Performance of Pile Foundations During Earthquake

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***Abstract*— In this paper, a review has been done on the seismic performance of pile foundations in liquefiable soil. The paper provides a useful and current overview of this aspect of design of pile foundations for practicing engineers. Historically, there have been many cases where pile foundations have suffered either total collapse or severe damage during earthquake loading conditions. During an earthquake, a pile is considered as a laterally loaded beam and its bending is governed by strength of the pile material. As per the prevailing code of practice followed in many countries, piles are designed on the basis of bending mechanism where lateral loads due to inertia or slope movement (lateral spreading) induces bending failure in the piles. At the time of seismic activity, due to liquefaction, confining pressure of the surrounding soil on pile foundation decreases and pile would buckle because of axial loading. Therefore, failure of pile during liquefaction is due to combined action of buckling and bending.**

***Index Terms*— Liquefaction, pile, pile-soil interaction, bending, buckling**

I. Introduction

A pile is a vertical structural element acting as a deep foundation. It is generally used to bypass the load through the weak soil up to a hard stratum when high load is transferred by multistoried buildings, bridges, towers, dams, etc. When pile foundation is constructed in river where water table is high and soil is fine granular, chances of liquefaction increase during seismic loading. As the soil liquefies, unsupported length of the pile will increase due to which axial load carrying capacity of the pile will decrease. Consequentially, pile will buckle under axial load. It is generally acknowledged that the failure of the structures is caused by the lateral earth pressure applied by the laterally spreading liquefied sand and any non-liquefied stabilized crust resting on the top of the liquefied soil. This mechanism is therefore based on flexure of the pile causing a bending failure of the pile foundation.

However, research by Bhattacharya et al (2004) suggested an alternative explanation recognizing the fact that pile foundations are normally carrying significant axial loads at the time of the earthquake. When the soil around the pile liquefies, it loses much of its stiffness and strength and the piles act as unsupported long slender columns, and simply buckles under the action of the axial loads. The stresses in the pile section will initially be within the elastic range, and the buckling length is the entire 'unsupported' length in the liquefied soil. Lateral loading, due to slope movement, inertia or any out of alignment eccentricities will increase lateral deflections. When the pile suffers sufficient lateral deflections, plastic hinges can form, reducing the buckling load, and promoting more rapid collapse. Therefore, this hypothesis is based on a buckling failure of the pile foundation

When analyzing the behavior of piles in liquefied soils, it is useful to distinguish between two different phases in the soil-pile interaction process,

- A cyclic phase at the time of the high ground shaking. A load on the pile will act due to soil movement, whether liquefaction occurs or not.

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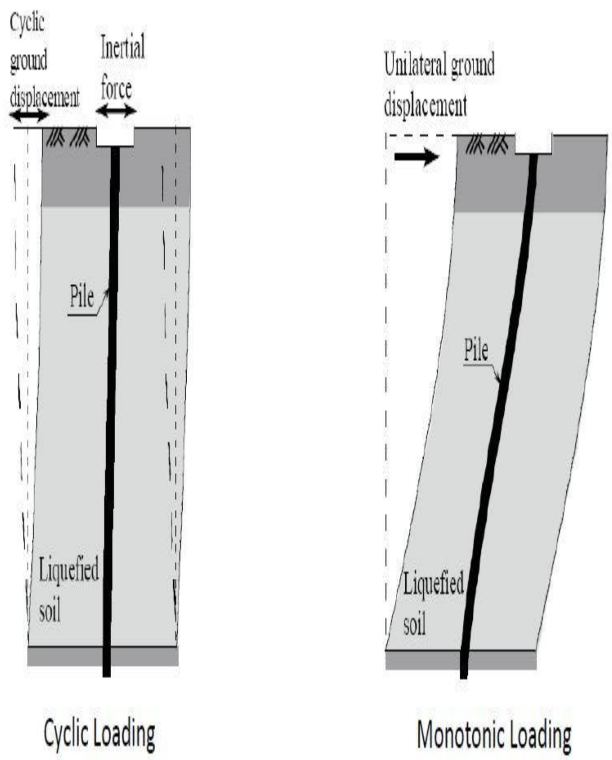
- When liquefaction occurs a permanent deformation of soil will occur due to this deformation comprise lateral spreading or flow failure and/or vertical settlement will occur. This permanent horizontal deformation of the ground around the pile creates load on the pile.



(after Ghosh et al, 2012)

II. STRUCTURES SUPPORTED ON PILES DAMAGED DURING EARTHQUAKE

Tohoku (Japan) Earthquake (March 2011): The magnitude (9.0 Mw) earthquake occurred on 11th March 2011 in the North-Western Pacific Ocean at a relatively shallow depth of 32 km with its epicenter approximately 72 km east of the Oshika Peninsula of Tohoku, Japan, lasting approximately for 6 min. This resulted in a major tsunami that brought widespread destruction. Severe liquefaction was also observed. Many structures such buildings, manholes were tilted and sunk into the sediments, even when they remained structurally intact.

