COMMON BEHAVIOR OF BUILDING FOUNDATIONS DURING THE HYOGOKEN-NAMBU EARTHQUAKE

Madan B. KARKEE	Manager of Development Division, GEOTOP Corporation, Tokyo
Koushiro NAGAI	Professor, Setsunan University, Osaka, Japan
Hitoshi OGURA	Technical Coordinator, GEOTOP Corporation, Tokyo, Japan
Hideaki KISHIDA	Professor, Science University of Tokyo, Shinjuku-ku, Tokyo

Abstract

The details about behavior of building foundations during the Hyogoken-Nambu earthquake are still emerging as the impaired structures are demolished, inspected, repaired and upgraded at different stages. Some important trends can be noted from the observations to date. Slight or no structural damage amongst buildings with foundation damage indicate the development of energy absorption mechanism through failure of piles, thus reducing the action on the superstructure due to ground shaking. Many buildings with foundation damage, particularly those located at sites without large scale ground failure, were repaired by jacking-up operations. Judging from over-ground, a tilting building structure is a most likely indication of foundation damage. Foundation damage caused by severe ground shaking, and those caused by ground failure due to different reasons, were characteristically different in nature as may be generally expected during extreme seismic events.

Background of the Study

It has been two years since the Kinki region of Japan was devastated by the Hyogoken-Nambu earthquake of January 17, 1995. The earthquake has attracted the interest of researchers worldwide, and there have been multifarious reports published covering different aspects of the disaster. However, the details about how the various foundation structures behaved during the earthquake are still emerging as the structures in the affected region are demolished, inspected, repaired and upgraded at different phases. In this paper, attempt is made to present an update on the common patterns evident in the behavior of building foundations. Statistical aspects of foundation damage discussed in the paper are based on the report (AIJ, 1996) on post-earthquake survey covering about 180 buildings in Kobe area.

A clear picture on the characteristic behavior of foundation structures during extreme seismic events is not easily forthcoming because the information derived from over-ground visual inspection is rather limited in nature. For example, a large separation between structure and ground may indicate some sort of foundation damage, although the extent and the nature of the damage would be far from apparent. Identification of significant tilting and differential settlement of the structure is often considered a reason for excavation and closer examination by integrity testing, borehole video camera etc., while there may be damage to foundation of a building deemed to be practically in plumb. Attempt is made in this paper to summarize the significant patterns of behavior conspicuous from different survey reports (e.g. AIJ, 1996; GEOTOP, 1996 etc.) considering the nature of ground conditions generally encountered and the type of foundation utilized. Relation to the typical features of the building structure, such as the extent of damage, year of construction, number of stories, tilting, etc. are also discussed.

Relation to Building Structural Damage

Figure 1 shows an interesting cross-correlation between the foundation damage and the damage in superstructure, where apparently inverse relation can be noted. Fewer instances of the foundation damage (denoted by 'Yes' in Figures 1 to 6) in case of heavily damaged buildings is evident in Figure 1, where only 22% of the heavily damaged buildings were confirmed to have some sort of foundation damage, in contrast to close to 80% confirmed cases of foundation damage amongst buildings with 'slight' structural damage. It may be noted that the existence of foundation damage is 'Not Clear' (marked NC in Figures 1 to 6) in significant number of cases amongst buildings with medium to heavy damage. However, the trend is discernible all the same. Also, it can be noted from Figure 2 that most of the buildings surveyed had pile foundations rather that direct foundations. The inverse relation in the instances of foundation damage and the extent of superstructure damage can be explained from the fact that the damage in foundations, primarily piles, may have served as an energy absorption mechanism resulting in smaller earthquake energy being transmitted to the superstructure.

