stress and can no longer offer sufficient support. Furthermore, the pile may collapse even before lateral spreading starts once the surrounding soil liquefies; in contrast to the buckling failure, the bending failure due to internal and kinematic forces arising from the soil's deformation surrounding the soil pile.

Table 1: Piles of failure mechanisms in Liquefiable soils

Authors	**Project type**	**Failure or damage type**
Wang et al. [73]	Bridges are located near the impact band of rivers	Three types of failure; 1-shear and bending 2- flexural-shear 3- Uneven settlement of structures

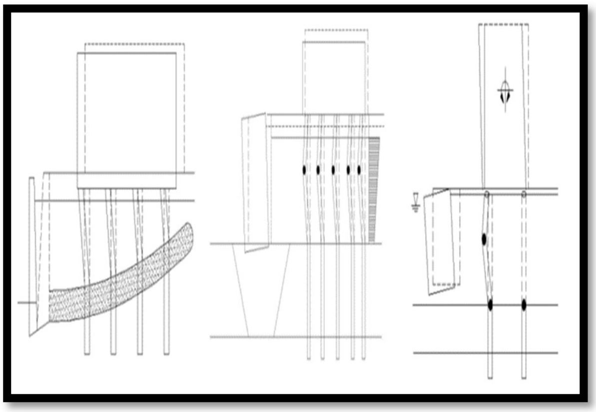


Figure 10: Types of failure modes of piles [73]

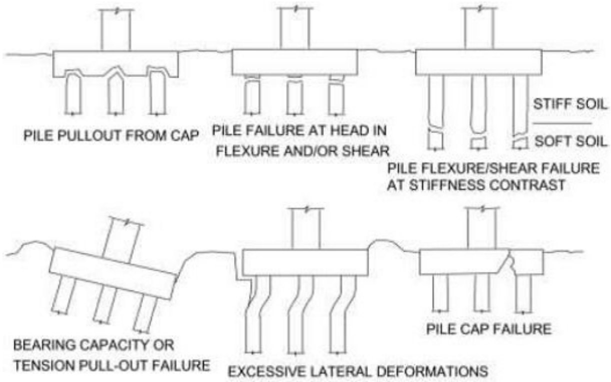


Figure 12: Failure modes of pile group subjected to seismic shaking [58]

The piles in liquefiable soil may undergo large displacement and fail due to bending from the provided Table and Figure. The soil behaviour becomes nonlinear; dissipation of pore pressure may reduce strength and stiffness of soil in the presence of large bending moments and shear forces on the pile. The potential of displacements and damaging of pile foundation results from liquefaction is complicated to predict reliably. In engineering practice, empirical formulas based on field data from past earthquakes can be used as a predictor equation developed in Japan [33]. The deformed shape of a pile caused by these post-liquefaction displacements is shown in **Fig. 11**, [27].

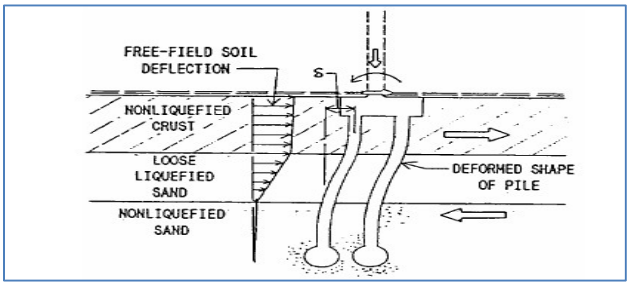


Figure 11: Distortion of pile foundation by lateral soil displacement [27]

Meymand **[58]** and other researchers discussed the possible outcomes causing damage in the pile group foundation into six types, as shown in **Fig. 12** below.

(**Fig.13**) showed the different loading modes on pile-supported structure; before the earthquake, the axial loads were equilibrium with shaft and end bearing resistance of the piles. As the shaking, and before the pore water pressure build-up, piles were mostly loaded by inertia forces generated by the oscillation of the superstructure and lateral load caused by the soil-pile kinematic interplay. At this stage, the bending mechanism was expected to govern the internal stresses within the pile. While the onset of liquefaction, the pore water pressure with build-up (excess pore pressure reached the overburden vertical effective stress), the soil loses its strength, and stiffness and pile act as unsupported column over the liquefied depth [48].

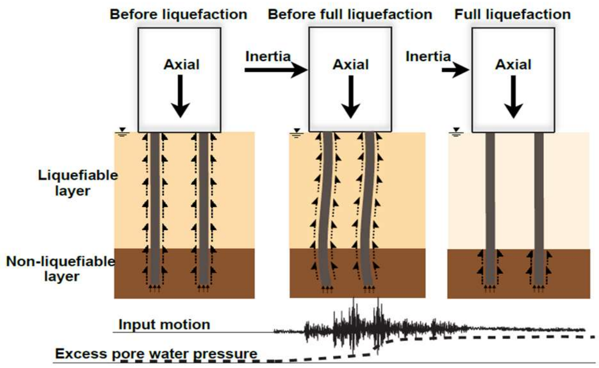


Figure 13: Schematic of loading conditions acting on a typical pile-supported structure subjected to seismic induced liquefaction [48]

