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An Overview of Soil-Pile Interaction in Liquefying Soils under Earthquake Condition

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Abstract: *Piles are of enormous structural and geotechnical importance as they help to transfer heavy super-structural loads to the geological formation that carries the superstructure. Piles are used in bridges, high-rise structures and other structures of importance. However, in seismic zones, piles in liquefiable soils are susceptible to failure during earthquake events despite that the current codes of practice provides for the design of piles against seismic effect. This study summarizes the current knowledge of the soil-pile-structure interaction, and behaviour in liquefiable soils subjected to earthquake loadings; and investigates the failure mechanisms of seismic piles despite that codes of practice covers seismic design of piles; and goes further in suggesting design approaches that allow for a conservative design of seismic piles.*

Key Words: *Piles, Soil, Liquefaction, Earthquake, Lateral Spreading*.

1. INTRODUCTION:

One of the leading geotechnical engineering complications is Liquefaction; a very complex phenomenon in earthquake engineering [1]. It is a leading cause of structural and geotechnical failure of civil engineering constructions [2], [3]. Tall buildings or important structures in the cities have to be founded on piles to avoid excessive ground settlements. This problem is more eminent around loose cohesionless sands and silts below the water table, as the high pore water pressures generated lead to liquefaction during strong earthquake shaking [4]. The most frequently encountered soil profile for piles in liquefied deposits consists of three distinct layers, as shown in Fig. 1 where the liquefied layer is sandwiched between a non-liquefied crust layer at the ground surface and non-liquefied base layer [5]. In addition to static load transferred from the dead load of the structures, piles are also subject to dynamic loads. The most commonly encountered dynamic loads on a pile–soil–structure system are those due to earthquakes. Past earthquake events demonstrate that damages in piles are commonly induced during moderate to strong earthquakes [6]. Pipe, and pile-supported structures' failure are eminent during earthquake events despite the large factor of safety against axial capacity and bending due to lateral loads that is employed in their design.

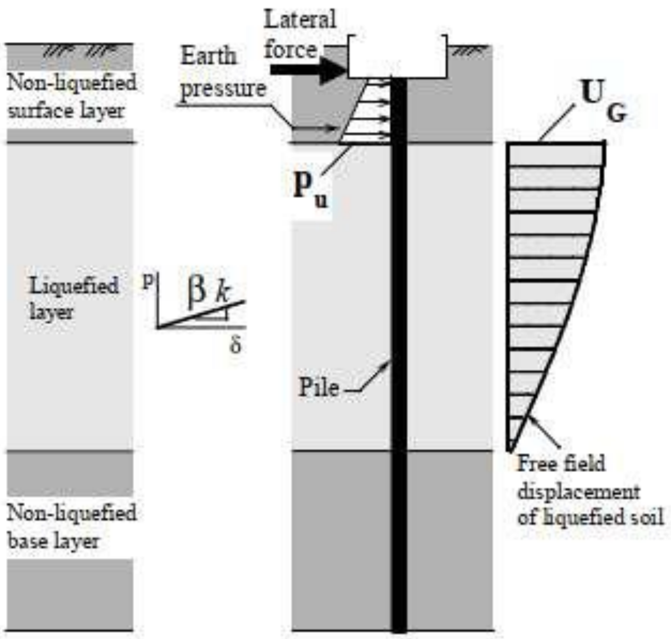

Figure 1: Simplified kinematic mechanism of lateral spreading. (Source: Cubrinovski, et al. [5])

There are analysis and design procedure developed for predicting pile behaviour under earthquake loading as contained in the codes of practice; however, these procedure don't accurately predict pile behaviour under liquefied condition since the performance of piles in liquefied soil layers is much more complex than that of non-liquefying soil layer because the surrounding soil exert different dynamic loads on pile and generation of large bending moments and shear forces since the stiffness and shear strength of the surrounding soil reduces significantly over time as a result of pore water pressure generation and non-linear behaviour of soil [3], [7]. This implies that the current design methodologies do not consider some appropriate combinations of effects [8]. Liquefaction thrives in the fact that its prediction is difficult, although there have been headways recently, in terms of increased prediction accuracy of liquefaction during earthquake events. There are a number of methods that can be used to accurately predict liquefaction behaviour of a liquefiable soil and it can affect the pile foundation and the super structure have been developed. This include the shake table test, centrifuge test and numerical methods [9]. This paper investigates the current knowledge on pile-soil-structure behaviour under liquefiable soils during seismic events.