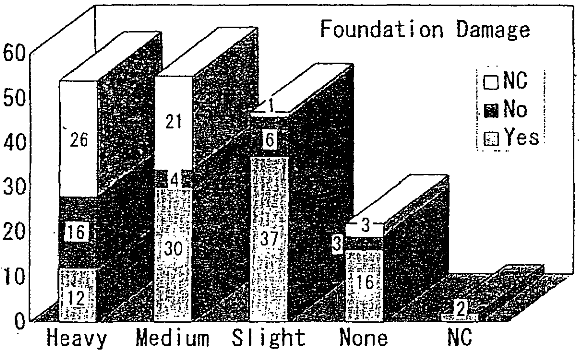


Figure 1: Relation to Superstructure Damage

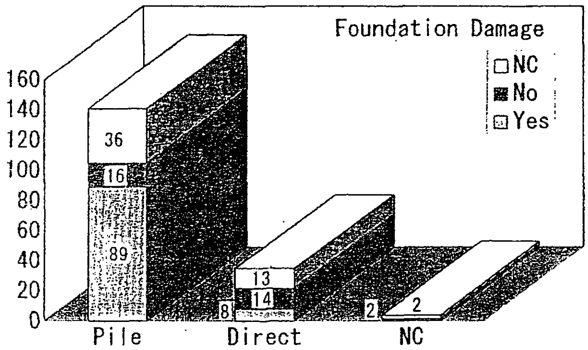


Figure 2: Pile & Direct Foundations

Damage statistics discussed herein, as well as another detailed case study (Harasawa, Karkee & Kishida, 1996), indicate that the existence of damage to foundation structure may often mean lesser damage to the building superstructure. Further detailed investigations are required, but it may be possible to utilize the trend noted in Figures 1 & 2 towards developing a design strategy for extreme level earthquake. Considering that the ordinary building structures are expected to sustain some damage without collapse during extreme level earthquakes (Karkee, Sugimura & Tobita, 1992), it may be possible to design for such damage to occur at the structure-pile interface, such that the resulting energy absorption mechanism would serve as some sort of passive control system for the superstructure.

Relation to Year of Construction and Number of Stories

Figure 3 does not indicate any clear relation of the instances of foundation failure to the year of construction, where overall about 50% confirmed instances of foundation failure can be noted in each case. This is in contrast to the damage to building superstructure which is noted to be very dominant in case of older construction (AIJ, 1995). Relatively larger instances of foundation failure in fewer storied buildings can be noted in Figure 4.

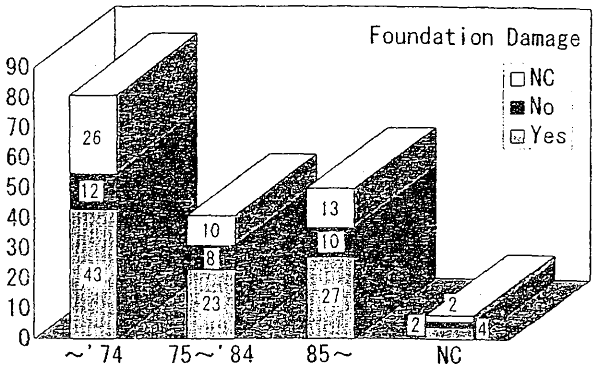


Figure 3: Relation to Year of Construction

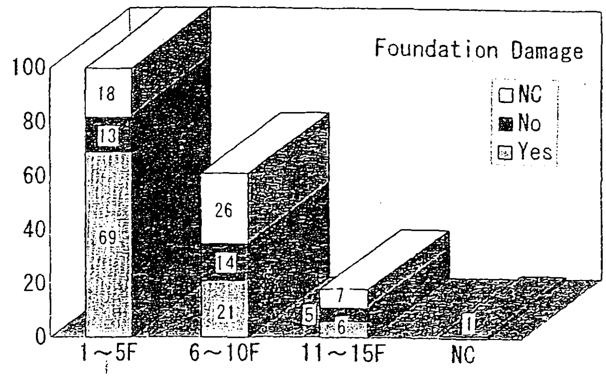


Figure 4: Relation to Number of Stories

Relation to Differential Settlement and Tilting

Figure 5 shows the relation of observed differential settlement to the instances of foundation failure. It can be noted that the existence of the differential settlement (DS) indicates higher chances of foundation failure in comparison to where there is no differential settlement (NDS). However, the instances of the foundation damage is even more conspicuously evident if the building structure is found to be tilted (out of plumb) as is apparent from Figure 6. This reconfirms the validity of checking the verticality of a building structure as a first step towards assessment for signs of foundation failure.

