A REVIEW ON PILE FOUNDATION DESIGN IN LIQUEFYING SOIL

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ABSTRACT

During recent strong earthquakes, a large number of pile foundations of modern structures have been severely damaged or collapsed in liquefied soils. The current codes of practice for pile design are based on a bending mechanism where lateral loads due to **inertia or lateral spreading** induces bending failure in the pile. These codes omit considerations necessary to avoid **buckling of a pile** due to the axial load acting on it during soil liquefaction due to the diminishing confining pressure surrounding the pile. This paper investigates buckling as an alternative mechanism for pile failure due to soil liquefaction. Based on the study of case histories and centrifuge test results, additional design criteria are proposed taking into account, the buckling effects.

Keywords: *Pile foundation, Liquefying soil, Buckling of Pile*

1. Introduction

Pile foundations are primarily designed to transfer vertical loads from the superstructure to the bearing stratum. For this reason, piles are relatively vulnerable to lateral loads such as those imposed by ground shaking during strong earthquakes. In the case of soil liquefaction, this vulnerability is particularly pronounced since the loss of strength and stiffness in the liquefied soil results in a near complete loss of lateral support for the embedded piles. It is known from previous earthquakes that liquefaction can cause very large loads on pile foundations, both from inertial loads from the superstructure and from lateral displacements of liquefied soil. The extensive damage and failure of piles have affected numerous bridges, buildings and storage tanks in the past. One such example of foundation failure involving toppling of apartment blocks due to liquefaction during the 1964 Niigata Earthquake is presented in Figure 1.

Fig.1:- Tilted apartment buildings

During recent strong earthquakes, a large number of pile foundations of modern structures have been severely damaged or collapsed in liquefied soils. In the 1995 Kobe earthquake, for example, massive liquefaction of reclaimed fills caused damage to numerous pile foundations of multi-storey buildings, storage tanks and bridge piers. The unprecedented level of damage to foundations of modern structures instigated a great number of research studies in order to better understand soil-pile interaction in liquefied soils and to improve the seismic performance of pile foundations. In the initial stages of these studies, detailed field investigations of the damage to piles, *in situ* soil conditions and permanent ground displacements were carried out. These investigations were then followed by detailed experimental studies aiming to clarify the mechanism of damage by means of seismic centrifuge tests and shake table tests including benchmark experiments on full-size piles. Based on these studies, new concepts and analysis procedures have been proposed in an effort to explore design based methodologies for piles in liquefied soils.

Collapse of piled foundations in liquefiable soil has been observed in the majority of recent strong earthquakes despite the fact that a large margin of safety is employed in their design. The current codes of practice for pile design such as Euro code 8, NEHRP 2000, JRA1996 and IS 1893 is based on a bending mechanism where lateral loads due to inertia or slope movement (Lateral spreading) induces bending failure in the pile. These codes omit considerations necessary to avoid buckling of a pile due to the axial load acting on it during soil liquefaction due to the diminishing confining pressure surrounding the pile. The provisions in the current codes are inadequate and buckling needs to be addressed. This paper investigates buckling as an alternative mechanism for pile failure due to soil liquefaction. Based on the study of case histories, a new design approach is proposed taking into account, the buckling effects.

2. BUCKLING OF PILES

2.1 Current Design Methods-Overview

The current understanding of pile failure (as noted in the literature and design codes) is as follows: Soil liquefies, losing its shear strength, causing it to flow taking with it any overlying non-liquefied crust. These soil layers drag the pile with them, causing a bending failure. This is often referred to as failure due to lateral spreading. In terms of soil-pile interaction, the current mechanism of failure assumes that the *soil pushes the pile*. The Japanese Highway code of practice (JRA 1996) has incorporated this concept as shown in Figure 2. The code advises practicing engineers to design piles against bending failure assuming that the non-liquefied crust offers passive earth pressure to the pile and the liquefied soil offers 30% of total overburden pressure. Other codes of practice such as the USA code (NEHRP 2000), Euro code 8, part 5 (1998) and Indian code (IS 1893:2002) also focus on the bending strength of the pile. Based on the assumption that lateral spreading is the cause of pile failure, research work into this pile failure mechanism has been conducted by various researchers and they conclude that the forces predicted by JRA (1996) are over-conservative.

