Mechanism of failure of three pile-supported structures during three different earthquakes

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SUMMARY:
To understand plausible mechanisms of failure of piles three cases of severe tilting of piled buildings are chosen from three different earthquakes. These three buildings were founded in liquefiable soils and all experienced lateral spreading. The buildings are: (a) Kandla Port and Customs Tower in Kandla (India) that tilted during the 2011 Bhuj earthquake; (b) Three story building on a jetty in Kobe (Japan) that tilted during the 1995 Kobe earthquake; (c) NHK building in Niigata (Japan) that tilted during the 1964 Niigata earthquake. All the three buildings tilted during strong seismic events and leaned towards the down slope of the ground. The cause of failure for all the three buildings was initially reported to be lateral spreading. A detailed quantitative analysis of the three buildings is carried out in the paper highlighting the various mechanisms of failure, not necessarily associated with lateral spreading yet producing similar kind of surface observations i.e. lateral spreading induced damages.

Keywords: Mechanism of pile failure, pile failure in liquefiable soils

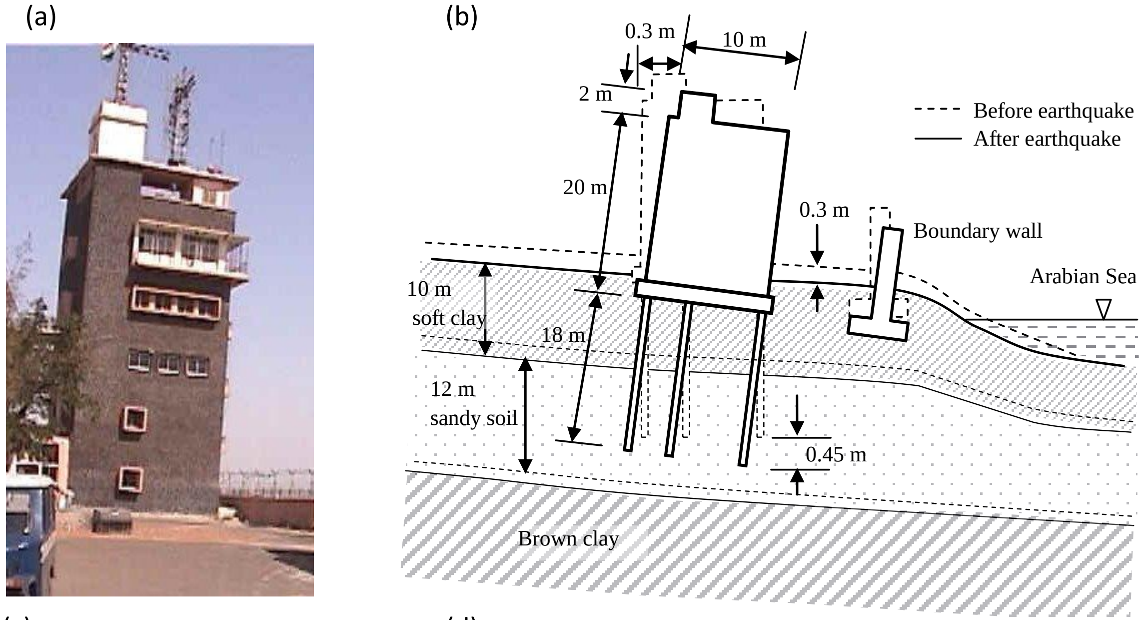
1. INTRODUCTION

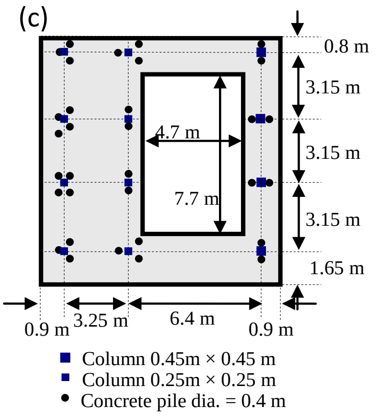
Reported observations of the failure of pile-supported structures in liquefiable soils dates back into early 20th century (e.g., 1906 San Francisco Earthquake, USA). However, the recurrences of similar kind of failures in many recent earthquakes pose a continuous concern to the earthquake geotechnical engineering community. Many observations of pile failure in past earthquakes showed that the buildings in liquefiable soils on sloping ground tilts towards the ground slope. These failures are believed to be mainly bending induced by the lateral spreading of liquefied soil. The qualitative surface investigation supports the above hypothesis. However, looking at the foundation failure pattern, this hypothesis cannot adequately explain some cases of pile failure observed. Some recent researches also signify the importance of buckling failure as a major failure mechanism for piles liquefiable soils. Dash (2010) summarises the probable mechanisms of pile failure in liquefiable soils as bending, buckling, shear, settlement or dynamic amplification, and the piles may fail either due to any of the mechanisms or a combination of some or all of them (See Dash et al., 2009 and Dash et al., 2010).