Cheng and Jeremic [10] in their numerical study highlighted the various past earthquake events. During Alaskan Earthquake (1964), liquefaction was the main cause of severe damage to 92 highway bridges, moderate to light damage to another 49 highway bridges, and moderate to severe damage to 75 railroad bridges [11]. During Niigata Earthquake (1964), liquefaction induced damage to foundation piles under Yachiya Bridge. During that same earthquake, girders of Showa Bridge toppled as the support structure and piles moved excessively due to liquefaction. During Kobe Earthquake (1995), liquefaction was the primary cause of damage to many pile supported or caisson supported bridges and structures. For example, Shin– Shukugawa Bridge was subjected to excessive pile foundation movement due to liquefaction [12]. Mizuno [13] also reported the earthquake induced damage in Japan from 1923 to 1983 including the great Kanto earthquake. Damage have also been observed at the 1989 Loma Priere earthquake [14]. Therefore, liquefaction has been a constant cause for worry in seismic zones. Fig. 2 (a) shows a pile-supported structure following the 1995 Kobe earthquake, and Fig. 2 (b) shows the schematic of the same building along with the location of the crack as documented by [8].

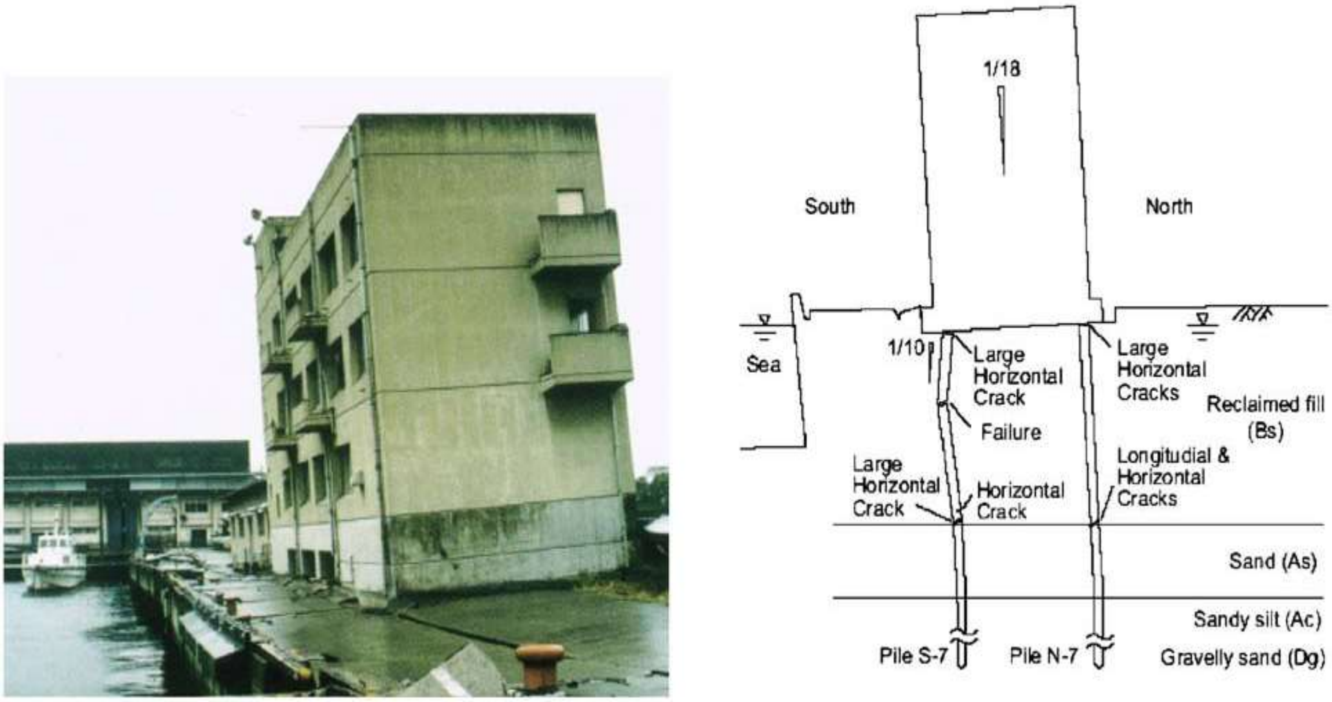

Figure 2: (a) Tilting of a pile-supported building following the 1995 Kobe earthquake; (b) formation of crack. (Source: Bhattacharya, et al. [8]).

Varun [15] stated that one of the most common methods for simulating static and dynamic liquefaction problems is the p-y approach. The fundamental assumption in this approach is that each layer of soil behaves differently, independently on the adjoining layers, and hence can be replaced by a discrete spring. This approach is simpler, and less computational than the Finite Element analysis while it presents a fairly accurate prediction of soil-pile response under seismic load. However, it does not take into account the shear stress transfer between adjoining layers. The simple operability of the p-y method has made it a popular tool for the simulation of both static and dynamic soil-pile problems.

Piles in loose cohesionless deposits in seismic zones are vulnerable to significant reduction of bearing capacity, liquefaction and lateral spreading during seismic. Shear failure also results from excessive force imposition from ground displacement on the piles, this consequently results in collapse of the superstructure. Varun [15] reported that the most widely employed approach for the simulation of pile response in liquefiable soils is the use of load–displacement curves (referred to as p–y curves) for non-liquefiable soils, scaled by reduction factors (referred to as p–y multipliers) as a function of the pore-pressure ratio in the soil to account for the soil strength reduction during liquefaction. The most widely employed p–y curves in practice are the ones developed by Matlock [16], Reese et al. [17] and API [18], while p–y multipliers have been suggested by the Japan Road Association [19], the Architectural Institute of Japan [20], Liu and Dobry [21], Wilson et al. [22], and Brandenberg et al. [23].