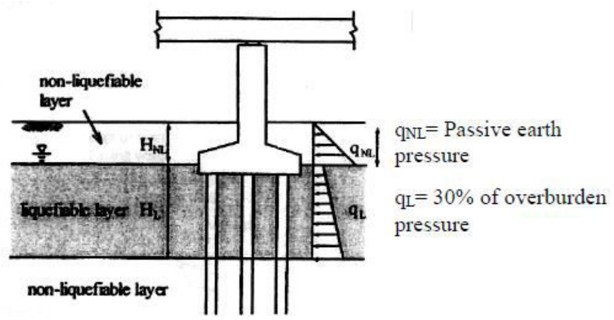

Fig.2:- Schematic Sketch Showing Pressure Distribution against the Piles due to Lateral Soil Flow associated with Liquefaction (JRA, 1996)

Structural failure of piles passing through liquefiable soils has been observed in many of the recent strong earthquakes. This suggests that the bending moments or shear forces that are experienced by the piles exceed those predicted by their design methods (or codes of practice). All current design codes apparently provide a high margin of safety (using partial safety factors on load, material stress which increases the overall safety factor), yet occurrences of pile failure due to liquefaction are abundant. This implies that the actual moments or shear forces experienced by the pile are many times higher than the predictions. It must be concluded that the current design methods may not be consistent with the physical processes or mechanisms that govern liquefaction-induced failure.

2.2. Collapse of pile foundation in level ground

It was observed that pile foundations collapsed even in level grounds in a similar way to that observed in laterally spreading grounds. After the detailed investigation of the failure of piles during 1995 Kobe earthquake, it was found that in the liquefied level ground, most PC piles (Prestressed Concrete pile used before 1980's) and PHC piles (Prestressed High Strength Concrete piles used after 1980's) bearing on firm strata below liquefied layers suffered severe damage accompanied by settlement and/or tilting of their superstructure. Figure 3 shows the failure of a piled foundation in a level ground. The foundation tilted in the direction of the asymmetrical mass i.e. in the direction of the eccentricity of vertical loading. It is surprising that a piled foundation collapses in a similar way in level ground i.e. in absence of lateral spreading and in laterally spreading grounds i.e. in the presence of lateral spreading. If lateral spreading is the main cause of failure, it is most unlikely that a piled foundation will collapse in level grounds. It must also be noted that most of PHC piles which had a high bending strength also failed.

Fig.3: Failure of Pile Foundation In Level Ground, Bhuj 2001 Earthquake

2.3 Location of hinge formation

It has been revealed after the excavation of the buildings in the Kobe earthquake (1994) and the Niigata earthquake (1964) (Figure 4) that hinges formed in piles occurred within the top third of the pile or even at the middle of the liquefiable layer. Had the cause of pile failure been lateral spreading, the location of the plastic hinge would have been expected at the interface of liquefiable and non-liquefiable layer as this section would experience the highest bending moment.

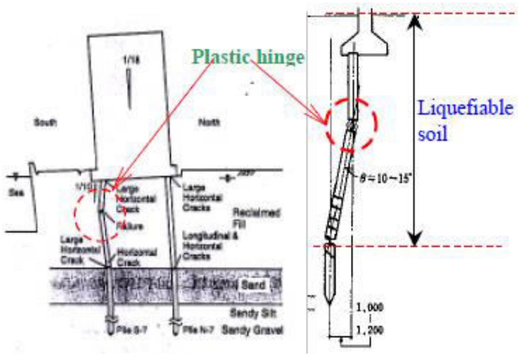

Fig.4:- Collapsed buildings showings location of plastic hinge

2.4 A case study of the Showa Bridge, Niigata Earthquake (1964)

The example of the failure of the Showa Bridge (Figure 5) is extensively used to illustrate the effects of lateral spreading loads to piled foundations. The bridge was built over river Shinano and was completed just a month before the earthquake. The bridge had a width of 24m and total length of 303.9m. The superstructure of the bridge consisted of 12 composite girders. The foundations of each pier consisted of a row of 9steel tubular piles connected laterally as shown in Figure 5. After the earthquake five girders (G3to G7) fell into the river as shown.

Fig.5:-Failure of the Showa Bridge after the 1964 Niigata Earthquake.

Figure 6 shows the schematic representation of the failure of the bridge. The diagram only shows half of the bridge. It must be noted that the direction of deflection shown by the red dashed circle contradicts the assumption of lateral spreading. As can be seen, piles under pier no. P5 deformed towards the left and the piles of pier P6 deformed towards the right. Had the cause of pile failure been lateral spreading, the piers should have deformed identically in the direction of the slope. Furthermore, the piers close to the riverbanks did not fail, whereas the lateral spread is seen to be most severe at these places. It is found that the piles of the Showa Bridge are safe against the current code provisions of the JRA code with a factor of safety of 1.84 but the bridge actually collapsed.

