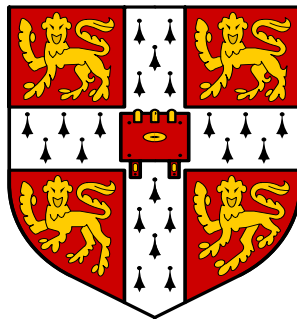


PILE INSTABILITY DURING EARTHQUAKE LIQUEFACTION



by

Subhamoy Bhattacharya

A dissertation submitted for the degree of Doctor of Philosophy at the
University of Cambridge
Cambridge, UK

Trinity Hall

September 2003

Pile instability during earthquake liquefaction

ABSTRACT

Large magnitude earthquakes are low-probability but high-risk events. While these events cannot be accurately predicted or prevented, understanding the behaviour of structures under such events enables engineers to design safe earthquake-resistant structures.

This thesis describes the results of an investigation into the failure mechanism of piled foundations, which are a particular type of deep foundation for heavily loaded structures e.g. high rise buildings, bridges, ports, flyovers where these occur in areas of potential seismic liquefaction. Detailed dynamic centrifuge testing, in-depth study of field case records and analytical studies form the basis of this investigation.

Collapse of piled foundations in liquefiable soils is still observed after strong earthquakes despite the fact that a large factor of safety (against bending due to lateral loads) is employed in their design. This thesis critically reviews the current design methods and the underlying mechanism behind them. The current method of pile design under earthquake loading is based on a bending mechanism where inertia and slope movement (lateral spreading of soil) induce bending moments in the pile. This thesis aims to show that this hypothesis of pile failure is inconsistent with the observed mode of failure. The well-known case study of the Showa Bridge is used to illustrate that although the design of the piles in the bridge satisfies the latest Japanese Code of Practice (JRA, 1996), the bridge actually failed during the 1964 Niigata earthquake.

A theory of pile failure, based on buckling instability is proposed in this thesis. The main postulate of this theory is that if piles are too slender they require lateral support from the surrounding soil if they are to avoid buckling instability. During earthquake-induced liquefaction, the soil surrounding the pile loses effective confining stress and can no longer offer sufficient support to the pile. A slender pile may then buckle sideways in the direction of least elastic bending stiffness pushing aside the initially liquefied soil, and eventually rupturing under the increased bending moment and shear force. Lateral loading due to slope movement, inertia or out-of-straightness increases lateral deflections, which in turn induces plasticity in the pile and reduces the buckling load, promoting more rapid collapse. These lateral loads are, however, secondary to the basic requirements that piles in liquefiable soil must be checked against Euler's buckling. This theory has been formulated based on a study of fifteen case histories of pile foundation performance and verified using dynamic centrifuge tests. Analytical studies also support this theory of pile failure. A hypothesis of post-buckling pile-soil interaction is also developed to fit the centrifuge test data.

Centrifuge tests were designed in level ground to avoid the effects of lateral spreading and the main aim was to study the effect of axial load as soil liquefies. The failure mode observed in the tests was very similar to those observed in the field in laterally spreading soil. It is concluded in this thesis that it is not necessary to invoke lateral spreading of the soil to cause a pile to collapse. The pile may even collapse before lateral spreading starts. The key parameter identified to distinguish whether the pile pushes the soil (buckling) or the soil pushes the pile (lateral spreading) is the slenderness ratio of the pile in the liquefiable region. The critical value of this parameter is approximately 50.

In summary, it has been shown that the current codes of practice for pile design omit considerations necessary to avoid buckling in event of soil liquefaction. These codes are inadequate and buckling needs to be addressed. It has been identified that many of the structures designed based on the current codes of practice may be unsafe and may need retrofitting. Therefore, a design method is proposed taking into consideration the buckling effect.

Keywords: Pile failure, Buckling instability, Liquefaction, Case histories, Centrifuge tests, Slenderness ratio, Lateral spreading

Acknowledgements

This research could not have been possible without the support of a number of individuals and I would like to extend my sincere thanks to them. First and foremost I would like to express my immense gratitude to Prof. Malcolm Bolton without whom the research would not have seen its completion. His role was more than a supervisor and no less than a GURU. His unique reading club taught me the art of reviewing papers.