2. OVERVIEW OF BASIC CONCEPTS:

Winkler models for piles in liquefied soil: The pile–super-structure system vibrates monolithically during earthquake shaking as a coupled system. It should logically be analyzed as a monolithic system. However, this kind of analysis is not practicable, as yet. Many of the popular structural analysis programs cannot include the pile foundation directly into a computational model. This has popularized various approximate methods as computational demands are extravagant. A very common approach is the Winkler Springs system [4].

Beam on Non-linear Winkler foundation (BNWF) also known as ''p–y'' method is used commonly in analyzing piles under liquefied condition [18]. In this method, the soil is modelled as non-linear springs. The lateral soil pressure per unit length of pile is 'p' while 'y' denotes the lateral deflection. Fig. 3 shows a particular p–y model for non-liquefied soil and its corresponding liquefied condition based on an empirical method as documented by [8]. The reduction of strength is carried out using p-multiplier and typical values of this multiplier can be found in [20], [21]. It is important to note that the initial stiffness (represented by the slope of the initial portion of the p-y curve) reduces significantly when the soil transforms from solid to fluid. Dash et al. [24] presents a detailed discussion on the shapes of p-y curves for liquefied soils. However, analysis of the full-scale tests such as Rollins et al. [25], centrifuge tests such as Bhattacharya et al. [26], laboratory tests on liquefied soil by Yasuda et al. [43], Takahashi et al. [27] suggests that the ''p–y'' curve for liquefied soil should look like an S curve. The main parameters of a load–displacement (p–y curve) relationship are the stiffness and strength of liquefied soil. The stiffness of the soil, i.e. the initial tangent stiffness of ''p–y'' curve, is the resistance of soil to unit pile deformation. Under non-liquefied condition, when the differential soil–pile movement is small (i.e. the soil is not pushed to its full capacity), the resistance on pile depends on the initial stiffness of the soil and the value of deflection (Fig. 4a). In contrast, the strength of soil is an important parameter while dealing with high-amplitude soil–pile interaction. In other words, when the differential soil–pile movement is large, the resistance offered by soil over pile is governed by the ultimate strength of the soil (Fig. 4a). For liquefied soil (see Fig. 4b), the pile response will be different for small and large amplitude vibrations. The lack of initial stiffness and strength of the liquefied soil will increase the P-delta effect for small amplitude vibration, and may promote buckling mode of failure of piles [28], [29], [30], [26].