Therefore, to understand the possibility of different mechanisms of pile failure in liquefiable soils for similar kind of surface failure pattern, three cases of piled building failure have been chosen in this study. They are; (A) Kandla Port and Customs Tower in Kandla (India) which failed during 2001 Bhuj earthquake, (B) four story firehouse building on a jetty in Kobe (Japan) which failed during 1995 Kobe earthquake, and (C) NHK building in Niigata (Japan) which failed during 1964 Niigata earthquake. All these buildings failed during earthquakes and had similar kind of failure pattern and were in liquefiable soils. Details of these buildings and their responses during the corresponding earthquakes are discussed in the following sections.

2. BUILDING A: FAILURE OF KANLA PORT AND CUSTOMS TOWER (INDIA)

The Kandla Port and Customs Office Tower is a 22 m high six-floor building located in the Kandla port area very close to the waterfront. This pile-supported building leaned about 30cm at its top and separated from its adjacent building during the 2001 Bhuj earthquake. The building was founded on 32 short cast-in-place concrete piles. Each pile was 18m long and 0.4 m in diameter. The piles were passing through 10m of clayey crust and then terminated in a sandy soil layer. The loads from superstructure are transferred to the piles through the foundation mat, which eventually acts like a pile cap. The service load of the building is estimated to be 10749kN. The details of the calculations can be found in Dash et al (2009). Assuming equal sharing of the vertical loading, the static axial load per pile is about 336 kN. The Port of Kandla is built on natural ground comprising of recent unconsolidated deposits of inter-bedded clays, silts and sands. The water table is about 1.2 - 3.0 m below the ground level. Figure 1 shows the tilted building, schematic of its failure pattern, foundation plan and structural details of the building.





(d)

Building details	
Building height	22 m
Building plan at sill level	9.6 m × 9.8 m
Foundation raft	11.45 m × 11.9m × 0.5 m
No. of column	12
No of pile	32
Length of pile	18 m
Diameter of pile	0.4 m
Pile material	Concrete (M20)

Figure 1. (a) Building A: Kandla Port and Customs Tower (b) Schematic of building's failure during 2001 Bhuj Earthquake (c) Foundation plan of the building showing piles, raft and columns (d) Details of the building. (Ref: Dash et al., 2009)

There were very little damage to the superstructure and all the damages were in the foundation. A numerical model was developed using SAP2000 to study the seismic response of the foundation during earthquakes (Dash et al 2009). The mat-pile-soil interaction model was used for the foundation system. The column loads were applied at the foundation mat level at their locations. The analysis was carried out by applying the superstructure load as well as the lateral spreading simultaneously to investigate the combined response of settlement and lateral spreading.