I would also sincerely thank Dr Gopal Madabhushi for giving me an opportunity to carry out research with the Cambridge Geotechnical research group. His supervisions and the discussions were extremely helpful in designing the experiments and during the development of various ideas presented in this thesis. The enthusiastic support and inspiration from Dr Kenichi Soga, Mr Allan McRobie, Prof Chris Calladine, Prof. T.D.O' Rourke and Dr Subrata Chakroborty had a strong impact on this research. I would like to sincerely thank Stuart Haigh for his constant advice and help in performing the tests, even on Easter Monday!

The centrifuge tests were possible because of the excellent technical support from Chris Collison, John Chandler, Chris McGinnie, Alistair Ross and Jason Waters. Chris Collison's idea of placing three piles in a single centrifuge test was excellent.

Andrew Brennan was always like a friend, philosopher and guide. His help in running Matlab programs was invaluable. Discussions and comments from Dave White, Dimitrios Selemetas, Andy Take, Esve Jacobsz, Thusly, Lis Bowman, Berrak Teymur, Gary Choy, T.C.Teh, Asaf Klar, Aleksander Spasojevic and Barnali Ghosh were very fruitful especially during writing up this dissertation.

I am grateful to Hilary and Margaret for their help in getting "weird" literature from various places in the world. Anama, how can I thank you for getting so many appointments with Malcolm and maintaining such a fantastic environment in this Centre?

Long hours in the lab and far away from home were not felt due to the help from many of the close friends especially Barnali – whose love and affection in a crisis and inspiring advices led me sail through. Life in Cambridge was very enjoyable in these three years due to many of my friends. To name a few, Debdulal Raman – "my matured friend", James, Sanjib – for keeping eye on my afternoon siesta, Arnab – "local guardian", Gideon, Aroul, Helen, Paulo, Marcelo, Andrew Merritt, Xavier and Fiorien. The drinking sessions in "The Alma" followed by a curry or a nightclub are unforgettable.

This page would remain incomplete if I don't thank my family and specially my parents and brother for providing constant support and encouragement.

I would like to thank Cambridge Commonwealth Trust and Nehru Trust for Cambridge University for providing the financial support. I would also like to acknowledge the support provided by the Committee of Vice Chancellors and Vice Principals for awarding me the Overseas Research Student (ORS) award.

Thank you – dearest Paromita for your patience, unconditional love and support.

Declaration

I hereby declare that except where specific reference is made to the work of others, the content of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification at this or any other university. This dissertation is entirely the result of my own work and includes nothing which is the outcome of work done in collaboration. This dissertation contains less than 65,000 words and less than 150 figures.

Subhamoy Bhattacharya

5th September 2003

Cambridge

TABLE OF CONTENTS

Abstract	(i)
Acknowledgments	(ii)
Declaration	(iii)
Table of contents	(iv)
Nomenclature	(ix)

Chapter 1: Introduction

1.1	Background	1-1
1.2	Failure of structures during earthquakes	1-2
1.3	Pile supported structures still collapse during earthquakes	1-3
1.4	Current understanding of pile failure and design methods	1-4
1.5	Inconsistency of the current understanding with the observed seismic pile failure at liquefiable sites	1-6
1.6	Does the soil push the pile or vice versa?	1-7
1.7	Pile failure as an instability problem during liquefaction	1-8
1.8	Aims and scope of work	1-9
1.9	Structure of the dissertation	1-10

Chapter 2: Literature Review

2.1	Introduction	2-1
2.2	Liquefaction	2-1
2.2.1	Theoretical framework for behaviour of sandy soil	2-2
2.2.2	Typical data of liquefiable soil under monotonic and cyclic loading in triaxial apparatus	2-4
2.2.3	Definition of liquefaction	2-6
2.2.4	Liquefaction susceptibility	2-9
2.3	Pile foundations	2-11
2.3.1	Structural nature of pile	2-11
2.3.2	Load settlement of end bearing piles	2-13
2.3.3	Current understanding of buckling of piles	2-14
2.4	Theories of pile failure in areas of seismic liquefaction	2-16
2.4.1	Ishihara's (1997) concept of pile failure	2-16
2.4.2	Failure theory based on Tokimatsu et al. (1998)	2-17
2.5	Review of design methods in the major codes of practice	2-18
2.5.1	Development of Japanese Code of Practice (1972-1996)	2-18
2.5.2	Eurocode 8 (Part 5)	2-22
2.5.3	NEHRP(2000) code	2-22

