Chapter 1: Introduction

1.1 Background

Earthquakes cause damage to engineering structures (Figure 1.1) and often result in loss of lives. The recent Indian earthquake at Bhuj on 26th January 2001 is estimated to have cost more than 5 billion U.S. dollars but, more significantly, the death toll was more than 20,000. Forecasting the exact time of an earthquake can at best reduce casualties, which at present appears to be an impossible task. Therefore, structures need to be designed to withstand the impact of an earthquake and prevent collapse, as "it is buildings that kill people, not earthquakes".

Figure 1.1: (a) Failure of a residential building during the 2001 Bhuj earthquake (India); (b): A highrise building during the 1995 Kobe earthquake, after U.C. Berkeley (1995); (c): Tilting of a building during the1999 Koeceli earthquake (Turkey), after EERI (1999).

Earthquakes in the past have shown the shortcomings of current design methodologies and construction practices, at the cost of structural failures and loss of lives. Post earthquake investigations have led to improvements in engineering analysis, design and construction practices. A brief historical development of earthquake engineering practice showing how earthquake engineers have learned from failures in the past is outlined in Table 1.1

Table 1.1: Historical development of earthquake engineering practice.

Earthquake	Remarks	Post earthquake developments
28^{th} Dec, 1908 Reggio Messina earthquake (Italy). Reitherman (2000)	120,000 fatalities A committee of nine practising engineers and five professors were appointed by Italian government to study the failures and to set design guidelines.	Base shear equation evolved i.e. the lateral force exerted on the structure is some percentage of the dead weight of the structure, (typically 5 to 15%).
1923 Kanto earthquake (Japan) Kawashima (2002)	Destruction of bridges, buildings. Foundations settled, tilted and moved.	Seismic coefficient method (equivalent static force method using a seismic coefficient of 0.1 - 0.3) was first incorporated in design of highway bridges in Japan (MI 1927).
10^{th} March, 1933 Long Beach earthquake (USA) Fatemi and James (1997)	Destruction of buildings specially school buildings.	UBC (1927) revised. This is the first earthquake for which acceleration records were obtained from the recently developed strong motion accelerograph.
1964 Niigata earthquake (Japan)	Soil can also be a major contributor of damage.	Soil liquefaction studies started.
1971 San Fernando earthquake (USA)	Bridges collapsed, dams failed causing flood. Soil effects observed.	Liquefaction studies intensified. Bridge retrofit studies started.
1994 Northridge earthquake (USA)	Steel connections failed in bridges.	Importance of ductility in construction realised.
1995 Kobe earthquake (Japan) Kawashima (2000)	Massive foundation failure. Soil effects were the main cause of failure.	Downward movement of a slope (lateral spreading) is said to be one of the main causes. JRA (1996) code modified (based on lateral spreading mechanism) for design of bridges.

1.2 Failure of structures during earthquakes

Normally the failure of structures during earthquakes is the result of structural inadequacies, foundation failure, or a combination of both. Figure 1.1(a) shows the failure of a residential building predominantly due to structural inadequacies such as poor ductility and improper beam-column detailing. On the other hand, the failures shown in Figures 1.1(b & c) are not due to any structural inadequacies but due to foundation failure. In such failures the soil supporting the foundation plays an important role.

The behaviour of foundations during earthquakes is often dictated by the response of its supporting soil due to the ground shaking. In general, there are two types of ground response that are damaging to structures, Dobry and Iai (2000). In one, the soil fails typically by liquefaction, such as in the 1995 Kobe earthquake. In the other, the soil amplifies the ground motion (see, for example the 1989 Loma Prieta earthquake in California).

Figures 1.2 (a, b and c) shows collapse of some pile-supported structure founded on or passing through liquefiable soils during earthquakes. The focus of this research is to investigate the failure mechanisms of this type of foundations during earthquakes.