The analysis for service condition of the building shows that the maximum settlement of the building at service condition is about 0.2 cm, which is within the permissible limits as suggested in most of the codes of practice. The analysis shows that the foundation raft settled about 4.7cm at right top corner of the building plan during the earthquake. The mass distribution of the superstructure would hint that the building would tilt away from the creek (i.e. towards the eccentric building mass or towards the left in Figure 1(a)) as the centre of mass (CM) is on the left of the geometric centre of the building. However, the cut-out in the foundation mat shifts the centre of resistance (CR) even left of the centre of mass causing the building to lean towards right as in Figure 1 (a).

The pattern of the tilting of the building from the analysis matches fairly with that of the field observation. The total pile settlement predicted by the analytical study is 34.7cm (30cm is ground settlement + 4.7cm building settlement). In contrast, the observed settlement of pile tip is about 45cm which seems quite reasonable, if viewed in isolation.

3. BUILDING B: FAILURE OF FIREHOUSE BUILDING IN KOBE PORT (JAPAN)

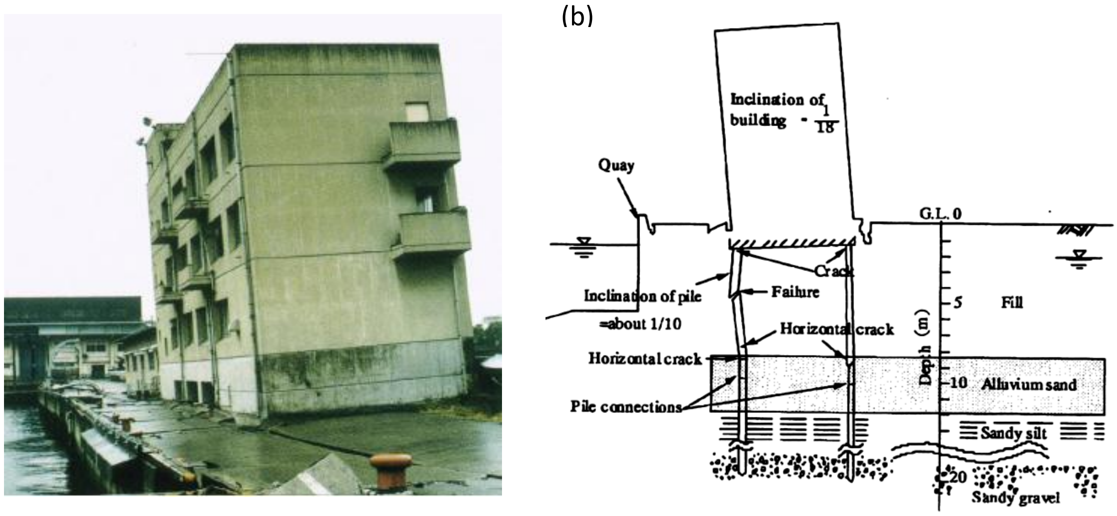
The four-storied firehouse building at the foot of the Kobe O-Hashi Bridge on Port Island moved and tilted towards the sea during 1995 Kobe earthquake. The building was founded on 400 mm diameter pre-stressed concrete piles of 30 m long (Tokimatsu et al., 1996). After the 1995 Kobe earthquake, the quay wall was displaced by 2 m towards the sea and the building tilted by 3 degrees. Post-earthquake excavation showed that compressional shear failure in piles occurred on the seaside with minor flexural cracks on the opposite side. From the soil report of Port Island, it was estimated that the top 18 m was likely to provide almost zero restraint to the pile (fill + liquefied soil + very low strength weak soil beneath the liquefied soil) (Bhattacharya 2003). The water table in the site was approximately 1.6 m below ground level. Hence, the length of the pile in liquefiable soil was about 16.4 m. Figure 2 shows the tilted building, the failure pattern of its foundation, foundation plan and building details.

