



IIT ROORKEE



NPTEL ONLINE
CERTIFICATION COURSE

EARTHQUAKE RESISTANT DESIGN OF FOUNDATIONS

Lecture 25: Design of Piles in Liquefiable Soils-1

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ERD of Foundations - Modules

1. Introduction
2. Shallow Foundations
- 3. Pile Foundations**
4. Well Foundations
5. SSI for Deep Foundations



Module - 3

Pile Foundations

Module -3: Chapters

1. Piles for Static Vertical Load
2. Lateral Loads on Piles
3. Dynamic Analysis of Piles
4. Design for Lateral and Dynamic Loads
5. Combined Pile Raft Foundation (CPRF)
6. Design of Piles in Liquefiable Soils



Acknowledgement - Reference

Most of the contents of this lecture are taken from following literature.
This is gratefully acknowledged:

Madabhushi G., Knappett J. and Haigh S., (2010). Design of Pile Foundations in Liquefiable Soils. Imperial College press.

Design of Piles in Liquefiable Soils - 1

- **Introduction**
- **Performance of Pile Foundation in Past Earthquakes**
- **Modes of Failure in Liquefiable Soils**
 - **Failure Mechanism for Single Pile**
 - **Failure Mechanism for Pile Groups**

Introduction - Liquefaction

- When loosely deposited sandy soil layers are subjected to shaking from earthquake loading, the soil grains tend to reorganize into a dense packing thereby exhibiting a volumetric contraction.
- If the soil layer are fully saturated then the contractive tendency of the soil layer is manifested as a rise in the pore water pressure as there is insufficient time for the pore water pressure to escape from the soil layers.
- If the excess pore water pressure increases sufficiently to match the effective stress in the soil, then it is said that soil layer is fully liquefied.
- If the excess pore water pressure that are generated in the soil due to the earthquake loading are limited, then the soil may still soften and the soil is said to have partial liquefaction.

Effects of Liquefaction on Foundations

- The foundations of civil engineering structures suffers settlement and/or rotation when the soil layers suffer liquefaction.
- Pile foundations can be particularly vulnerable to soil liquefaction. If the soil below the base of the pile becomes liquefied, then there is a decrease in the base capacity and the pile can suffer excessive settlements.
- If the depth to which soil liquefies is rather limited, say in a relatively small magnitude earthquake, the soil surrounding the shaft may liquefy and loss of shaft friction may be expected. This can cause an increase in the base load of the pile, which can lead to an increased settlement.
- In addition to these simple cases, pile foundation are also vulnerable to laterally spreading ground.

Effects of Liquefaction: Lateral Spreading

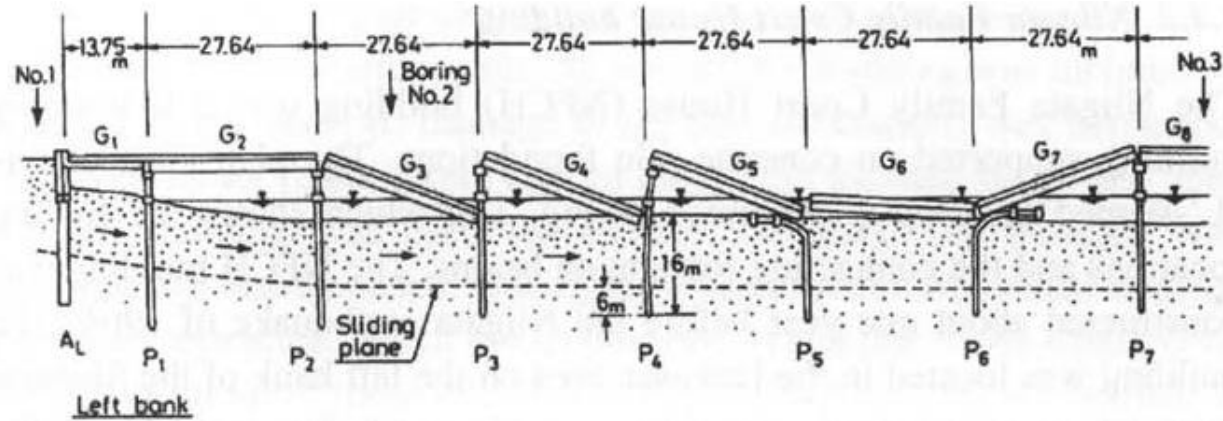
- Lateral spreading of sloping ground can occur if the soil layer suffer either full or partial liquefaction. When excess pore pressure are generated in a sloping layer, the slope may no longer be able to resist the static shear stress and can start to flow.
- Pile foundation that are passing through a laterally spreading ground will be subjected to lateral kinematic loads. Generally, if the soil layer has fully liquefied then the lateral forces exerted on the piles by flowing ground may be considered to be relatively small.
- However, if there is stiff soil layer above the liquefied layer, such a layer would also spread. These nonliquefied layers can exert large lateral loads on pile foundation as they are able to generate significant passive pressure against the piles and/or pile cap

