Chapter 8: Conclusions and further research

8.1 Introduction

Collapse of pile-supported structures in areas of seismic liquefaction 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 understanding of this failure is based on a bending mechanism where inertia and slope movement (lateral spreading of soil) induce the bending moment in the pile, and where axial load effects are ignored.

The work presented in this thesis was carried out without making the presumption that it is the bending moments induced by the lateral loads that cause the failure of piles in areas of seismic liquefaction. During seismic liquefaction, a pile foundation also continues to experience the axial load of the superstructure. Thus, the effect of axial load as the soil liquefies was carefully studied. Detailed dynamic centrifuge testing, in-depth study of case histories and analytical studies form the basis for investigating the mechanism of pile failure during seismic liquefaction. Based on these studies, the buckling mechanism has been identified as the most probable failure mechanism for pile foundations and is expected to precede failure due to lateral spreading.

In this chapter, the major conclusions are drawn from the extensive study carried out. The implications of this research are also discussed and further research needs are identified.

8.2 Specific conclusions

Each chapter in this thesis ends with a summary. Specifically chapter 6 unifies the study of case histories with the observations of the centrifuge tests and detailed findings on the research work covered in this thesis. This section points out the major conclusions and recommendations.

The major conclusions are:

- **Buckling of fully embedded piles**

Fully embedded end-bearing piles passing through saturated, loose to medium dense sands and resting on a hard layer can buckle under the action of axial load alone if the surrounding soil liquefies during earthquake. The stress in the pile section will initially be within the elastic range and the buckling length will be the entire length of pile in liquefied soil. Lateral loading, due to slope 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.

- **Effect of lateral loads on pile failure**

Unless the (P/P_{cr}) ratio is high enough (Figure 6.2), lateral loads – however large they may be – cannot cause buckling instability to a piled structure, (see section 6.4). However, the piled foundation may collapse by forming a plastic collapse mechanism, (see for example, Figure 7.2 where failure takes place due to imposed moment exceeding pile bending strength).

- **Replication of pile failure in centrifuge tests**

A failure mode similar to full-scale piles observed after real earthquakes in a laterally spreading liquefiable soil has been replicated in a small-scale centrifuge model. The model piles were made of dural alloy tube and the tests were carried out in level grounds. Analytical studies and field case records also justify the observations. Thus there is no need to invoke lateral spreading of the soil to cause a pile to fail. The pile can fail under the action of axial load alone, even before lateral spreading starts.

- **Identification of an error in the current design method leading to pile failure in seismic liquefaction**

It has been shown through an example that, in Limit State design approach, unless wrong design concepts are employed, structural failure of piles are unlikely. This is because of different partial safety factors employed in design, which increases the overall safety against the assumed failure mechanism.

The current design codes for pile design in areas of seismic liquefaction, for example, the USA code (NEHRP 2000), Japanese Road Association Code JRA (1996) and Eurocode 8, part 5 (1998) focus on bending strength and omit considerations of the bending stiffness required to avoid buckling in the event of soil liquefaction.

Bending and buckling require different approaches in design. Bending is a stable mechanism and is dependent on strength whereas buckling is dependent on geometric stiffness and is almost independent of strength. Designing against bending would not automatically suffice the buckling requirements.

The design of piles based on a bending mechanism is inappropriate for slender piles (i.e. for $L_{eff}/r_{min} > 50$). The missing parameter identified in the current design method (JRA 1996) is the slender nature of the pile and the effect of axial load when the soil surrounding the pile liquefies. The JRA (1996) code was formulated by back analysing piled foundations, which were not seriously damaged. It is worth noting that these foundation piles had a diameter of 1.5m and penetrated only 15.9m of length in liquefiable layer, (Yokoyama et al., 1997). The slenderness ratio in the liquefiable layer is 42 and they could be categorised as short column, which would only fail in crushing and not buckling. Such piles would remain stable irrespective of soil support, but they would need to be checked against bending moments induced due to lateral spreading.

It has been shown (section 2.7.1), through the example of the failure of the Showa Bridge that, although the design of the piled foundation of the bridge satisfies the latest code of practice (JRA 1996) with a factor of safety of 1.84, the structure actually failed during the 1964 Niigata earthquake.

- **A new theory of pile failure in areas of seismic liquefaction**

A theory of pile failure, based on buckling instability, is proposed in this thesis. The hypothesis of this theory is postulated by back analysing field case studies of pile foundation performance. Centrifuge tests were carried out to verify the pile failure hypothesis and the test results match satisfactorily with the newly proposed theory of pile failure i.e. buckling instability. Analytical studies also justify the case studies and centrifuge tests.