To summarize, the limitations of the current understanding of pile failure/ codes of practice are:

- This hypothesis of pile failure assumes that the pile remains in stable equilibrium (i.e. vibrates back and forth and does not move uni directionally as in case of instability) during the period of liquefaction and before the onset of lateral spreading. In other words, the hypothesis ignores the structural nature of pile.
- The effect of axial load as soil liquefies is ignored.
- Some observations of pile failure cannot be explained by the current hypothesis.

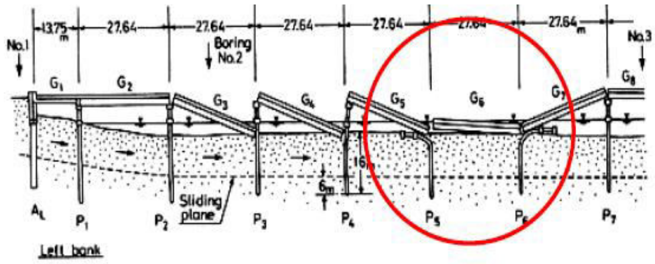

Fig.6:-Schematic Diagram Of The Failure Of The Showa Bridge.

3. Pile Buckling

Pile behaves as a slender column when it is not laterally supported by soil. Hence during soil liquefaction, one has to consider the phenomenon of pile buckling in addition to the bending failure due to lateral loads. Generally, as the length of the pile increases, the allowable load on the pile increases primarily due to the additional shaft friction but the buckling load (if the pile were laterally *unsupported* by soil) decreases inversely with the square of its length following Euler's formula. Figure 7 shows a typical plot for the variation of allowable load (P) and buckling load (P_{cr}) of a pile (if *unsupported*) against length of the pile. The pile in the above example has a diameter of 300mm (typical pile dimension in 1964 Japan) and is passing through a typical liquefied soil.

The allowable load (P) is estimated based on conventional procedures with no allowance for liquefaction. Structural engineers generally demand a factor of safety of at least 3 against linear elastic buckling to allow for eccentricities, imperfections and reduction of stiffness due to yielding. Thus, if *unsupported* over a length of 10m or more, such columns could fail due to buckling instability and not due to crushing of the material.

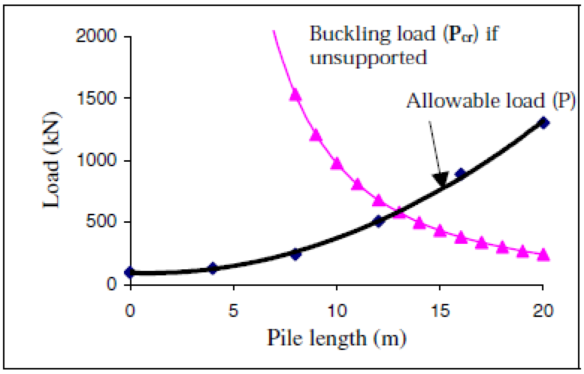

Fig.7:-Allowable Load And Buckling Load Of A Pile (If Unsupported)

During earthquake-induced liquefaction, the soil surrounding the pile loses its effective confining stress and can no longer offer sufficient support to it. The pile, if sufficiently slender, may now act as an unsupported column prone to axial instability. The instability may cause it to buckle sideways in the direction of least elastic bending stiffness under the action of axial load, eventually causing a plastic hinge Figure 8 shows instability of a frame supported on slender columns, as load is increased. At a particular load the frame becomes unstable and this is often termed as Euler's critical load (P_{cr}). Imperfections, such as lateral loads or out-of-line straightness will increase lateral deflections, which in turn induces plasticity in the strut and reduces the buckling load, promoting a more rapid collapse.

4. CRITERIA FOR DESIGN

4.1 Essential criteria for design of pile foundations in liquefiable areas

A safe design procedure should ensure the following:

1. A collapse mechanism should not form in the piles under the combined action of lateral loads imposed upon by the earthquake and the axial load. Figure 8 (A) shows such a mechanism. At any section of the pile, bending moment should not exceed allowable moment of the pile section. The shear stress at any section of the pile should not exceed the allowable shear capacity.
2. A pile should have sufficient embedment in the non-liquefiable hard layer below the liquefiable layer to achieve fixity to carry moments induced by the lateral loads. If proper fixity is not achieved, the piled structure may slide due to the kinematic loads. The fixity depth is shown by D_F in Figure 8(B).
3. The pile has enough strength and stiffness to carry the axial load acting on it during full liquefaction without buckling and becoming unstable. It has to sustain the axial load and vibrate back and forth, i.e. must be in stable equilibrium when the surrounding soil has almost zero stiffness owing to liquefaction. As mentioned earlier, lateral loading due to ground movement, inertia, or out-of-straightness, will increase lateral deflections which in turn can cause plastic hinges to form, reducing the buckling load, and promoting more rapid collapse. These lateral load effects are, however, secondary to the basic

requirements that piles in liquefiable soils must be checked against Euler's buckling. This implies that there is a requirement of a minimum diameter of pile depending on the likely liquefiable depth.