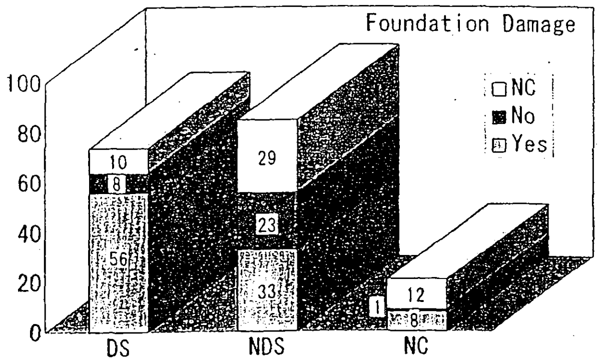


Figure 5: Effect of the Differential Settlement in the Vicinity

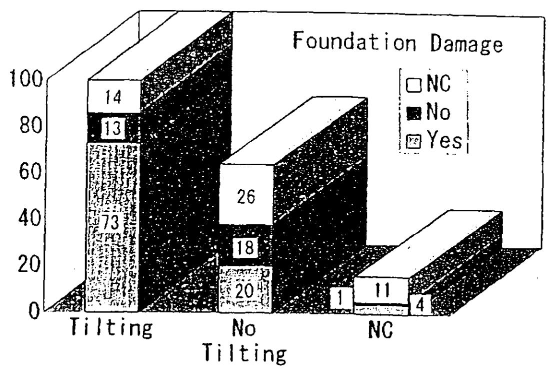


Figure 6: Relation to the Tilting of Building Superstructure

The behavior of the foundation can be expected to relate, directly or indirectly, to the behavior of ground at the site during earthquake shaking. The ground behavior affecting the foundation response, however, can be considered to manifest in two distinct ways: *ground shaking* and *ground failure*. Significant extent of differential ground settlement and structural tilting are generally the result of *ground failure* due to different reasons such as lateral spreading, slope failure, cracking etc., or their combinations. Major instances of foundation failure amongst tilted building structures in Kobe area was found to be in cases where the tilt was more than 1 in 100, indicating significant role of ground failure in the building foundation damage during the Hyogoken-Nambu earthquake. This trend clearly indicates the importance of detailed site investigations to assess the chances of ground failure, rather than only concentrating on the identification of soil parameters needed for linear to nonlinear response analysis. The consequential indication of the importance of *ground failure* in Kobe area exemplifies the need for future design concerns in this respect.

Foundation Failure Investigation and Rehabilitation

As noted above, most of the foundation damage occurred in buildings with less severe structural failure. Consequently, the confirmation of some sort of foundation damage did not result from excavation after demolition of the damaged superstructure. It was necessary to check the integrity of foundations under the existing buildings using the usual techniques such as digging in for direct inspection, sonic integrity testing, other sounding methods etc. as well as more advanced techniques such as the use of borehole camera. Figure 7 shows the example of cracking in a drilled shaft identified by borehole camera inserted into a cored hole.