The theory in short states that:

Once the surrounding soil has its effective stresses eliminated due to seismic liquefaction, a susceptible pile starts to buckle in the direction of least elastic bending stiffness. This susceptibility depends on the slenderness ratio (L_{eff}/r_{min}) of the pile exceeding a critical value in the liquefiable region. If the soil around the pile remains liquefied for long enough, the pile will suffer gross deformations and the superstructure will either tilt or deform as observed in the aftermath of real earthquakes. The proposed theory assumes that a pile can buckle and push the soil monotonically. It is not necessary to invoke lateral spreading of the soil, which pushes the pile to cause it to fail, as currently believed.

- **A hypothesis of pile-soil interaction during buckling**

Pile buckling is different from Euler's classical buckling, (see section 6.5). In the case of Euler's classical buckling, the resistance to the buckling strut is air. On the other hand for buckling of piles the resistance is due to the dilating, "initially liquefied and then subsequently monotonically sheared" near field soil. The liquefied soil offers resistance and dictates the point of hinge formation but cannot prevent the initiation of buckling. It has been hypothesised that resistance of the liquefied soil decreases with increased deformation of the pile due to transient flow from the neighbouring "liquefied but not sheared soil". The buckling of pile can be described as:

"*Euler's classical buckling in a non-linear resistive medium*".

The pre-buckling behaviour is controlled by "Euler's Critical Load". On the other hand the post buckling behaviour and the location of hinge formation is dependent on the resistance of liquefied soil, which can be well modelled using "Critical State" soil mechanics.

- **A method of analysis of case histories**

A method of analysis for reported case histories is formulated in this research work, section 3.2. This method allows the analysis of a case history through physical parameters rather than a qualitative description of the failure.

- **New design method of piled foundation**

Criteria for design of pile foundations in areas of seismic liquefaction are proposed. A new methodology is formulated. This method ensures the stability of piled foundation throughout its design period. It also takes care the serviceability limit state criteria by controlling settlement during full liquefaction. A simplified design chart is proposed for choosing pile diameter depending on the depth of the liquefiable soil.

8.3 Recommendations to practice

1. Codes of practice need to include a criterion to prevent buckling of slender piles in liquefiable soils. The designer should first estimate the equivalent length for Euler's buckling, by considering any restraints offered by the pile cap, or the zone of embedment beneath the liquefiable soil layer. It is then necessary to select a pile section having a margin of factor of safety against buckling under the worst credible loads.
2. Designers should specify fewer, large modulus piles, in order to avoid problems with buckling due to liquefaction.
3. Cellular foundations of contiguous, interlocked sections should also be effective.

8.4 Suggestions for further research

The research presented in this thesis has identified the limitations of the existing design methods of piled foundations in liquefaction hazard areas for e.g. Japanese Road Association JRA (1996), Eurocode 8 (1998), and NEHRP (2000). It seems that many of the bridges and buildings designed based on the existing design codes are unsafe. Based on the above fact the following research need is identified. The immediate need is to re-evaluate the safety of the structures designed based on the existing design methods. Structures that are unsafe will need retrofitting to withstand future impacts of earthquakes. Keeping this view in mind, the suggested future research work is outlined below:

1. Formulating an earthquake resistant design philosophy for design of new piled foundations in seismic liquefiable areas. A preliminary work is carried out in this thesis and is described in chapter 7.
2. Identifying the parameters for systematic evaluation of safety of existing structures founded on piles designed based on existing design methodologies. Some of the parameters identified are:
    - Site characterisation i.e. depth of liquefiable soil at the site of the structure, slope of the ground, seasonal variation of ground water table. This would help to identify the non-liquefied crust at the site and expected lateral loads in the pile.
    - Slenderness ratio of piles in liquefiable region. This would check the stability of pile against Euler's buckling. A method is suggested in section 6.4.1

3. Once unstable structures (for e.g. abutment/piers of bridges, or piled buildings) are identified, strategies for retrofitting have to be researched. This will involve means to improve stability of foundations.
4. Development of a numerical algorithm to accommodate instability, plastic collapse mechanism and soil-pile interaction towards a more detailed analysis. Separately dynamic centrifuge tests can also be carried out to validate the numerical code.
5. Comparative study of different foundation system (raft, piled, piled rafts or piled raft with deep basements) for optimum design of safe foundations in liquefiable areas.
6. Further experimental studies to understand pile-soil interaction mechanism.