Bhattacharya (2006) studied this case history to understand the mechanism of its pile failure. The piles were axially loaded heavily (412 kN each) and was laterally unsupported for 16.4m of their length due to liquefied soil layer. The factor of safety against buckling for the piles was found to be 0.81 (Bhattacharya, 2006). This suggests that the pile could probably have failed due to buckling at full liquefaction of the ground during the earthquake. The site was also subjected to lateral spreading, which could have made the piles to bend towards the direction of soil spread (i.e., towards sea side). The pile being hollow also indicates that it is weak in shear.

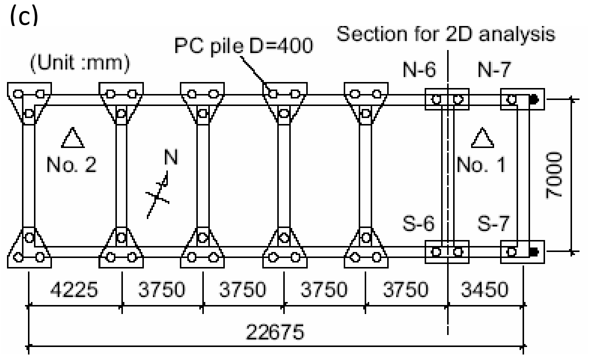
4. BUILDING C: FAILURE OF NHK BUILDING (JAPAN)

The NHK building in Niigata City is a four-storey R.C frame building supported on reinforced concrete piles, which tilted during the 1964 Niigata earthquakes. Widespread liquefaction and lateral spreading of the soil were observed near the building site. The piles have a diameter of 350 mm solid section and are 11 to 12 m long. The inclination angles of the building after the earthquake were 0.76° in long span direction (SN) and 0.23° in short span direction (EW). Twenty years after the 1964 Niigata earthquake, 74 piles were investigated by excavation and it was found that all of them were similarly damaged (see Hamada, 1992). Figure 2 shows the tilted building, damage pattern of piles after excavation, typical damage of a pile and the building details. The piles failed mostly at two positions, 2.5 to 3.5 m from the upper end of the piles and 2.0 to 3.0 m from the bottom as shown in the figure. The location of the water table is not documented in Hamada (1992). It is assumed that the water table is about 1.7m below the ground level. From the soil investigation report, the liquefied layer is most likely to be the top 11m. Thus the pile tip was only founded in 1m to 2 m in non-liquefiable layer. Hence the length of the pile in liquefiable soil is 9.3m (11m – 1.7m). From Figure 2 (c) it may be noted that the pile base rotated 10 to 15 degrees and this suggests that pile base was pinned. Hence the effective length of the pile (that is required for buckling load capacity estimation) is twice the length of the pile in liquefiable soil.

(a) (b)



(c)



(d)

Building Height	14.5 m above Ground Level
Building Dimensions	22.675×7 m
Foundation Type	Precast Pre-stressed Concrete Driven Pile
Building Type	R.C.C. Framed
Dead Load of the Building	15656 kN
Axial Load on Each Pile	412 kN
Length of Pile	20 m
External Diameter of Pile	400 mm
Internal Diameter of Pile	240 mm

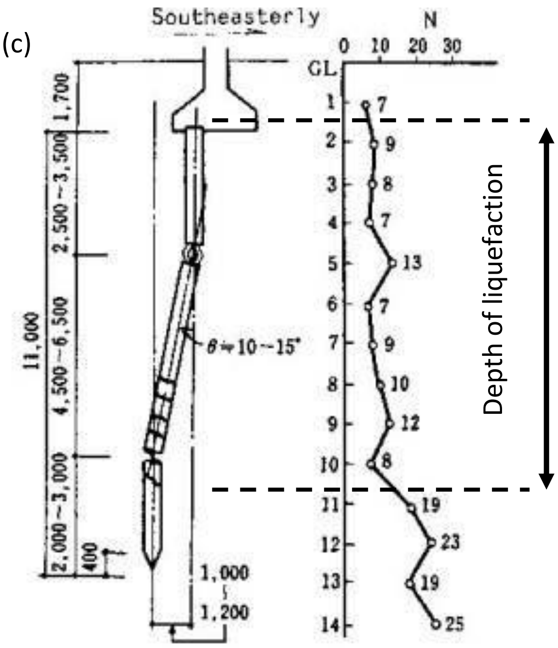
Figure 2. (a) Building B: Tilted firehouse building (b) Schematic of building's foundation failure during 1995 Kobe earthquake (c) Foundation plan (d) Details of the building. (Ref: Bhattacharya, 2006)