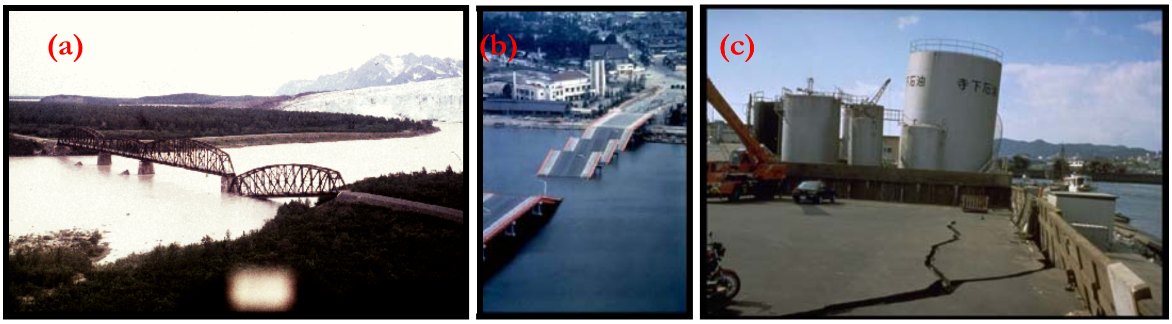

Figure 1.2: (a) Piled "Million Dollar" bridge after 1964 Alaska earthquake (USA); (b): Piled "Showa Bridge" after 1964 Niigata earthquake (JAPAN); (c): Piled tanks after 1995 Kobe earthquake (JAPAN), photo courtesy NISEE.

Pile foundations are often used to transfer axial loads through soft soils to stronger bearing strata at depth. Piles transfer load to the soil partly by shear generated along the shaft (shaft resistance) and partly by normal stress generated at the base (base resistance). Base resistance dominated piles are described as end-bearing piles while shaft resistance dominated piles are described as friction piles. One would expect that in earthquake prone areas end-bearing piles should perform better than friction piles due to their end restraints. However, a significant number of cases of damage to end-bearing piles and pile-supported structures have been observed in most major earthquakes. The objective of this research is to gain an insight into the failure mechanism of end-bearing piles in liquefiable soils during earthquakes.

1.3 Pile-supported structures still collapse during earthquakes: What is missing?

Structural failure by the formation of plastic hinges in piles passing through liquefiable soils has been observed in many of the recent strong earthquakes. Figure 1.3 shows two such cases from past earthquakes. This suggests that the bending moments or shear forces that are experienced by the piles exceed those predicted by 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 those predicted. It may be concluded that design methods may not be consistent with the physical mechanisms that govern the failure. In other words, something is missing. This research investigates what is missing from the current understanding of earthquake-induced pile failure by analysing the postulated hypothesis of the existing design codes of practice, such as the Japanese Road Association Code (JRA 1996), NEHRP (2000), and Eurocode 8 (Part 5).

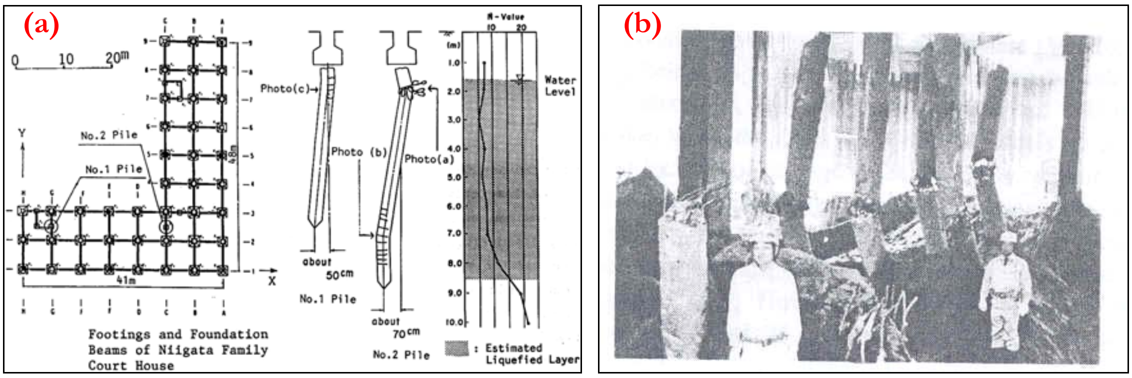

Figure 1.3(a): Pile failure of Niigata Family Court House building during 1964 Niigata earthquake, Hamada (1992a); (b): Pile failure observed during the excavation of the NHK building after 1964 Niigata earthquake, Hamada (1992a).

Appendix-A shows a typical example of the design of a piled foundation using limit state design philosophy. It has been shown that the overall safety factor against plastic yielding of a typical concrete pile considering the bending mechanism may range between 4 and 8. This is due to the multiplication of partial safety factors on load (1.5), material (1.5 for concrete), fully plastic strength factor (Z_P/Z_E = 1.67 for circular section) and practical factors such as minimum reinforcements or minimum number of bars. Therefore, one should not expect failures unless wrong failure mechanisms are postulated.