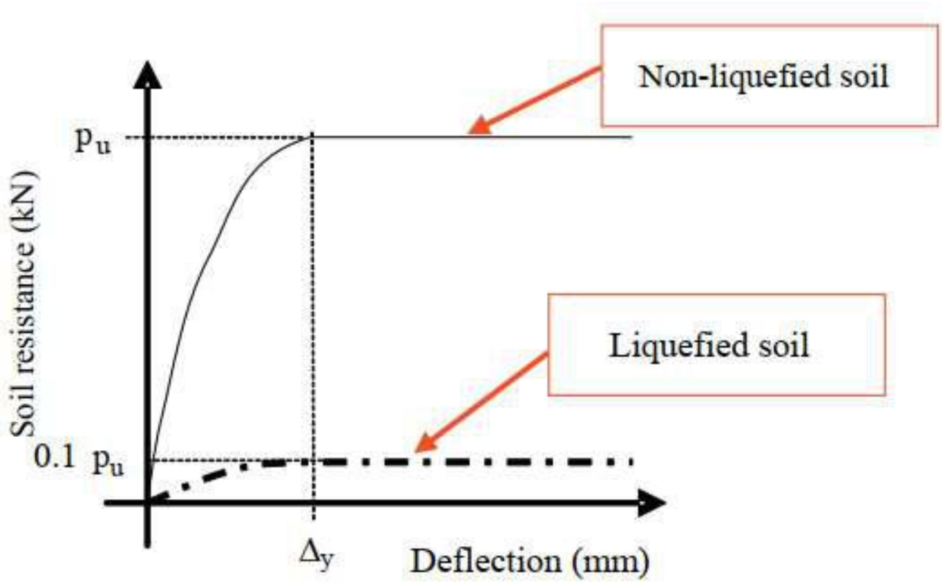

Figure 3: p–y curve for non-liquefied soil and liquefied soil using p-multiplier. (Source: Bhattacharya et al. [8])