2.6	Recent research into the effect of lateral spreading on pile foundations	2-23
2.7	Critical review of the current understanding of pile failure mechanisms	2-27
2.7.1	A case study: Failure of Showa Bridge after 1964 Niigata earthquake	2-27
2.8	Summary	2-30

Chapter 3: Analysis of reported case histories of pile foundation performance during past earthquake

3.1	Introduction	3-1
3.3.1	Past work and this study	3-2
3.2	Method of analysis of case histories	3-2
3.2.1	Example of the Showa Bridge	3-3
3.2.2	Parameters in the analysis	3-7
3.3	Reported case histories of pile foundation performance during earthquakes	3-9
3.3.1	Good performance of pile foundations	3-10
3.3.2	Poor performance of pile foundations	3-18
3.4	Analysis and Discussion	3-31
3.5	Hypothesis of pile failure arising from the study of case histories	3-33
3.6	Summary	3-35

Chapter 4: Centrifuge Modelling

4.1	Why centrifuge modelling?	4-1
4.1.1	Aims of the centrifuge testing	4-2
4.1.2	Contents of the chapter	4-2
4.2	Principles of centrifuge modelling	4-2
4.3	Dynamic centrifuge modelling	4-3
4.4	Centrifuge facilities at Cambridge University	4-4
4.4.1	10m beam centrifuge	4-4
4.4.2	SAM actuator	4-5
4.4.3	ESB Box	4-5
4.4.4	Pore pressure transducer	4-6
4.4.5	Accelerometers	4-7
4.4.6	LVDT	4-7
4.4.7	Pressure transducers	4-8

4.5	Centrifuge test program	4-9
4.5.1	Sand used in the tests	4-10
4.5.2	Earthquake input motions	4-11
4.6	Development of model pile	4-13
4.6.1	Characterisation of composite pile used in test SB-01	4-14
4.6.2	Choice of material for model pile	4-17
4.7	Structural testing of model pile	4-19
4.7.1	Buckling test of model piles treated as struts	4-19
4.7.2	Plastic moment capacity of model pile	4-23
4.8	Comparison of model pile with an equivalent concrete pile	4-25
4.8.1	Transforming the prototype dural alloy section into an equivalent hypothetical concrete section	4-26
4.8.2	Transforming the prototype dural alloy section into an equivalent hypothetical steel tubular section	4-27
4.9	Model preparation and test procedure	4-28
4.10	Factors controlling failure of a pile in a centrifuge	4-30
4.10.1	Decoupling effects of axial and inertia	4-31
4.10.2	Investigation of pile-soil interaction	4-34
4.11	Summary	4-35

Chapter 5: Experimental modelling of seismic pile-soil interaction in level ground

5.1	Introduction	5-1
5.1.1	Visual observations after the tests	5-7
5.2	Summary of pile performances and verification of the hypothesis	5-11
5.3	Behaviour of pile under axial load alone	5-13
5.3.1	Excess pore pressure generation	5-15
5.3.2	Buckling initiation	5-17
5.3.3	Near field pore pressures	5-19
5.3.4	Earth pressures on front and back faces of the pile	5-21
5.4	Behaviour of pile under the combined action of axial load and inertia	5-28
5.4.1	Failure of pile under combined bending and axial load	5-28
5.4.2	Piles that vibrated and did not fail during seismic liquefaction	5-30
5.5	Summary	5-34