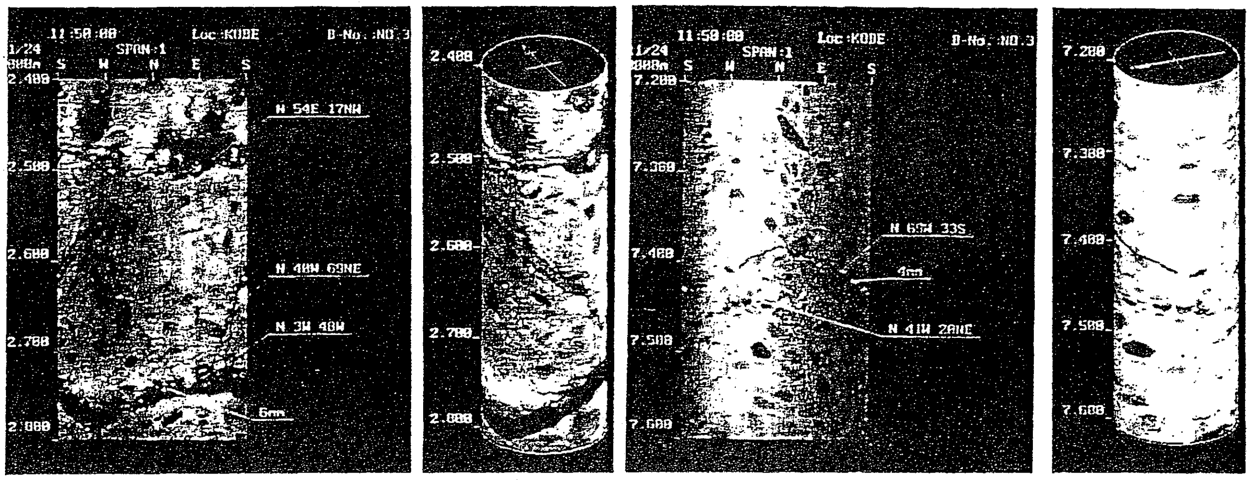


Figure 7: Cracking in a Drilled Shaft Identified by Borehole Camera

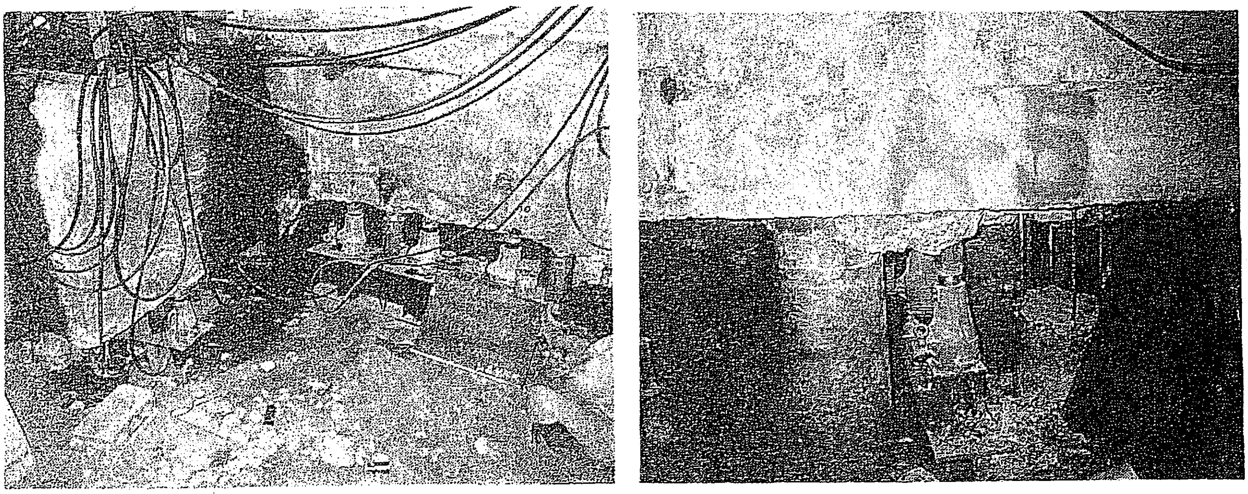


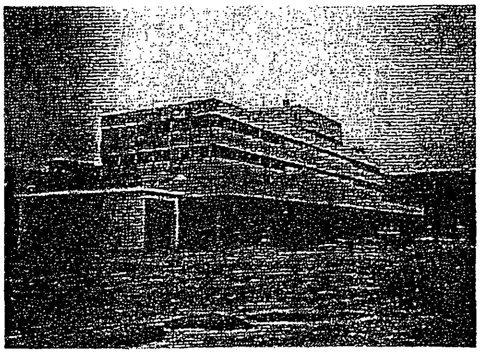
Figure 8: A Typical Scene of Jack-up and Repair of a Building with Damaged Pile Foundation

When the foundation damage is identified in buildings with little or no structural damage, it is logical to think of ways to rehabilitate the structural system by repairing and strengthening the foundation-structure system. There were several such rehabilitation projects carried out in and around Kobe (e.g. Harasawa, Karkee & Kishida, 1996). In cases where there was significant tilting and differential settlement, the buildings were jacked up to plumb and level before the load was finally transferred to repaired and strengthened foundation. A typical scene of jack-up and repair scene in a building with damaged pile foundation is shown in Figure 8.

General Pile Foundation Damage Scenarios

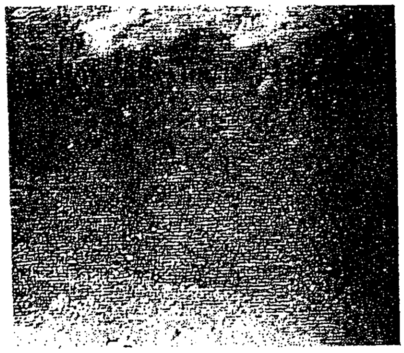
The common patterns of the damage to pile foundation can be quite diverse if attempt is made to deal with individual types of precast (e.g. PHC, PC, RC, Steel, SC, PHC

Nodular etc.) piles and drilled shafts that are routinely used in Japan. Moreover, there are varieties of installation methods involved. It would not be possible here to reflect on the significant features of different pile types and installation methods individually because of the limited extent of the database. Under the circumstances, an attempt is made to present typical cases of pile damage in different ground conditions with a view to highlight the general features.