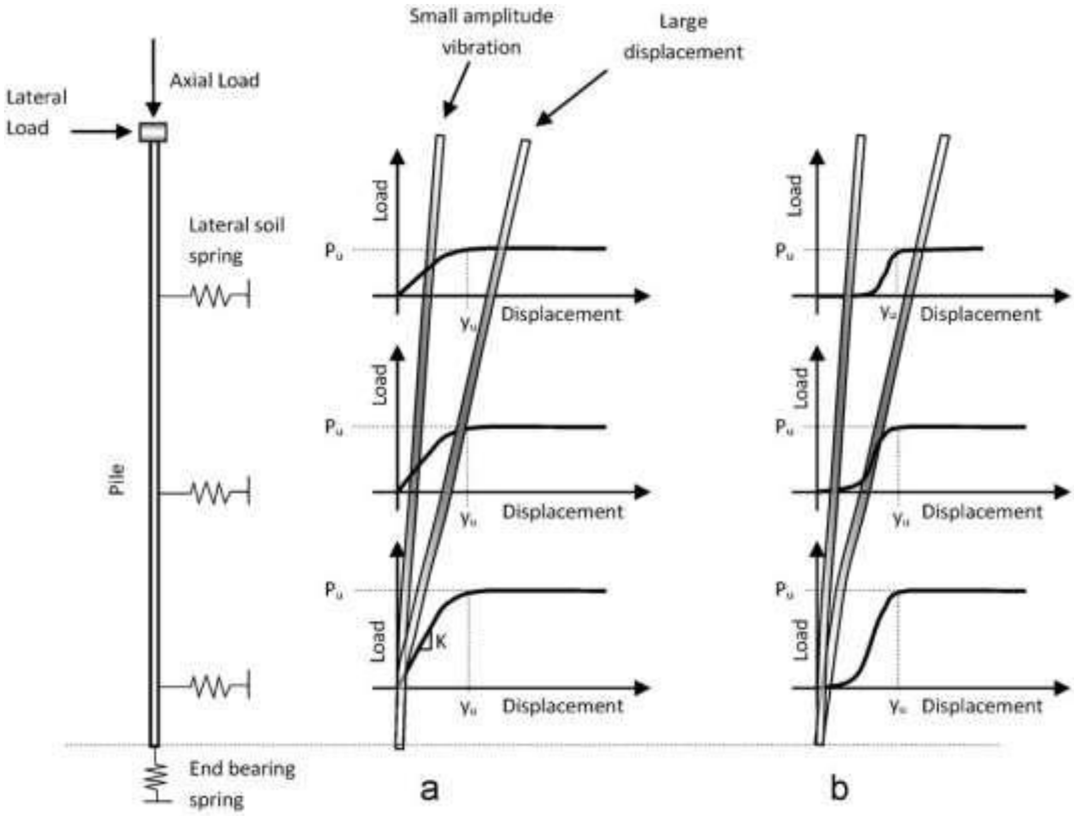

Figure 4: Soil–pile interactions for two types of p–y curves (a) for non-liquefied case; (b) for liquefied case. (Source: Bhattacharya et al. [8]).

Finite Element Analysis: A viable alternative for predicting pile-structure behaviour under liquefied condition is the Finite Element computational model which uses a finite element continuum analysis based on the actual soil properties. Dynamic non-linear finite element analysis in the time domain using the full 3-D wave equations is not feasible for engineering practice at present because it is excessively time-consuming. However, Finn et al. [4] stated that by relaxing some of the boundary conditions associated with a full 3-D analysis, it is possible to get reliable solutions for non-linear response of pile foundations with greatly reduced computational effort. The results are very accurate for excitation due to horizontally polarized shear waves propagating vertically. A full description of this method, including numerous validation studies, has been presented by Wu and Finn [31], [32]. The computer program used in incorporating the method is PILE-3D. A Quasi-3D model for analysis of pile foundations is presented in Fig 5. as presented by Finn et al. [4].

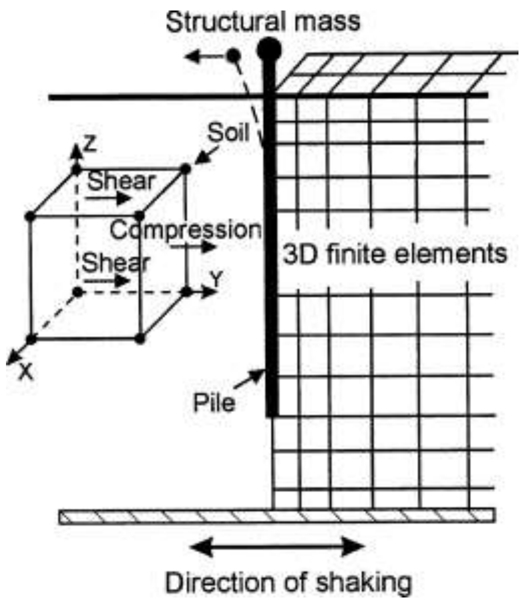

Figure 5: Quasi-3D model for analysis of pile foundations. (Source: Finn et al. [4]).

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3. FAILURE MECHANISMS OF PILES IN LIQUEFIABLE SOILS:

Bending and shear failure due to lateral spreading and inertial effect: It has been established that lateral spreading is a major concern for pile foundations in sloping grounds where a thick non-liquefied soil layer overlies a liquefied soil layer and piles are embedded in competent non-liquefiable soil layer below the liquefied soil (see Case I in Fig. 6). Down slope movement and/or lateral movement of non-liquefied crust has the potential to induce large bending moments in the piles leading to failure. The kind of failure that results from lateral spreading is generally categorized as bending failure of piles. In circumstances where the shear capacities of piles are very low, such as in hollow sections, lateral spreading of soil may cause the piles to fail in shear. In addition to the inertia effect of the super structure, lateral spreading forces will make the pile more susceptible to failure by bending and shear.