Chile Earthquake (Maule) (2010): A large magnitude (8.8 Mw) earthquake strike Chile on 27th Feb 2010. The epicentre of the earthquake was located in the offshore Maule VII Region of Chile at a depth of 35 km as reported by the USGS. Three bridges over Bio River were severely damaged**.**

Bhuj (India) Earthquake (2001): The Bhuj earthquake (7.0 Mw) that struck the Kutch area in Gujarat at 8.46 AM (IST) on January 26, 2001 was the most damaging earthquake in India in the last 50 years. The epicentre of the quake was located at 23.4^0N, 70.28^0E and at a depth of 25 km, which is to the north of Bacchau town. This earthquake has caused extensive damage to the life and property. Kandla port tower was located in laterally spreading ground. The tower tilted possibly due to the interaction between axial loads induced settlement owing to liquefaction and bending due to lateral spreading.

Wenchuan Earthquake (China) in (2008): Wenchuan earthquake was one of the major earthquakes that struck China. In this earthquake, several hundred bridges collapsed. The reasons for collapse of so many bridges can be summarized as follows: (a) Site effects: many of the bridges that collapsed were near the epicentre of the earthquake due to strong near-field motion (b) Geological hazards due to earthquake i.e. mainly due to landslides, rock fall. These failures occurred immediately or during the earthquake. (c) Effects of liquefaction mainly in the river bridges; (d) inadequate structural consideration: Poor beam column stiffness, irregular shape causing stiffness irregularity (bridges curved in plan); (e) Active Fault movement and surface fracture induced by active fault.

Kobe Earthquake 1995: The Kobe earthquake occurred on 17th January 1995 southern part of Hyogo Prefecture, Japan. It measured 6.8 on the moment magnitude scale (USGS). The tremors lasted for approximately 20 s. The focus of the earthquake was located 16 km beneath its epicentre, on the northern end of Awaji Island, 20 km away from the city of Kobe. Liquefaction caused damage to pile supported structures.

III. FAILURE MECHANISMS OF PILES IN LIQUEFIABLE SOILS

Bending: Bending failure generally occurs due to transverse or lateral seismic load or due to inertia of the superstructure. Effect of this lateral flow of soil will be more in case of sloping ground called lateral spreading of the ground. Bending in the pile due to lateral spreading of ground is often regarded as the root cause of many bridge failure.

Buckling: As the process of liquefaction progresses, confinement of pile by surrounding soil will decrease to such a low value that pile will start acting like a long slender column. Axial load coming from the superstructure will cause buckling and pile will not be able to support the superstructure load. Magnitude of buckling will depend upon the stiffness of the pile, depth of the liquefiable soil and magnitude of ground shaking during earthquakes.

Shear: This type of failure occurs due to lateral load such as kinematic or inertia load or combination of both. This type failure is generally observed in hollow circular concrete piles having low shear capacity.

Settlement: Due to combined action of buckling and bending it may be possible that structure will settle vertical or it may tilt in one direction.

Dynamic failure: As we move away from abutments to the central pier of the river bridge, the depth of water increases and depth of embedment decreases and hence, the unsupported length of pier increases. This elongates the natural period for the central bridge pier as compared to the neighbouring piers and abutment and many bridges fail due to collapse of central piers. The collapse of Showa Bridge (1964 Niigata earthquake) is considered to demonstrate this mechanism.

IV. DIFFERENT STAGES OF LOADING IN THE PILE DURING EARTHQUAKE:

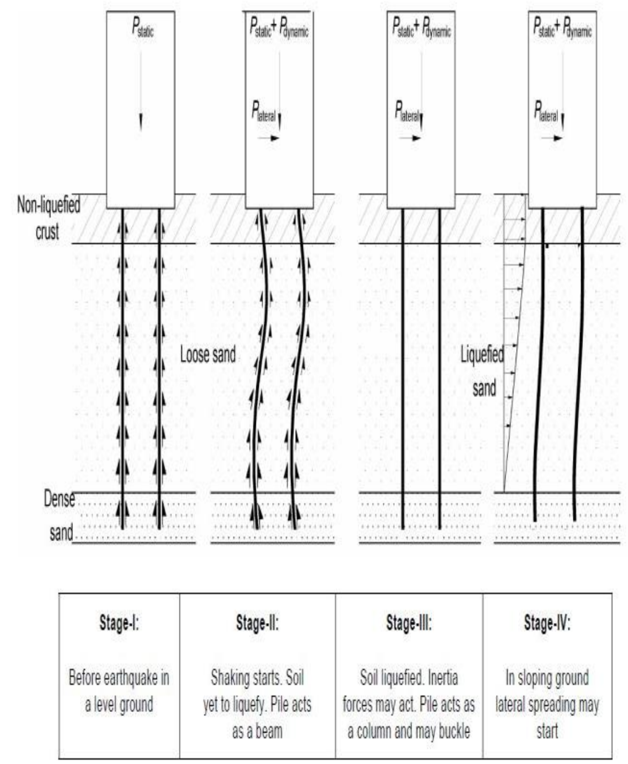
At the time of earthquakes, soil layers overlying the bedrock are subjected to seismic excitation consisting of numerous incident waves, such as shear (*S*) waves, dilatational or pressure (*P*) waves, and surface (Rayleigh and Love) waves, which result in ground motion. As the seismic waves arrive in the soil surrounding the pile, the soil layers tend to deform. This seismically deforming soil tries to move the piles and the embedded pile cap with it. Subsequently, depending upon the rigidity of the superstructure and the pile cap, the superstructure may also move with the foundation. The pile may thus experience two distinct phases of initial soil-structure interaction.