Performance of Piles in Past EQs

No. Case history	Earthquake event	Pile material	Pile diameter (m)	Pile length (m)	Lateral spreading observed?	Pile performance
1	10 storey-Hokuriku building earthquake 1964	RCC	0.4	12	Yes	Good
2	Showa bridge earthquake 1964	steel tubular	0.6	25	Yes	Poor
3	Landing bridge Edgumbe earthquake, 1987	PSC (square)	0.4	9	Yes	Good
4	14 storey building in American park earthquake, 1995	RCC	2.5	33	Yes	Good
5	Hanshin expressway pier earthquake, 1995	RCC	1.5	41	Yes	Good
6	LPG tank 101 earthquake,	RCC	1.1	27	Yes	Good

No. Case history	Earthquake event	Pile material	Pile diameter (m)	Pile length (m)	Lateral spreading observed?	Pile performance
7	Kobe Shimim hospital earthquake, 1995	steel tubular	0.66	30	Yes	Good
8	NHK building earthquake 1964	RCC	0.35	12	Yes	Poor
9	NFCH building earthquake 1964	RCC hollow	0.35	9	Yes	Poor
10	Yachiyo Bridge earthquake 1964	RCC	0.3	11	Yes	Poor
11	Gaiko Ware House earthquake, 1983	PSC hollow	0.6	18	Yes	Poor
12	4 storey fire house earthquake, 1995	PSC	0.4	30	Yes	Poor
13	3 storied building, Fukae at Kobe earthquake, 1995	PSC	0.4	20	Yes	Poor

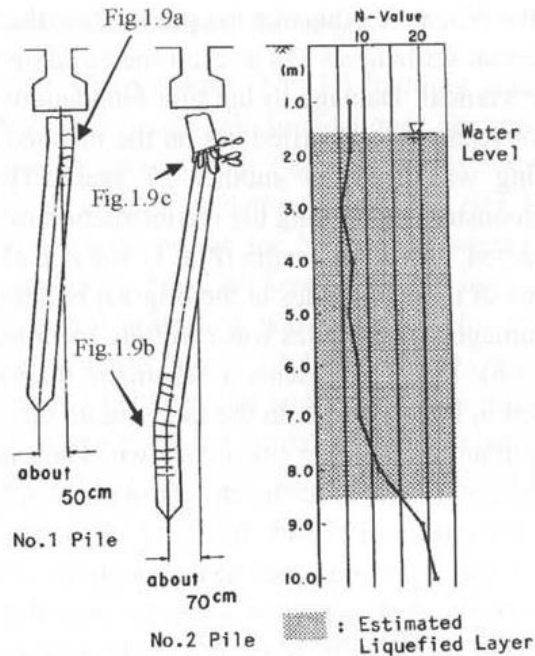
Performance of Pile Foundation in Niigata EQ



Schematic diagram showing the fallen decks of the Showa bridge. (Takata *et al.*, 1965).

View of collapsed Showa Bridge (Photo by V V Bertero)

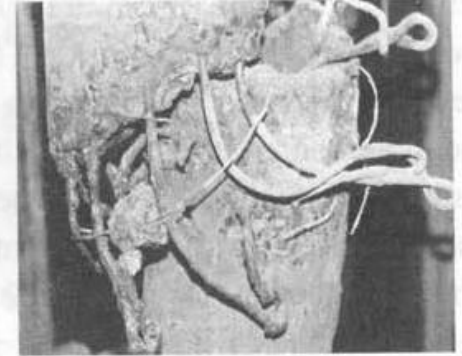
Performance of Piles in Niigata EQ



a) upper part of Pile 1



b) lower part of Pile 2



c) upper part of Pile 2

Photographs of extracted piles showing damaged sections of Piles 1 and 2.