4. Lateral Responses in Liquefied Soil

Lateral loads generated by soil movements cause additional deflections and bending moments in piles. The lateral soil response and its impact on deep foundations are still under investigation via laboratory and field challenging issues such as (the mobilized strength of the liquefied soil, the amount of lateral soil displacement developed during and the lateral spread phase, etc.). The significant challenges in analyzing piles in liquefied soil undergoing lateral spreading include how far the crust layer would move, the amount of driving internal force on the piles, and the varying strength of the liquefied soil layer in the near field. Many approaches, including shaking Table and centrifuge tests and numerical methods, have been developed to respond to single and group piles under dynamic loading (e.g. [46, 62, and 66]. The soil-pile structure interaction has been studied using shaking table test (e.g. [5, 28, 42, 39, 53, and 68)] and centrifuge test (e.g. [21, 24, 36, and 74]). The laterally loaded pile is a nonlinear pile-soil interaction problem, and the pile behaviour under lateral loads concerns the interaction between the pile and the soil. Many available methods for the analysis of the laterally loaded pile such as: (limit state method (foundation-soil reaction method, elasticity analysis method, P-Y curve method, and finite element method), [18]. P-Y curves method is efficient in evaluating the behaviour of laterally loaded piles. (**Fig. 14**) shows the states of p-y curves before and during liquefaction.

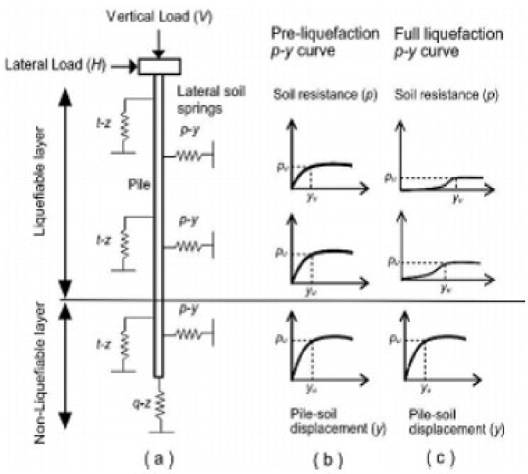


Figure 14: (a) BNWF model of pile-soil interaction, (b) Pre-liquefaction, and (c) Post-liquefaction (P-Y) [18]

Laterally loaded piles are significantly distinguished from vertically loaded piles in terms of behaviour design and load principles. The design of laterally loaded piles requires estimating the lateral displacement and bending moment under the load concerning desired project criteria, pile geometry and soil conditions. Bhattacharya [12] studied the effect of piles in liquefied soil by using a centrifuge model. From the results, the soil loses strength and leads to the collapse of piles due to the bending effect. Bhattacharya and Bolton [14] showed that the bending moment effects must be considered when design pile in liquefied soil under earthquake eve. The bending moment and lateral displacement of piles in liquefied soil were analyzed using (P-Y) method in LPILE software and the linear spring method in **SAP2000** software. Kinematic interaction was neglected in the calculation, and the only internal effect was considered. The author suggested that the P-Y method in which plasticity properties are considered and deformations are defined as a function of these properties is better [41].

Ilamaruthi and Madhumathi [39] studied the effect of lateral ground movement on the behaviour of piles with three L/D ratios: (10, 20 and 27) placed at distances of 2d, 3d and 4d embedded in loose and medium dense sand behind a retaining wall by using a steel tank with dimensions (650×400×600) mm. The study indicates that the deflection of piles is more in loose sand compared to the medium dense sand bed.

Liyanapathirana and Poulos [47] studied the lateral seismic response of pile in liquefying soil using the BNWF model and compared the results with two centrifuge models. The numerical analysis and centrifuge results are agreements well, as the cap mass can increase the bending moment by increasing the inertia forces acting on the pile. Bao [10] studied the lateral response of pile under dynamic load in liquefied soil based on the nonlinear pseudo-static analysis. From experimental and numerical analyses, it can be shown that the excess pore pressure ratio rapidly increased and equalled to (1) or slightly lower from bottom to top in the vertical direction. Singh et al. [9] showed the analytical strain wedge (SW) model technique used for studying lateral soil spreading by using (2×3) pile group model with (1.17) m diameter pile with a large pile cap embedded in non-liquefied crust. The pile group had no superstructure and was tested under conditions of lateral spreading of soil; three shaking events scaled to the Kobe earthquake were applied to the model ranging from 0.1g to 0.67 g. From the results, it can be shown that the significant event created complete liquefaction along with the loose soil layer and partial liquefaction in the dense sand layer. Several previous studies described the behaviour of piles under combined loads by taking into account several parameters like (pile materials, combined lateral value, and slenderness ratios of the pile) (e.g. [1, and 58]. Al-Azzawi [3] described the pile load capacity under various kinds of loading. The results of lateral pile tests showed that piles' behaviour as short or long pile depends mainly on the yield moment of the pile section. However, the lateral load capacity of the long pile decreases with increasing the length of the pile that was contrary to the case of the short pile. Abbas and Hussain [2] showed the lateral behaviour of pile when subjected to combined loads by taking into account the deformation along with the pile depth and lateral displacement, using aluminium and steel piles with a slenderness ratio (L/D) of (25 and 45) embedded into the sandy soil. Based on the test results, it can be concluded that the increase of axial load with lateral load was affected on the upper pile part, and the presence of vertical load leads to a decrease in the pile deflection. Bakshi et al. [31] studied the behaviour of (2×2) pile groups in three-layer soil profiles consisting of a base non-liquefiable layer, a middle liquefiable layer, and an upper non-liquefiable layer. Lumped mass was attached to one of the pile groups to investigate the effect of the superstructure on the pile response during lateral spreading. From the results, it can be shown the maximum lateral ground displacement was up to (200) mm near the mid-height of the liquefied layer, and the maximum positive bending moment is observed at the base of liquefied layer, while the maximum negative bending moments occur at a depth almost close to the middle of the liquefied layer. Dorby and Adoun [25] showed examples of earthquake events such as (Limon and Niigata). From the results, it can be found the critical locations in the bending moment, and shear response of deep foundations to lateral spreading is the bottom of the liquefied layer and the head of the foundation, and when the non-liquefiable layer overlies the liquefied layer, a third critical point is the top of the liquefied layer.