1.4 Current understanding of pile failure and design methods

The *current* understanding of pile failure is as follows. Soil liquefies, it loses its shear strength, causing it to flow and dragging with it any overlying non-liquefied crust. These soil layers drag the pile with them, causing a bending failure as shown in Figure 1.4. 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 deformation of the ground surface adjacent to piled foundations is often suggestive of this mechanism. Figure 1.5 shows surface observations of lateral spreading observed after earthquakes.

The Japanese highway code of practice (JRA 1996) has incorporated this understanding of pile failure as shown in Figure 1.6. The code advises practising engineers to design piles against bending failure assuming that non-liquefied crust offers passive earth pressure to the pile while the liquefied soil itself offers a drag equal to 30% of total overburden pressure.

Other codes such as the USA code (NEHRP 2000) and Eurocode 8, part 5 (1998) also focus on the bending strength of the pile.

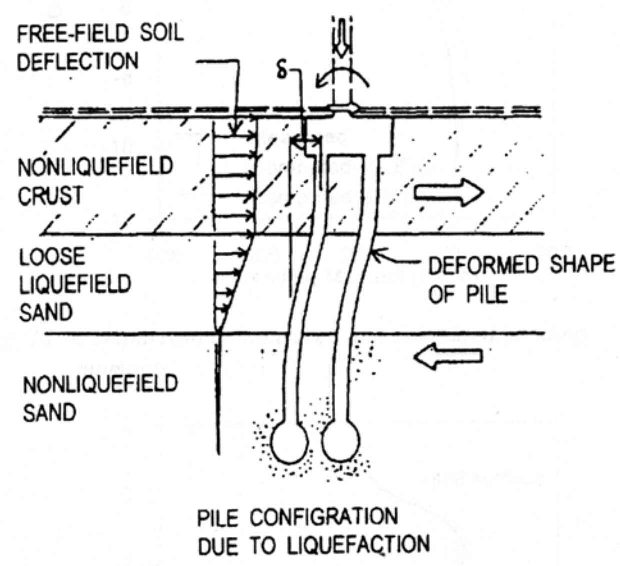

Figure 1.4: Current understanding of pile failure, Finn and Thavaraj (2001).

Figure 1.5 (a): Surface observations of lateral spreading at a bridge site in 1995 Kobe earthquake after NISEE; (b): Navalakhi port in 2001 Bhuj earthquake, Madabhushi et al (2001).

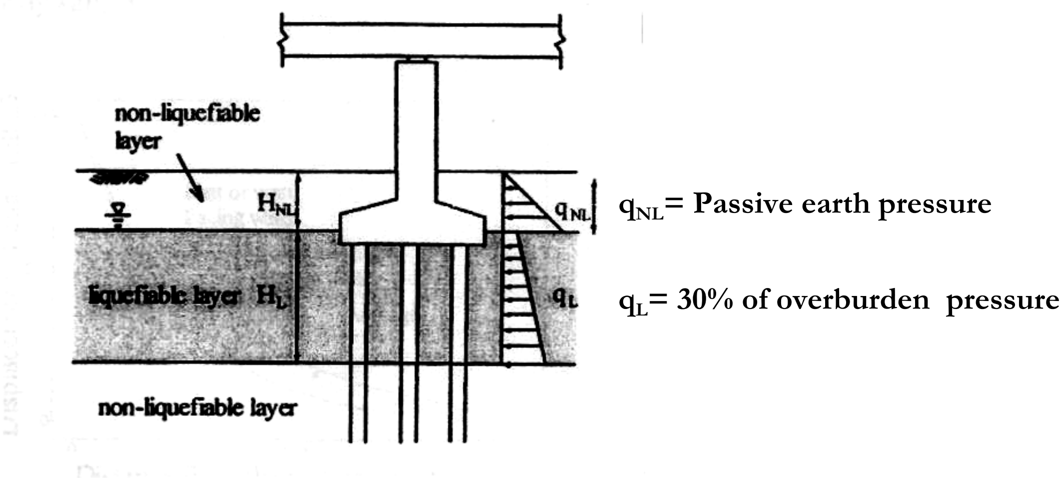

Figure 1.6: JRA (1996) code of practice showing the idealisation for seismic design of bridge foundations.

1.5 Inconsistency of the current understanding with observed seismic pile failure at liquefiable sites

This section highlights the shortcomings of the current understanding of pile failure in the light of a well-documented case history of Showa Bridge during the 1964 Niigata earthquake. The failure of the bridge as shown in Figures 1.2 (b), 1.7 and 1.8 is widely accepted as being due to lateral spreading of the surrounding soil: see, for example, Hamada (1992a), Ishihara (1993).