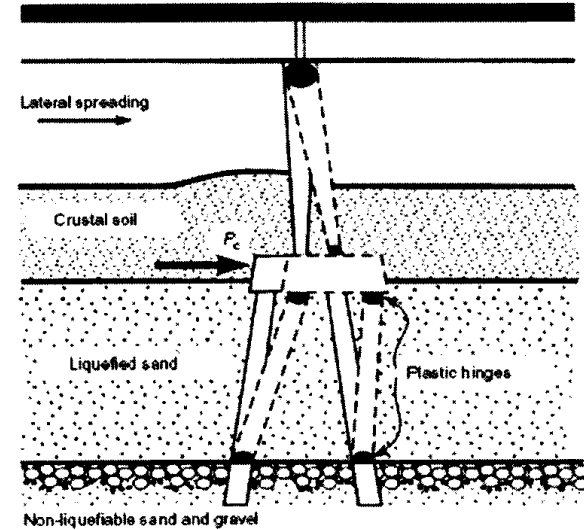
Schematic diagram showing the distressed piles 1 and 2 after excavation.

Niigata family court House building

Effect of Lateral Spreading on Piles and Pier in Niigata EQ



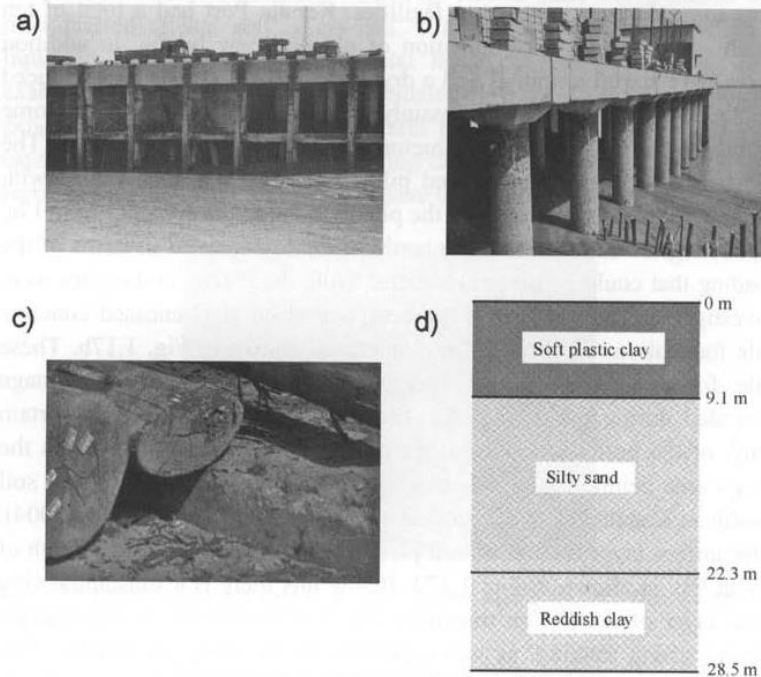
A view of Pier C in laterally spreading soil.



Failure mechanism by formation of plastic hinges in the piles and in the pier.

The Landing Bridge

Effects of Liquefaction on Pile Foundation during 2001 Bhuj EQ



The Harbour Master's Tower at Kandla Port

Liquefaction at Kandla Port, Gujarat, India: (a) view of the old berths with battered piles (b) view of the new berths with steel encased concrete piles (c) subsidence in the cargo handling area behind the new berths (d) typical soil profile at Kandla Port.

Failure Mechanism for Single Pile in Liquefiable Soils

Single piles with small pile caps are occasionally used to support individual column. Firstly the case of single pile in level ground is considered. Two possible mechanism of failure can be readily identified as shown in Fig 1.1. the single pile carrying large axial loads from the superstructure and located in a loose, liquefiable, saturated sandy layer overlying the bed rock is presented. When the earthquake-induced cyclic shear stresses lead to the generation of excess pore pressures in the sandy layer, the stiffness of this layer degrades significantly. Under those circumstances, the single pile can suffer buckling instability if sufficient length becomes 'unsupported' and can fail by forming a plastic hinge.