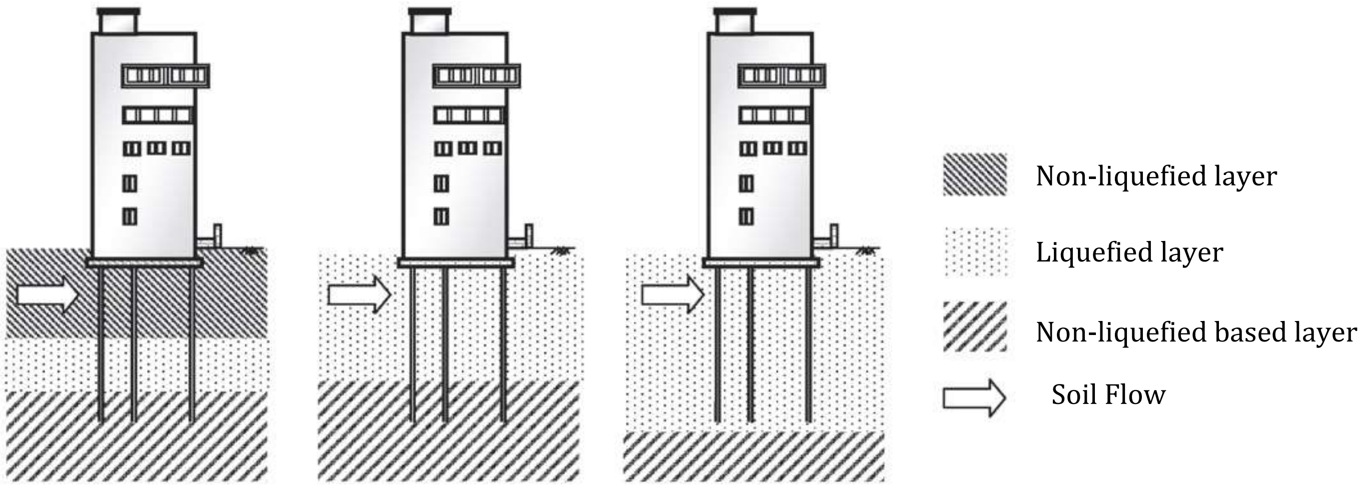

Figure 6: Figure Case II: Buckling is the governing failure mechanism, Case III: Settlement is the governing failure mechanism. (Source: Dash, et al. [33]).

Buckling failure due to unsupported length of the pile: In the absence of the top non-liquefied layer, drag force exerted on the piles by the flow of liquefied soil is usually very small [34], [35]. In such cases, if the soil liquefies to a deeper depth, the pile may lose significant amount of the lateral stiffness provided by the surrounding soil and may behave like a slender unsupported column. In the event of high axial load acting on the piles, buckling instability of the pile may be resulted [29] [30]. (See Case II of Fig. 6).

Failure due to excessive settlement: The axial load of the superstructure is transferred to the supporting soil by the pile through two mechanisms; (a) shear resistance generated along the surface of the pile due to soil–pile friction, and (b) point resistance due to end bearing at the base face of the pile. If there is significant degradation of soil strength during earthquake, the side friction and end bearing of piles may become insufficient to carry the superstructure load. Excessive settlement may results from this situation, leading to foundation failure. See (Case III of Fig. 6)

Resonance-type failure: Fig. 7 shows the different stages of loading of a pile-supported structure where the pile vibrates. In Stage II, when the full liquefaction of the soil still underway, the transverse bending governs the internal stresses within the pile. As the liquefaction progresses, the coupled buckling (due to the unsupported length of the pile) and frequency-dependent resonance force would govern the internal stresses in the pile (Stage III). In essence, the motion of the pile (and consequently the internal stresses leading to the failure) is a coupled phenomenon. This coupling is, in general, non-linear and it is not straightforward to exactly distinguish the contributions of the different mechanisms towards an observed failure. It is, however, certainly possible that one mechanism may dominate over the others at a certain point of time during the period of earthquake motion and till the dissipation of excess pore water pressure [8].