Figure 1.7: Failure of Showa Bridge after NISEE.

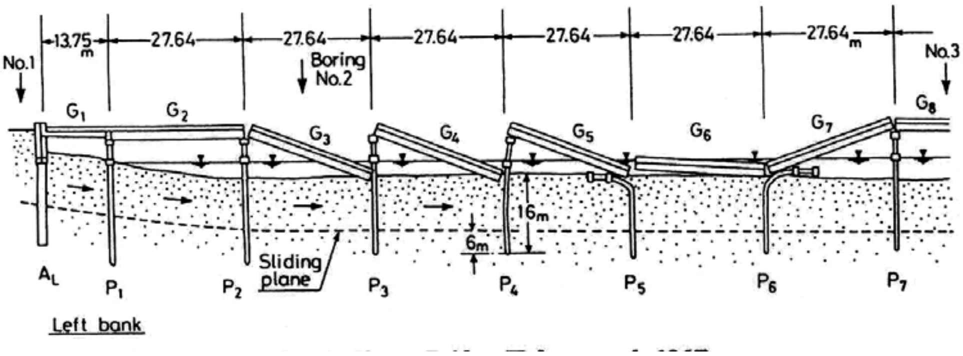

Figure 1.8: Schematic diagram of the Fall-off of the girders in Showa bridge (Takata et al., 1965).

As can be seen from Figure 1.8, piles under pier no. P_5 deformed towards the left and the piles of pier P_6 deformed towards the right (Fukuoka, 1996). Had the cause of pile failure been due to 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 severe at these places.

The location of a plastic hinge due to lateral spreading is expected to occur at the interface of the liquefiable and non-liquefiable layer as this section experiences the highest bending moment. It is often seen, however, that hinge formation also occurs within the top third of the pile as seen in Figures 1.3(b) and 1.8.

1.6 Does the soil push the pile or vice versa?

Structurally, piles are slender columns with lateral support from the surrounding soil. Generally, as the length of the pile increases, the allowable load on the pile increases due to the additional shaft friction but the buckling load (if the pile were to be laterally unsupported by soil) decreases inversely with the square of the length. Appendix-B illustrates the above statement for a typical pile. If unsupported, these columns will fail due to buckling instability and not due to crushing of the material. During earthquake-induced liquefaction, the soil surrounding the pile loses its effective confining stress and may not offer sufficient lateral support. The pile 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. In this case the *pile may push the soil* and it may not be necessary to invoke lateral spreading of the soil to cause a pile to collapse. This research aims to understand whether buckling instability can be a possible failure mechanism of pile foundations subject to earthquake liquefaction.

1.7 Pile failure as an instability problem during liquefaction

Figure 1.9 shows the time histories of shear stress, excess pore pressure, displacement of surrounding ground, soil stiffness and bending moment in the pile, after Yasuda and Berrill (2000). The current understanding of pile failure assumes that failure occurs after the ground starts moving monotonically, as shown by the green arrow in Figure 1.9.

Intuitively, it appears that even in sloping ground, before lateral spreading starts, i.e. prior to flowing of the soil and loading of the pile laterally, there will be a time instant when the pile has no lateral support from the surrounding soil. If the pile buckles due to diminishing effective stress and shear strength owing to liquefaction, buckling instability can be a possible failure mechanism irrespective of the type of ground - level ground or sloping. This study concentrates on the time interval before lateral spreading starts as shown in Figure 1.9 by a red rectangle. One of the aims of this study is to investigate whether piles can fail in level ground (i.e. in absence of lateral spreading) under seismic liquefaction.