In Fig. 1.1a the initial position of the pile is shown as a solid line and the anticipated failure mechanism is shown as a dotted line. Here, the location of the plastic hinge shown as a solid circle is of interest. It is reasonable to assume that the plastic hinge will form close to the interface of the liquefied sandy layer and the bed rock.

Failure Mechanism for Single Piles in Liquefiable Soils

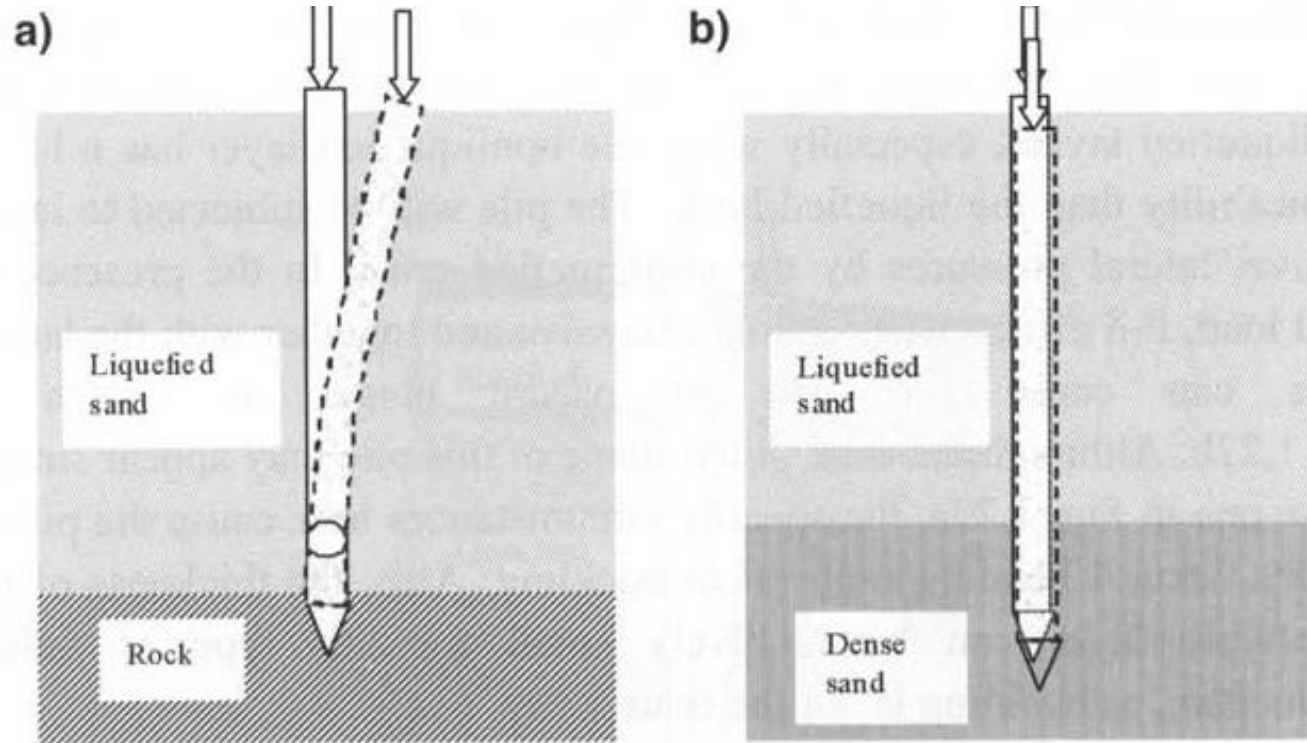


Fig. 1.1 Modes of collapse for single piles in liquefiable soil (a) buckling instability (b) bearing failure

Failure Mechanism for Single Piles in Liquefiable Soils

In contrast to this, the case of a single pile that carries large axial loads and passes through the loose, saturated layer and rests in a dense sand layer is presented in Fig. 1.1b. The loose, sandy layer will again see a significant rise in excess pore pressures and the consequential degradation of the soil stiffness. The excess pore pressure generated in the loose sand layer close to the interface between the loose and dense sand layers can be transmitted into the dense sand layer, further softening the dense sand.