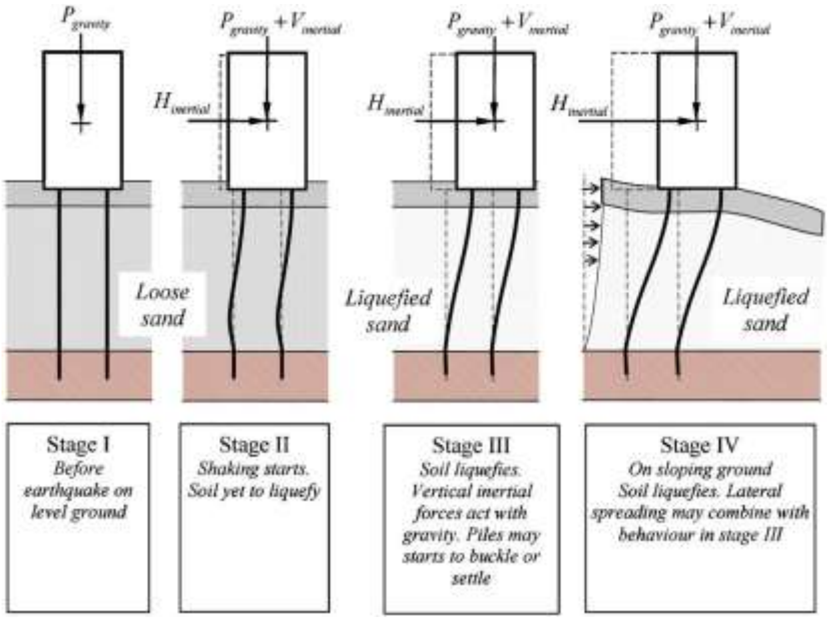

Figure 7: Different stages of the loading (Source: Sarkar et. al [36])

4. A REVIEW OF THE CODES OF PRACTICE: Sarkar et al. [36] reported that the Japanese Highway Code of practice (JRA) recommends that two different loading conditions be considered:

a. Oscillation-induced inertial force of the superstructure i.e. Stage II loading in Fig. 7;
b. Kinematic load exerted by the lateral pressure of the liquefied layer and any non-liquefied crust resting on the top of the liquefied deposit i.e. Stage IV loading in Fig. 7. The code also suggests designers to check against bending failure due to kinematic and inertial forces separately.

Also, Eurocode 8 [37] recommends that piles be designed against bending due to inertial and kinematic forces arising from the deformation of the surrounding soil. In the event of liquefaction, Eurocode 8 [6] also suggests that ‘‘the side resistance of soil layers that are susceptible to liquefaction or to substantial strength degradation shall be ignored’’.

Other provisions, such as the NEHRP code [38] and Indian Code [39] also focus on the bending strength of the piles. In essence, the codes of practice reviewed simply consider piles as laterally loaded beams and assume that the lateral load due to inertia and soil movement causes bending failure. The current underlying assumptions of the codes of practice are too basic and simple. There has to be a review of the codes, to account for the complexity of loadings that result during liquefaction events under earthquake condition.

5. CONCLUSION:

There are histories of pile failures during seismic events despite that current codes of practice cover seismic design of piles. This paper involves an investigative analysis of the current understanding of pile-structure behaviour in liquefiable soils during seismic events, and gives a general overview of the important factors that affect the seismic design of piles to resist earthquake loading in liquefiable soils during earthquake. The study reveals that the current understanding of pile-structure behaviour in liquefiable soils considers one of bending, shear, or buckling as a possible cause of pile failures. However, pile failure results from a complex combination of mechanisms. The failure of piles and pile-supported structures may result from different complex combinations of structural failure of piles (shear, bending, and buckling) and soil failure (settlement). Therefore, It is imperative for codes of practice to consider these combined, interactive mechanisms of failure in order to allow for conservatism in the event of liquefaction.

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