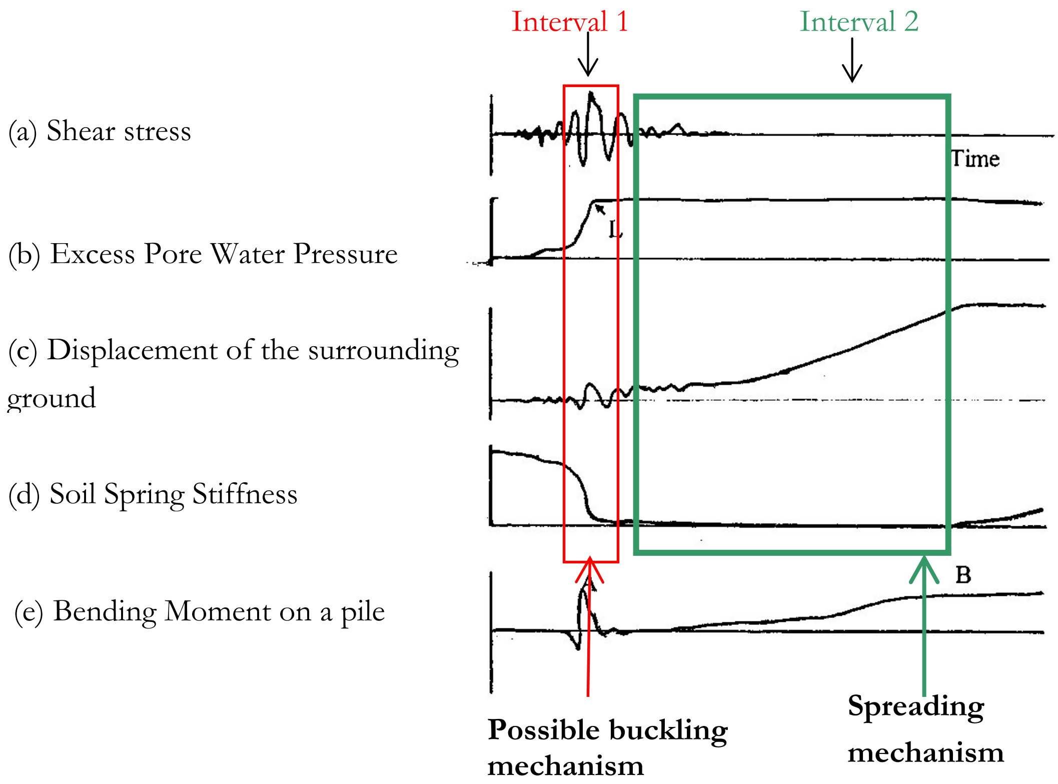

Figure 1.9: Time histories of events (Yasuda and Berrill, 2000).

1.8 Aims and scope of the work

Collapse of pile foundations in liquefiable areas is still observed after an earthquake despite the fact that a large margin of safety is employed in their design. The observed mode of failure is also not consistent with the current understanding of pile failure, i.e. lateral spreading. Thus, this research has been carried out without making the presumption that lateral spreading is the cause of failure. As a result, the events that precede lateral spreading are closely studied. Liquefaction clearly precedes lateral spreading and so the effect of liquefaction on an axially loaded pile is investigated first.

Specifically, the objectives of the present study are:

1. To determine the effects of axial load alone on an end bearing pile, when the surrounding soil liquefies in an earthquake using dynamic centrifuge modelling. In other words, to verify whether buckling instability is a possible failure mechanism of pile foundations during seismic liquefaction.

2. To investigate the missing parameter in the design method by studying case histories of pile foundation performance during past earthquakes.
3. To improve understanding of pile-soil interaction during earthquake liquefaction in the light of the experimental results.
4. To examine the effects of lateral spreading loads on pile foundations.
5. To develop a design method for the design of piled foundations in areas of seismic liquefaction.

1.9 Structure of the dissertation

The structure of this thesis is as follows:

Chapter 2 presents a brief literature review relating to liquefaction, buckling of piles, the structural nature of piles and the current understanding of pile failure during seismic liquefaction. Critical remarks are made on the current hypothesis of pile failure citing the example of the failure of Showa Bridge.

Chapter 3 analyses fifteen reported case histories of pile foundation performance during earthquakes. This chapter is divided into two parts. Firstly, the method of analysis of case histories is outlined and the results are summarised in the form of tables and plots. Secondly, a hypothesis of pile failure has been formulated based on case histories. The hypothesis is later verified using dynamic centrifuge modelling as explained in subsequent chapters.

Chapter 4 explains the significance of centrifuge modelling in this research. This chapter also describes the centrifuge testing facility at Cambridge University, the methodology used to perform the tests, the testing program and the development of the model pile.

Chapter 5 presents the results and analysis of the centrifuge tests carried out to verify the hypothesis of pile failure proposed in chapter 3.

Chapter 6 discusses the results of the centrifuge tests described in chapter 5 in relation to the verification of the hypothesis of pile failure proposed in chapter 3. This chapter also links the correlations obtained from the study of case histories with a theory of pile failure backed up with centrifuge test results.

Chapter 7 develops a design method for pile foundations in areas of seismic liquefaction. The method proposes new design criteria for such piles based on the mechanisms established during the course of the study. A practical example of the application of the method is also elucidated.

Chapter 8 summarises the key conclusions from this work. The implications of this research work are also highlighted. The scope for future work is also suggested.