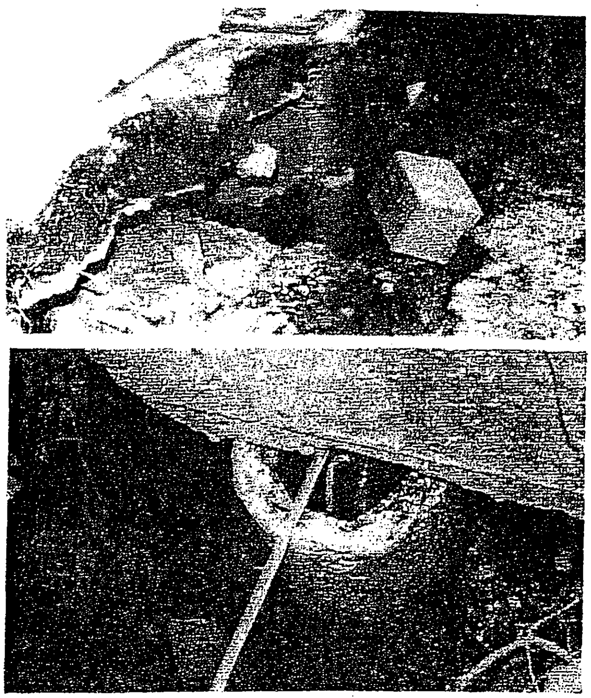
(a) Overall View of Building & Evidence of Soil Liquefaction

(b) Relative Settlement



(c) Damage to Pile was not Apparent

Figure 9: Example of ϕ500 SC-PHC Pile ($35 \sim 42m$ long) in Liquefied Reclaimed Ground



(a) ϕ350 RC Pile in Reclaimed Ground where Liquefaction with Lateral Spreading Occurred

(b) ϕ350 PC Pile in Ordinary Ground with Large Settlement due to Lateral Spreading

Figure 10: Examples of Precast Concrete Piles in Ground with Significant Lateral Spreading

Liquefaction without Lateral Spreading in Reclaimed Ground:

Figure 9 shows the instance of a combination of SC (steel encased concrete) pile at top and PHC (prestressed high strength concrete) pile at the lower portion to support a 4 storied RC building in a liquefied reclaimed ground. There was, however, no evidence of lateral ground spreading as a result of soil liquefaction. No clear evidence of pile damage was apparent in spite of about 750mm ground settlement relative to the building plinth.

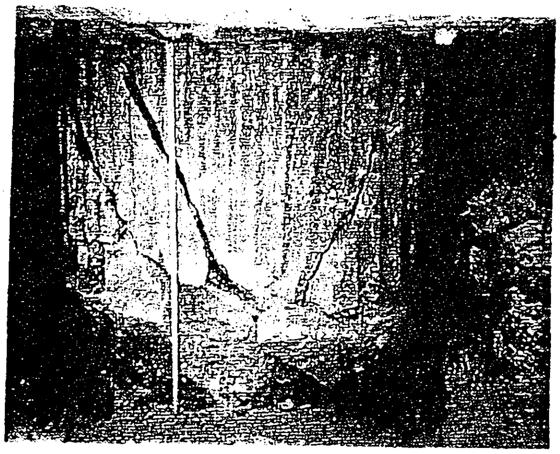
Lateral Spreading of Ground:

Figure 10 shows the severity of the effect of significant lateral ground movement on the piles. Figure 10(a) shows the case of a 14m long RC (reinforced concrete) pile supporting a 2 storied steel structure in a reclaimed site about 20m from the quay wall. There was extensive settlement and lateral spreading due to liquefaction. Ground settlement of the order of 60 ~ 100cm was observed. The RC pile was completely broken off, most likely due to the lateral ground movement. Similarly, Figure 10(b) shows the failure of a PC (prestressed concrete) pile of unknown length supporting a 6 storied concrete building in ordinary ground. The building was located about 10m from the quay wall. The ground settlement was of the order of about 200cm primarily caused by seaward movement of ground. As can be noted in Figure 10, pile damage at location with significant lateral ground movement were very severe indeed.

Firm Natural Ground Condition:

Figure 11 shows the typical cases of pile foundation damage in fairly firm natural ground where there was no clear evidence of ground failure. Figure 11(a) shows the typical case of the damage to a PHC pile. The PHC pile supporting a 5 story RC building is seen to be completely damaged near the top probably due to the severe ground shaking followed by inertial forces from the superstructure. The building structure had tilted by about 1 in 120 but otherwise was quite intact, falling into the category of 'slight damage' mentioned in Figure 1.