The situation will lead to following two conditions

- Loss of shaft friction of the pile; and
- A reduction in the base capacity of the pile.

Under these circumstances the pile foundation will suffer a bearing failure and will settle into the dense sand layer as shown in Fig. 1.1b. Settlement will continue until sufficient base capacity and shaft friction is mobilized to bring the axial load and the weight of the pile into equilibrium. The dilation of the dense sand layer will generate large suction pressures in the dense sand, which will also aid the process of reaching a vertical equilibrium.

Failure Mechanism for Single Piles in Liquefiable Soils

A commonly occurring field case is when the pile is located in layered ground with a non-liquefied crust underlain by a liquefiable layer that is in turn underlain by a dense sand layer or a stiff clay layer. The pile will normally be driven so that it bears in the dense sand layer to transfer the axial loads. Following liquefaction and lateral spreading, the pile can suffer some elastic bending due to the lateral earth pressure exerted by the non-liquefied layer. However, the pile may concurrently suffer bearing failure as shown in Fig. 1.2

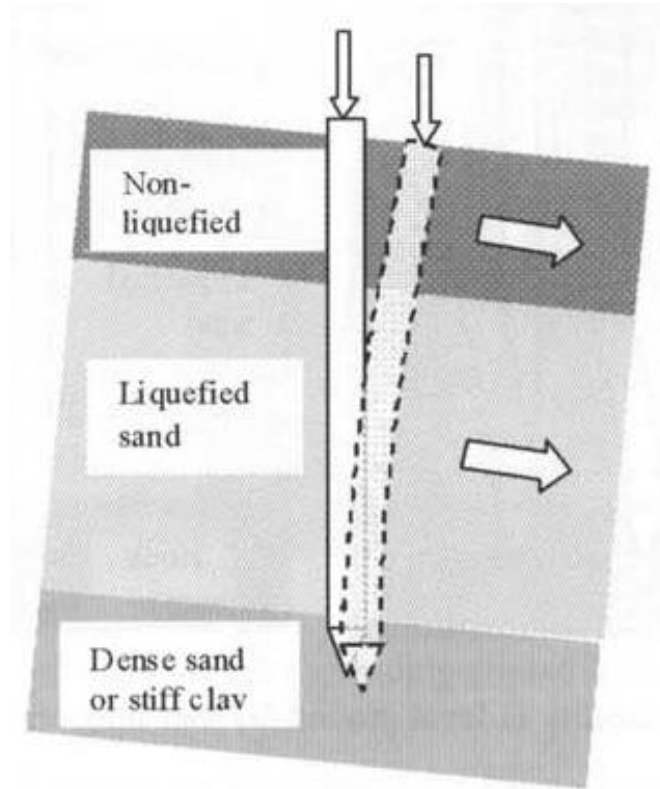


Fig. 1.2 Combined bending and settlement failure of pile in laterally spreading ground

Failure Mechanism for Pile Groups in Liquefiable Soils

Deep foundations are more commonly designed with group of piles. The failure mechanisms for pile groups in level ground are considered. The case of a single liquefiable layer overlying the bedrock is considered. Again, axial load is present on the pile group at the time of the earthquake loading. As described before, the liquefiable sand layer will lose its stiffness owing to the generation of excess pore water pressures. Under those circumstances, the piles become 'unsupported' and can fail as before due to buckling instability. Two further mechanisms of failure are possible as presented in Fig. 1.3.