At the time of earthquake, before the superstructure starts oscillating, the piles start to follow the soil motion, depending on the flexural rigidity (EI) of the pile. Here, the soil and pile may take part in ground oscillation due to earthquake which is different from normal oscillation. In this case, soil is yet to liquefy and pile will act like a beam. This may induce bending moments in the pile (Stage-II).

As the superstructure starts oscillating, lateral forces and overturning moments will act on the pile foundation. The pile cap then transfers these moments as varying axial loads and bending moments in the pile. Thus, the piles may experience additional axial and lateral loads, which cause additional bending moments in the pile.

The above two effects occur with only a small-time lag. Bending is dependent upon the section property and strength of pile materials. If section of the pile or strength of material is not adequate, bending failure may occur and pile behaves like a beam on an elastic foundation. At this stage, soil provides sufficient lateral support to the pile since confining pressure around the pile due to surrounding soil is not expected to decrease in this phase so shaft resistance remains constant. In loose saturated granular soil, as the shaking continues, pore water pressure will increase and effective stress will start decreasing and soil will liquefy.

As the liquefaction starts, an end bearing pile passing through liquefiable soil will experience different changes in its stress state. The following two different states may be used to describe the soil-pile-interaction during the ground motion.



Different stages of loading in the pile during earthquake (after Bhattacharya, 2008)

As the soil liquefies, confining pressure will start decreasing and pile will start losing its shaft resistance and there is a possibility of buckling (Stage-III) of pile foundation due to large axial load acting from superstructure.

As liquefaction commences, soil will lose its stiffness, due to which pile acts as an unsupported column (Stage-IV). Those piles, which have high slenderness ratio, will be prone to axial instability, and buckling failure of the pile will occur. This buckling is enhanced by the lateral disturbing forces and decrement in bending stiffness because of plastic yielding.

V. CASE HISTORIES OF PILE FAILURES IN LIQUEFIABLE GROUND (AFTER WANG, 2016)

Case name	Earthquake event	Failure mode	Reference
605A bridge	1964 Alaska	Lateral (no superstructure)	Ross et al. (1973)
Tianjin Ocean Petroleum Institute Factory	1976 Tangshan	Lateral (no superstructure)	Liu et al. (2010)
Showa bridge	1964 Niigata	Lateral	Iwasaki (1986)
NHK building	1964 Niigata	Lateral	Hamada (1992)
NFCH building	1964 Niigata	Lateral	Hamada (1992)

Railway bridge	1995 Kobe	Lateral	Soga (1997)
Varreux terminal wharf	2010 Haiti	Lateral	Eberhard et al. (2010)
Puerto de Coronel Muelle bridge	2010 Chile	Lateral	Yen et al. (2011)
LPG oil tank	1995 Kobe	Lateral (no lateral spread)	Ishihara (1997)
3 story building	1995 Kobe	Lateral (no lateral spread)	Tokimatsu et al. (1998)
2 story building	1995 Kobe	Lateral (no lateral spread)	Liu (1999)
Yachiyo bridge	1964 Niigata	Lateral, vertical settlement	Fukuoka (1966
Harbour master's building	2001 Bhuj	Lateral, buckling	Madabhushi et al. (2005)
Juan Pablo II bridge	2010 Chile	Vertical settlement	Yen et al. (2011)
Highway bridge	2010 Baja California	Vertical settlement	Stewart and Brandenberg (2010)
14 story building	2011 Tohoku	Vertical settlement	Tokimatsu et al. (2012)

VI. CONCLUSION

Buckling depends on the stiffness of the pile and bending depends upon section property and strength of pile foundation. Both have different design approaches since buckling is designed for lateral stability of pile due to axial load but bending is designed for lateral deflection due to transverse or horizontal load. Currently, piles in liquefiable soils are designed considering only the bending criterion which does not provide safeguard buckling failure. There must be some design consideration to increase the stiffness of the pile to avoid buckling. It can be achieved by increasing diameter of the pile depending on depth of the liquefiable soil and boundary condition at the top and bottom of liquefied zone. Bending and buckling mechanisms interact and therefore should not be viewed in isolation as both will superimpose during an earthquake to cause the pile failure.

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