(a) ϕ500 13m PHC Pile



(b) ϕ1200 12.5m Drilled Shaft Supporting a 11 Storied SRC Building Structure

(c) ϕ500 × 9mm Steel Pile

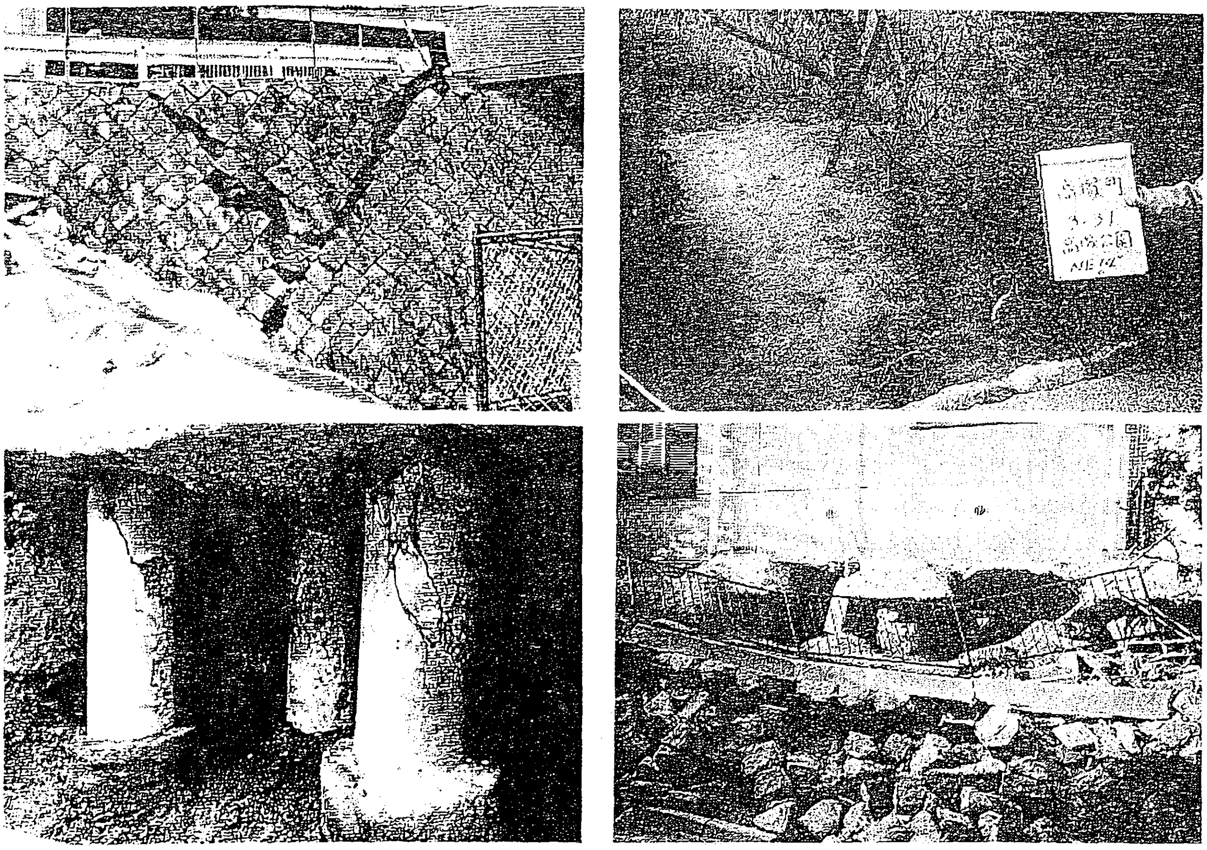
Figure 11: Examples of Pile Foundations in Fairly Firm Natural Ground Conditions

Figure 11(b) shows the damage to a drilled shaft near the top in similar situation. However, in this case the SRC (steel and reinforced concrete composite) building structure was found to suffer extensive damage accompanied by a rather precarious tilting of about 1 in 30. Similarly, Figure 11(c) shows the case of a steel pipe pile (15m and 7.5m long) supporting a 10 storied RC structure. The first story columns of the building were found to have damaged due to a combination of shearing and compression action. The underside of the column footings were excavated for inspection. Damage to steel piles was not clearly apparent, but some lateral ground movement could be discerned, apparently due to inertial forces of the structure during severe ground shaking.

Sloping Ground Condition:

Figure 12 shows typical cases of foundation failure in sloping natural ground conditions where large movement occurred due to slope failure or other reasons. Figure 12(a) shows the damage in a PC pile and the cracking in the retaining wall indicating slope failure. Extensive bending-shear cracks as wide as about 10mm were observed within the top 60cm of the piles under the footing. The reason for the damage is most probably related to the complex soil layering system at the site accompanied by cut and fill operations to facilitate the relatively large scale construction consisting of the four buildings at the site.