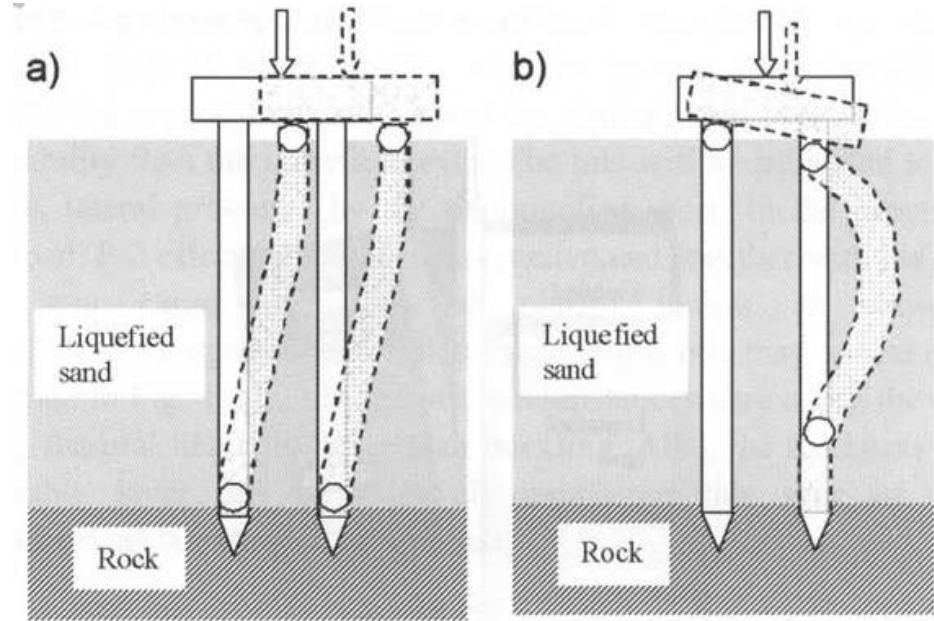


Fig. 1.3 Pile group instability in level ground (a) four hinge mechanism (b) three hinge mechanism

Failure Mechanism for Pile Groups in Liquefiable Soils

In Fig. 1.3a the piles fail by forming plastic hinges both at the bases and the pile heads. This assumes that the piles are well rock-socketed into the bedrock. If this is not the case, i.e. the pile tips rest on the bedrock, then no plastic hinges will form at the pile tips. In this mechanism, the pile cap will suffer lateral displacements and small vertical settlements that may cause significant distress to the superstructure.

A second mechanism that can occur is a three-hinged mechanism shown in Fig. 1.3b. In this case the plastic hinges will form only at the pile heads. One of the piles has to fail by buckling instability. This mechanism can cause severe rotation of the pile cap causing significant - distress to the superstructure. Also note that this mechanism can occur even if the pile tips are well rock-socketed to mobilize full fixity at the pile tips.

Failure Mechanism for Pile Groups in Liquefiable Soils

The soil profile considered is the same as before with a nonliquefied crust layer underlain by a liquefiable sand layer, which in turn is underlain by bedrock. The pile group is socketed into the rock. The axial load from the superstructure is present on the pile group at the time of the earthquake loading. The failure mechanism for the pile group is shown in Fig. 1.4. Large lateral loads will be generated on the piles due to the passive earth pressures from the nonliquefied crust on the piles and pile cap. This, in combination with the axial load, can cause excessive bending of the piles leading to formation of four hinges as shown in Fig. 1. 4.

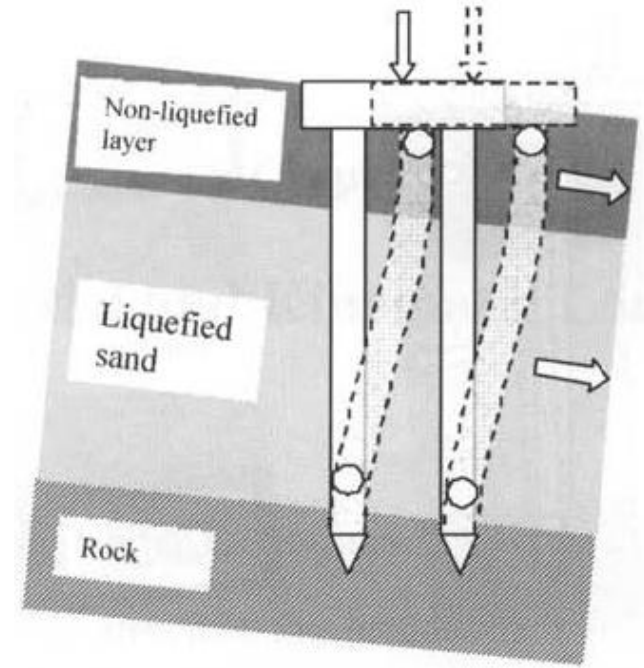


Fig. 1.4 Pile group failure in laterally spreading ground with nonliquefied crust

Thank You