A buckling calculation shows that the pile was subjected to an axial load of 430 kN and the buckling load capacity (Euler's elastic buckling load) is 520 kN. Hence, the factor of safety against buckling is about 1.2. It signifies that the pile could not have failed only due to buckling, but as the axial load is close to the buckling capacity of the pile, the bending moment in the pile if any could have amplified due to the P-delta effect.

Investigating the dynamic behaviour of the building, it is found that the building had fundamental period of about 2.5 Hz (0.4s) before earthquake, which reduced to 1.0 Hz (1.0s) during the earthquake after liquefaction, considering that the liquefied soil does not provide any lateral support to the piles. The predominant frequency of the 1964 Niigata earthquake in the band of peak acceleration occurrence was 2.4 Hz-1.4 Hz (Kudo et al, 2000). This signifies that the fundamental frequency of the building transiting due to liquefaction was close to the predominant frequency of the earthquake during that time, which could have amplified the response (i.e, bending moment and shear force) in the pile. Hence, a most probable cause of the pile failure under this building could be due to the combined effect of dynamic amplification, P-delta effect and lateral spreading.

(a) (b)

(c)



(d)

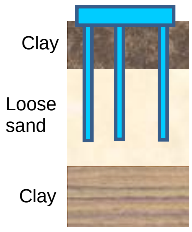
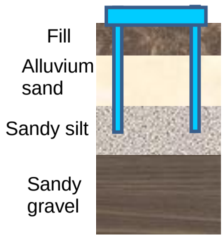
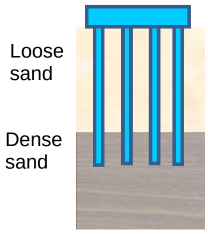
Building Superstructure	3-story RC frame building
Foundation Type	Solid Concrete Pile
Building Type	R.C.C. Framed
Axial Load on Each Pile	430 kN
Length of Pile	11-12 m
Diameter of Pile	350 mm

Figure 3. (a) Building C: Tilted NHK building during 1964 Niigata Earthquake (b) Failure pattern of the piles observed after excavation (c) A typical pile failure pattern of this building (d) Details of the building. (Ref: Tazoh, 2007)

5. DISCUSSION: RESPONSES OF THE THREE BUILDINGS

The three buildings discussed above shows that although the pattern of failure of the superstructure is same, the cause of foundation failure are different. Summary of observation and analysis of these building are presented in Table 1. The analysis shows that the most probable cause of building failure was settlement for Building-A, buckling/shear for Building-B and bending/dynamic amplification added with P-delta effect due to higher axial load for Building-C.

Table 5.1. Comparison of responses of three buildings studied.