Figure 12(b) shows the case of a PHC nodular pile supporting a small scale residential building complex in the hilly area to the east of Kobe city. The pile foundation was completely detached over part of the building structure that had tilted by about 1 in 150. PHC nodular piles are precast high strength concrete piles consisting of nodules at fixed intervals to enhance shaft resistance. The specification of the diameter as $\phi 440 - 300$ in Figure 12(b) means a pile axis diameter of 300mm with diameter at the nodules of 440mm. These piles are probably not known well outside Japan, but are often used as friction piles in Japan (Kanai, Ogura and Sumi, 1996).



(a) $\phi 350$ 5.0m Long PC Pile Supporting a 7 Storied Framed Structure

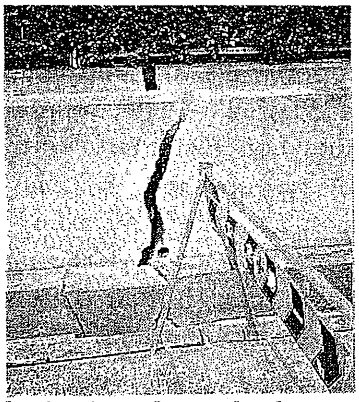
(b) $\phi 440 - 300$ PHC Nodular Pile Supporting a 3 Storied Apartment

Figure 12: Examples of Precast Piles in Sloping Natural Ground that Moved Significantly

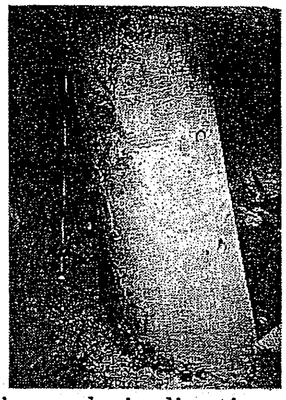
Unlike the nature of slope failure in Figure 12(a), it is reported (GEOTOP, 1996) that the ground failure shown in Figure 12(b) is due the existence of a fault (known as Koyo fault) that is passing right through where the structure is located. A typical crack visible on the ground surface close to the building, allegedly due to the movement of the Koyo fault, is also shown in Figure 12(b). It is apparent that the substantial movement of sloping ground, whether due to slope failure or due to fault movement, can cause severe damage to pile foundations.

Cracking of the Ground:

Figure 13 shows a 26m long $\phi 500$ PC pile foundation supporting a 11 storied SRC structure that was evidently damaged due to extensive ground cracking to the north of the building due to displacement of retaining wall to the south. As a result the building tilted precariously at about 1 in 40. A typical surface expression of ground cracking is shown in Figure 13(a). When the underside of footings were excavated, the PC piles were found to have inclined by a large angle as shown in Figure 13(b) as a typical example.



(a) Crack ripping through the concrete

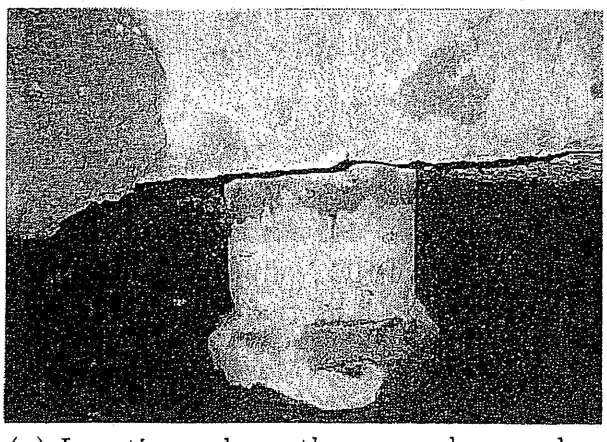


(b) Conspicuously inclination of PC pile

Figure 13: Examples of Damage to Pile Foundation due to Cracking of the Ground

Behavior of Friction Piles

Friction pile is the term generally used for piles where the major part of the bearing resistance is provided by shaft friction rather than end bearing. In Japan, precast concrete piles with preformed irregularities along the shaft are often used to enhance frictional resistance. These piles are often used in low to medium high buildings located at sites where the competent bearing stratum is very deep. One of such pile type is the PHC nodular pile, also mentioned in Figure 12(b). Based on the survey of buildings in and around Kobe area that are supported by PHC nodular piles, it is reported (GEOTOP, 1996; Kanai et.al., 1996 etc.) that there were relatively fewer instances of damage even at locations where liquefaction, settlement and lateral spreading was apparent to some extent.