Chapter 6: Discussion

6.1	Introduction	6-1
6.2	Verification of the proposed pile failure hypothesis	6-1
6.3	Replication of observed pile failure in centrifuge tests	6-2
6.4	Buckling of piles as soil liquefies	6-3
6.4.1	Concept of critical depth for buckling initiation	6-5
6.5	Euler's classical buckling and pile buckling	6-7
6.6	Resistance of liquefied soil	6-8
6.7	Pile-soil interaction during buckling	6-10
6.8	A simple experiment to demonstrate the failure of piles	6-12
6.9	Analytical approach for modelling the pile-soil interaction	6-14
6.9.1	Pre-buckling behaviour of pile	6-14
6.9.1.1	Fully embedded pile	6-16
6.9.1.2	Partially exposed pile	6-19
6.9.2	Post-buckling behaviour of pile	6-23
6.9.2.1	Comparison of the prediction of hinge formation	6-25
6.9.2.2	Increase in effective stress in the sheared soil	6-26
6.10	Summary	6-28

Chapter 7: Design method

7.1	Introduction	7-1
7.2	Distinguishing between bending and buckling	7-1
7.3	Possible failure mechanisms identified	7-2
7.4	Proposed design criteria for piled foundation	7-4
7.5	Proposed design approach	7-5
7.5.1	Effects of axial load	7-5
7.5.1	Lateral displacement amplification effects	7-7
7.5.3	Check against collapse due to lateral and axial loads	7-9
7.5.4	Point of fixity in non-liquefiable layer	7-10
7.5.5	Proposed design chart for pile diameter	7-11
7.5.6	Allowable lateral load for the piles having slenderness ratio 50	7-13
7.6	Flow chart of the design method	7-15

7.7	An example problem	7-16
-----	--------------------	------

7.8	Summary	7-19
-----	---------	------

Chapter 8: Conclusions and Future work

8.1	Introduction	8-1
-----	--------------	-----

8.2	Specific conclusions	8-2
-----	----------------------	-----

8.3	Recommendations to practice	8-5
-----	-----------------------------	-----

8.4	Suggested future work	8-5
-----	-----------------------	-----

Appendix- A

Estimation of “Factor of Safety” against plastic yielding for a typical pile

Appendix- B

Allowable load and buckling load (if laterally unsupported) of a typical pile

Appendix- C

Detailed calculations for two case studies of pile foundation performance during earthquakes

Appendix- D

Plotting of data from the centrifuge tests

References

Nomenclature

Roman symbols

A	Area
C	Damping
D	Diameter of the pile
E	Young's Modulus
EA	Axial stiffness
EI	Flexural stiffness
$H_{collapse}$	Collapse load (lateral)
H	Lateral load
H_c	Critical depth
I	Moment of inertia
I_D	Relative density of sand
K	Earth pressure coefficient
L	Length of the pile
L_0	Length of the pile in the liquefiable region
L_{eff}	Effective length of the pile in the liquefiable region
L_{eff}/r_{min}	Slenderness ratio in liquefiable region
M	Moment
M	Mass
M_p	Plastic moment capacity
P	Allowable load on the pile = Axial load on the pile
P_{cr}	Euler's critical load
V	Velocity of the pile
Z_p	Plastic section modulus
Z_E	Elastic section modulus
Z_h	Predicted hinge location
a	Acceleration
e	Voids ratio
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
f	Frequency
f_{ck}	Characteristics strength of concrete
i	Hydraulic gradient
k	Permeability of the soil
k	Modulus of foundation
p'	Spherical confining stress
q	Deviatoric stress
r_{min}	Minimum radius of gyration
t	Time
u	Pore pressure
u_{hy}	Hydrostatic pressure
v	Specific volume

Greek symbols

γ'	Submerged unit weight
λ	$\sqrt[4]{\frac{k}{EI}}$
λ	$\sqrt{\frac{P}{EI}}$
δ	Lateral displacement of the pile due to combined lateral and axial loads
δ_o	Lateral displacement of the pile due to lateral loads
σ_Y	Yield stress of the material
σ_{cr}	Elastic critical stress of the material
σ_f	Failure stress
ε_q	Deviatoric strain
ψ	Angle of dilatancy
τ_p	Shear stress
ϕ_{PTL}	Phase transformation Line
ϕ_{crit}	Critical state angle
η_h	Modulus of subgrade reaction