PILE INSTABILITY DURING EARTHQUAKE LIQUEFACTION

by

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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.

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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.

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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