(a) Location where the ground moved laterally by about 150mm

(b) Filled site with clear evidence of ground settlement

Figure 14: Examples of PHC Nodular Piles as Typical Behavior of Friction Piles

Figure 14(a) shows the nodular pile supporting a factory building in a reclaimed site right next to the quay wall. The factory building was found to have moved seaward by up to 400mm close to the quay wall due to lateral spreading probably resulting from soil liquefaction. The underside of the footing was excavated to directly inspect the top of piles for possible damage. There was reportedly no evidence of undue distress to the 11m PHC nodular piles supporting the the building.

Figure 14(b) shows another example of excavation inspection of PHC nodular pile. In this case a 5 storied RC building was supported by 13m long nodular piles in a filled ground. Originally the site was a pond. The ground was found to settle by about 10cm relative to the building plinth. Although there was practically no damage to the superstructure, the foundation was excavated for direct inspection because of the relative settlement. As can be seen in Figure 14(b), there was no damage in the PHC nodular piles supporting the building.

It may be argued that some limited ground settlement and lateral spreading may not have a drastic effect on friction piles because of reasons such as:

- Being generally short, friction piles are embedded in the upper layer of the usually layered ground condition encountered in practice, resulting in a relatively homogeneous embedment depth. This condition may make it easier for the foundation system to move with the ground without causing excessive stresses on piles during ground shaking. The stresses at the intermediate part of piles due to response of soil deposit as well as the stresses near the top of piles due to inertial force of the building structure can be significantly large when more than one distinct soil layers exist over the pile embedment depth.

- The weight of the structure may act as the surcharge over the upper layer of the ground where the major part of the load is transferred by friction piles, resulting in some sort of pressing down effect that cannot be expected when attempt is made to transmit the load directly to a competent stratum down below.

- As the bearing capacity of individual friction piles is comparatively small, use of the friction piles results in the installation of closely spaced piles, that may lead to stiffening and confinement effects in the ground directly under the structure.

- Having larger number of elements to transfer the load to the ground in case of the friction pile foundation is additionally advantageous because of the increased structural redundancy against failure under extreme seismic events

Of course there might be persisting concern about the possible loss of frictional resistance of the ground during earthquake shaking, including the adverse effects due to rise in the pore water pressure. This aspect may constitute the risk in relying on the frictional resistance, but the phenomenon involved is evidently very much dependent on the individual soil conditions. Detailed investigation of the possible positive aspects including those mentioned above, vis-a-vis the possible loss of frictional resistance of soil during ground shaking, would go a long way towards better understanding of the behavior of friction piles during extreme seismic events. Research in this direction has the potential of providing the explanation and confirmation of the positive aspects reported with regard to the behavior of friction piles during the Hyogoken-Nambu earthquake.

Concluding Remarks

An attempt is made in this paper to provide an overview of the behavior of building foundations during the earthquake. Some important deductions may be made based on the above discussions. Damage statistics indicate that there were fewer instances of foundation damage in buildings with medium to heavy structural damage while there was slight or no structural damage amongst buildings with foundation damage, most likely due to the existence of energy absorption mechanism through failure of piles, thus reducing the action on superstructures due to ground shaking.

The foundations of several buildings, specially those located at sites without large scale ground failure, could be fairly easily repaired by jacking-up operations. Considering that ordinary buildings are expected to sustain some damage during extreme seismic events, it may be possible to design for the structural system to develop energy absorption mechanism at the structure-pile interface.

The tilting of a building structure is noted to be a most likely indication of foundation damage. Foundation damage due to severe ground shaking and those due to ground failure were characteristically different in nature during the Hyogoken-Nambu earthquake as can be generally expected during extreme seismic events.

Post-earthquake survey reports indicate that friction piles behaved favorably during the earthquake. Further investigations to confirm the possible beneficial aspects of the use of friction piles in relation to the possible loss of frictional resistance of soil during ground shaking, would go a long way towards better understanding of the behavior of friction piles during extreme seismic events. Research in this direction has the potential of providing the explanation and confirmation of the positive aspects reported with regard to the behavior of friction piles during the Hyogoken-Nambu earthquake.

Acknowledgements

The content of the paper is primarily based on the data contained in the two post-earthquake survey reports: one by the 'foundation structure group' of the Kinki branch of the Architectural Institute of Japan (AIJ, 1996), of which the second author was the chairman, and the other by GEOTOP Corporation (GEOTOP, 1996). The authors gratefully acknowledge the meticulous efforts of a number of engineer colleagues involved in field observation and report compilation as members of the respective survey teams, without which this paper would not have been possible.

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