	Building A	**Building B**	**Building C**
			
Building Name	Port and Customs Tower of Kandla Port (India)	Firehouse building in Kobe Port (Japan)	NHK Building in Niigata City (Japan)
Earthquake in which it failed	2001 Bhuj Earthquake	1995 Kobe Earthquake	1964 Niigata earthquake
Surface observation	Tilted towards sea side	Tilted towards sea side	Tilted in the direction of lateral spreading
Pile type	Solid concrete piles	Pre-cast hollow concrete pile	Solid concrete piles
Soil profile along the pile			
Lateral spreading observed at site	Yes	Yes	Yes
Depth of water table below GL	1.2 - 3.0 m	1.6 m	1.7 m
Depth of liquefaction from GL	The top soil was clay but the layer (10m to 22m) is likely to have liquefied	The fill and the alluvium sand likely to have liquefied. The unsupported length of the pile is between 1.6m and18 m	The soil up to 11m is likely to have liquefied. It may be noted that water table is at 1.7m below ground.
Length of pile in liquefiable soil	10m	16.4 m	9.3 m
Field observation of settlement of the building	45 cm	--	--
Predicted Settlement from the analysis	35 cm	--	--
Axial load on pile	336 kN	412 kN	430 kN
F.O.S against buckling	Not Applicable (as the piles behave like floating piles during liquefaction)	0.81	1.2
Probable cause of pile failure	Settlement	Buckling / Shear	Bending/ Dynamic amplification

6. CONSLUSION

From the above study, the following may be concluded.

(i) It may be difficult to predict the failure mechanism of pile foundation in liquefiable soils only based on surface observation. Engineers need to carry out back of the envelope type calculations.

(ii) Similar kind of surface observation might be possible for different pile failure types. For example, bending, buckling, shear failure of the piles and uneven settlement of the pile group may lead to tilting of the superstructure. All the three buildings in liquefied soils studied in this paper titled after the earthquake, however the governing mechanism of their pile failure are very different.

(iii) It is however important to recognize the failure types (mechanisms), which will be governing the design of new foundation system or retrofitting of existing foundation system.

REFERENCES

Bhattacharya, S. (2003). Pile instability during earthquake liquefaction. **Ph.D. thesis**, University of Cambridge, UK.

Bhattacharya, S., (2006). Safety assessment of existing piled foundations in liquefiable soils against buckling instability. **ISET Journal of Earthquake Technology, Technical Note, Vol. 43,** No. 4, December 2006, pp. 133-147.

Dash, S. R., Govindaraju, L., & Bhattacharya, S. (2009). A case study of damages of the Kandla Port and Customs Office tower supported on a mat–pile foundation in liquefied soils under the 2001 Bhuj earthquake**. Soil dynamics and Earthquake Engineering**, **29(2)**, 333–346.

Dash, S.R., Bhattacharya, S., & Blakeborough, A. (2010). Bending-buckling interaction as a failure mechanism of piles in liquefiable soils. **Soil Dynamics and Earthquake Engineering**, **30(1-2)**, 32–39.

Dash, S.R. (2010). Lateral Pile Soil Interaction in Liquefiable Soils, **PhD Thesis**, University of Oxford, UK.

Hamada, M. (1992). Large ground deformations and their effects on lifelines: 1964 Niigata earthquake. Case studies of liquefaction and lifelines performance during past earthquake. **Technical Report: NCEER-92-0001**. National Center for Earthquake Engineering Research, Buffalo, NY.

Kudo, K., Uetake, T., & Kanno, T. (2000). Re-evaluation of nonlinear site response during the 1964 Niigata earthquake using the strong motion records at Kawagishi-cho, Niigata City. **Proc. 12the World Conference on Earthquake Engineering**, Auckland, New Zealand, 969.

Oh-oka, H., M. Iiba, A. Abe, and K. Tokimatsu (1996). Investigation of Earthquake-Induced Damage to Pile Foundation Using Televiewer Observation and Integrity Sonic Tests. (in Japanese) Tsuchi-to-kiso, **Vol. 44**, No. 3, The Japanese Geotech. Soc., No. 3, 28-30.

Tokimatsu K, Mizuno H. and Kakurai M. (1996): Building Damage associated with Geotechnical problems, Special issue of Soils and Foundations, **Japanese Geotechnical Society**, pp 219-234.

Tazoh T. (2007). Earthquake engineering research on pile foundations with emphasis on pile foundations subjected to large ground deformations. Book: **Design of Foundations in Seismic Areas: Principles and Applications**, Bhattacharya (ed) © NICEE, ISBN: 81-904190-1-3