4. The settlement in the foundation due to the loss of soil support should be within the acceptable limit. The settlement should also not induce end-bearing failure in the pile.

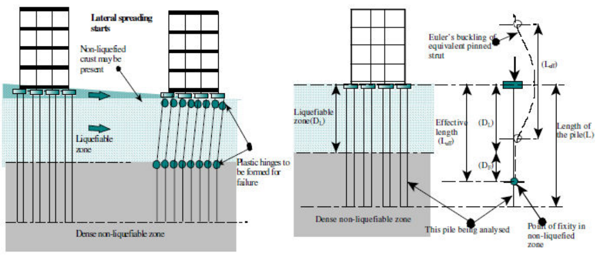

Fig.8 (A): Combined mechanism of axial and bending.
Fig.8 (B): Buckling mechanism.

4.2 Simplified procedure to avoid buckling

As can be seen in Figure 9(A), lateral spreading loads and inertia loads may act in two different planes. Thus the pile not only has axial stress but also may have bending stresses in two axes. The pile represents a most general form of a "beam-column" (column carrying lateral loads) element with bi-axial bending. If the section of the pile is a "long column", analysis would become extremely complex and explicit closed form solution does not exist. The solution of such a problem demand an understanding of the way in which the various structural actions interact with each other i.e. how the axial load influences the amplification of lateral deflection produced by the lateral loads. In the simplest cases i.e. when the section is "short column", superposition principle can be applied i.e. direct summation of the load effects. In other cases, careful consideration of the complicated interactions needs to be accounted. Designing such type of member needs a three-dimensional interaction diagram where the axes are: Axial (P), major axis moment (Mx) and minor-axis moment (My).The analysis becomes far more complicated in presence of dynamic loads. The above complicated non-linear process can be avoided by designing the section of the pile as "short column" i.e. for concrete section - length to least lateral dimension less than 15 (British Code 8110) or a slenderness ratio (effective length to minimum radius of gyration) less than 50.

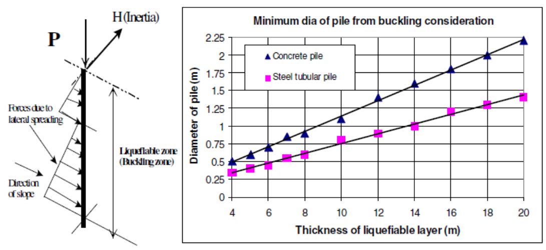

Fig.9 (A): Free body diagram______Fig.9 (B): Chart connecting diameter of pile and showing the generalized loading thickness of liquefying layer acting on a pile.

Figure 9(B) shows a typical graph showing the minimum diameter of pile necessary to avoid buckling depending on the thickness of liquefiable soil. The slenderness ratio is kept around 50. The main assumptions are that the piles are solid concrete section having E (Young's modulus) of 22.5×10^{3} MPa) and for steel E of 210GPa. The piles are not in a single row and at least in 2×2 matrix form. The thickness of the steel pile is based on API [35] code (American Petroleum Code) i.e. the minimum thickness is 6.35mm + (diameter of the pile/100).

5. CONCLUSION

- The design of pile foundations in liquefying soil needs an understanding of soil liquefaction, behaviour of soils following liquefaction and the soil-pile interaction. The practice of pile design in liquefying soil has progressed considerably in the last decade based on observations during the past earthquakes and experimental studies on centrifuge and large shake table tests.

- The current design methods take into account the effect of inertial load and lateral displacement alone and hence assumes a bending mechanism of failure for piles.
- Investigation of several case histories show that the fundamental effect of axial load has not been included in the design procedure and the effect of buckling is not considered, which can be the cause of pile failures in level grounds.
- The results from centrifuge test and the study of case histories show that piles having ratio P/P_{cr} ratios greater than 0.75 are not safe against buckling.
- Based on the investigations, a new theory of pile failure has been developed assuming that the pile behaves like a slender column during the process of liquefaction as it loses the lateral support of surrounding soil.
- Simplified design procedure considering the thickness of liquefiable layer and pile diameter can be developed. To avoid buckling instability of piles it has been recommended to keep the slenderness ratio of piles in the buckling zone below 50.

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