5. Conclusions

Base on the literature detailed above, it can be concluded that:

1-Many parameters are affected by the high liquefaction susceptibility, particle size, shape, and gradation. A well-graded soil is less susceptible to liquefaction than poorly graded soil, and soil with rounded particle shapes is known to densify more efficiently than soil with angular grains.

2-Pile foundations are regarded as the best alternative to support structures during seismic action. Large strains and nonlinear behaviour of the soil can be calculated during seismic loading. The shear modulus of the soil degrades, and damping increases with increasing strain, and so, pile stiffness should be determined for these strain effects. The generation of excess pore water pressure in liquefiable soil may result in loss of strength and stiffness, resulting in large shear forces and bending moments on the pile. Hence, the soil displacements and lateral spreading are related to the liquefaction phenomenon that may damage the lateral pressure of the piles.

4- The magnitude of bending moment and lateral displacement with time under dynamic events increase almost linearly with the scaled earthquake events

5-Major aspect identified from this paper related to bending moments near the pile cap was influenced by interaction force from the superstructure and changed from decreasing to increasing in the vertical direction from bottom to top. In contrast, the kinematic force occurs due to the deflection from the tip of the pile to the top.

6- The design of laterally loaded piles requires estimating the lateral displacement and bending moment under the load concerning desired project criteria, pile geometry and soil conditions.

7- It can be noticed that the effect of piles under the combination of laterally and axially loaded during earthquake events was not fully covered in most of the discussed researchers.

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مراجعة الدراسات السابقة لتصرف الركائز في الترب القابلة للتسييل

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نشر في : 30 ايلول 2022

الخلاصة –في هذا البحث لوحظ أضرار واسعة النطاق للجسور المدعومة بالركائز وغيرها من الهياكل في التربة القابلة للتسيل عند التعرض لعديد من مخاطر الزلازل حول العالم. حيث يمكن ان يحدث فشل في خصائص أساس الركيزة أثناء حدوث الزلزال في التربة القابلة للتسييل ويشمل الإزاحة الكبيرة ، والانحناء الافقي ، والقص الأقصى ، وزيادة ضغط ماء المسام اوغالباً ما يتسبب حدوث التسييل في حدوث تشوهات أرضية كبيرة تفرض أحمالًا حركية (جانبية ومحورية) على أساس الركيزة وتقليل قدرة الركائز على مقاومة الأحمال المحورية والجانبية (على سبيل المثال ، تقليل قابلية التحمل للركيزة وفقدان االركائز لمقاومة الاحمال المسلطة عليها) التي يمكن أن تؤدي إلى تشوهات مفرطة تحت الأحمال الساكنة والقصور الذاتي من البنية الفوقية وبالتالي أظهرت جميع الدراسات السابقة يجب الاخذ بنظر الاعتبار عند تصميم الركيزة التحمل الافقي حيث من اهم الخصائص هي حساب عزم القصور الذاتي على طول الركيزة والازاحة الافقية على راس الركيزة والذي تعتمد على خصائص الركيزة ومقدار الاحمال المسلطة وخصائص التربة. ومن ناحية اخرى ، فإن الدراسات المتعلقة بالاحمال المحورية والجانبية الساكنة على رأس الركيزة أثناء حدوث الزلزال محدودة وذلك لان جميع الدراسات السابقة اخذت بنظر الاعتبار الاحمال العمودية فقط على راس الركيزة. واخيرا أصبحت الدراسات العددية أسهل مع ظهور أجهزة كمبيوتر قوية وأدوات محاكاة مثل برنامج العناصر المحدودة من اجل دراسات تصرف الركائز اثناء حدوث الزلزال.

الكلمات الرئيسية – التربة القابلة للتسييل ، الهزات الارضية، فشل الركائز، تصرف الركائز تحت تاثير الاحمال الافقية