Geotechnical Engineering Bulletin: Vol. 7, No. 2, June 1998

Behavior of Friction Piles during the Hyogoken-Nambu Earthquake and its Implications to the Design Practice

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Observation of the overall pile foundations damage pattern during the Hyogoken-Nambu earthquake indicate distinct features depending on whether the local response is dominated by the ground shaking or the ground failure. Although the database specific to the behavior of friction piles is limited, there is a reasonable indication of favorable behavior during the earthquake. Attempt is made to identify possible reasons for the favorable behavior of friction piles, with a view to delineate future research directions. Possible implications to the future design practice in friction pile foundation are also discussed.

INTRODUCTION

Additional details of the nature and the extent of damage to building foundations due to the January 17, 1995 Hyogoken-Nambu earthquake continue to emerge even today as the structures are demolished or upgraded. This is because the absence of or minor damage to building superstructure does not directly correspond to the absence or otherwise of the damage to foundation. Statistically, the instances of foundation damage in buildings with heavy superstructure damage was significantly small in comparison to those with medium, slight and no structural damage [1]. The trend seems to indicate lesser instances of the simultaneous heavy damage to the building superstructure as well as the foundation.

It would be logical to see whether the local ground response to the incident earthquake excitation was dominated by ground failure effects or by ground shaking effects. Ground failure effects may be considered to include extensive liquefaction, lateral spreading and large ground movement etc. If the ground itself is considered susceptible to failure during earthquake shaking, relatively long piles taken down to a competent subsurface strata may be a preferred foundation solution. Ground shaking effects may be more predominant at locations without large-scale ground failure susceptibility. Foundation system consisting of shorter piles with the bearing capacity provided by a combination of skin friction and the end bearing may be advantageously utilized at such ground condition. This report is primarily concerned with the behavior of relatively short piles, commonly referred to as friction piles, at ground conditions where the ground shaking effects of earthquake are dominant rather than the ground failure effects.

In Japan, small diameter precast prestressed high strength concrete (PHC) nodular piles are used as friction piles to support low to medium rise buildings at ground conditions with deep soil deposits. There were several buildings in Kobe area that were supported by friction piles. Post-earthquake investigation has provided ample information regarding the response of such piles to intense earthquake shaking. This paper discusses the findings from the investigation in

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relation to their relevance to the current design practice. Attempt is also made to delineate some possible areas of improvement in the design approach to fully utilize the information derived from observed behavior.

PILE FOUNDATION DAMAGE STATISTICS

Figure 1 indicates the trend of interrelation between the foundation damage and the damage in superstructure based on the observations over a period of time after the Hyogoken-Nambu earthquake. Apparently there were fewer instances of foundation damage in case of heavily damaged buildings, while the instances of foundation damage was significantly large in case of buildings with slight structural damage. Based on the post-earthquake observation of 180 buildings comprising the database, only 22% of the heavily damaged buildings were confirmed to have some sort of foundation damage. In contrast there were close to 80% confirmed cases of foundation damage amongst buildings with `slight' structural damage [1]. Also, it can be noted from Fig. 2 that most of the buildings in the database were supported on pile foundations rather than direct foundations.

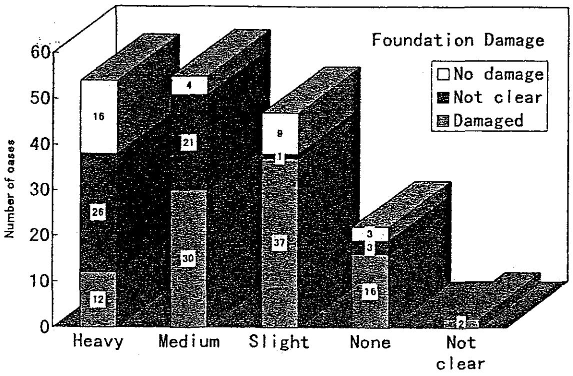


Fig. 1 Relation to superstructure damage.

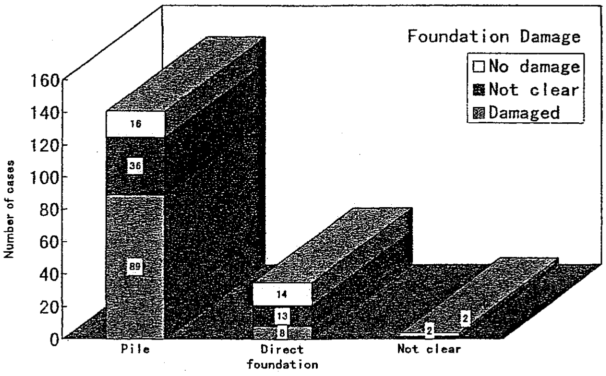


Fig. 2 Pile and direct foundations.

General pile damage statistics as well as the detailed investigation on an individual case [2], indicate the possibility of a lesser damage to the building superstructure as a result of the existence of damage in piles. This is most likely the phenomenon indicative of site conditions where the ground failure effects are not dominant. Smaller extent of damage to the superstructure may be partly due to the development of energy absorption mechanism resulting from the failure of piles. A credible energy absorption mechanism due to failure of piles may result in smaller earthquake energy being transmitted to the superstructure and hence relatively smaller extent of the damage.

Figure 3 shows the relation of the existence of differential settlement in the building with the instances of foundation failure. It can be noted that the existence of the differential settlement indicates higher chances of foundation failure in comparison to where there is no differential settlement. Figure 4 shows that the instance of the foundation damage has even more conspicuous correlation with the tilting of the building structure. The trend clearly confirms the validity of the practice of checking the verticality of a building structure, as a first step towards looking for the signs of foundation failure.

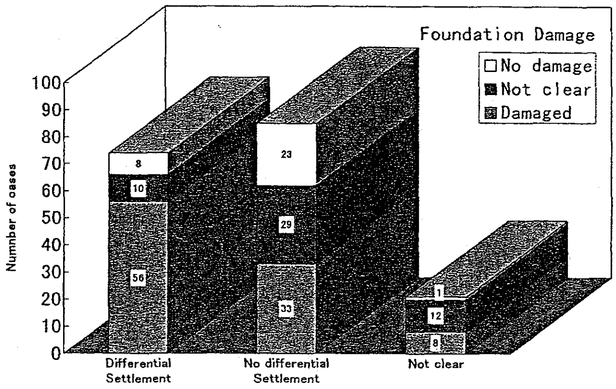


Fig. 3 Relation to the differential settlement in the vicinity.

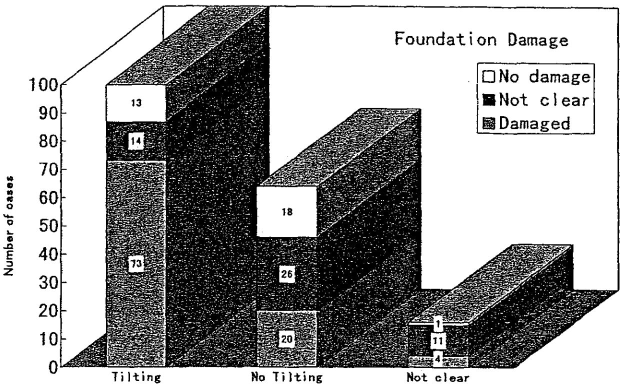


Fig. 4 Relation to tilting in the building superstructure.

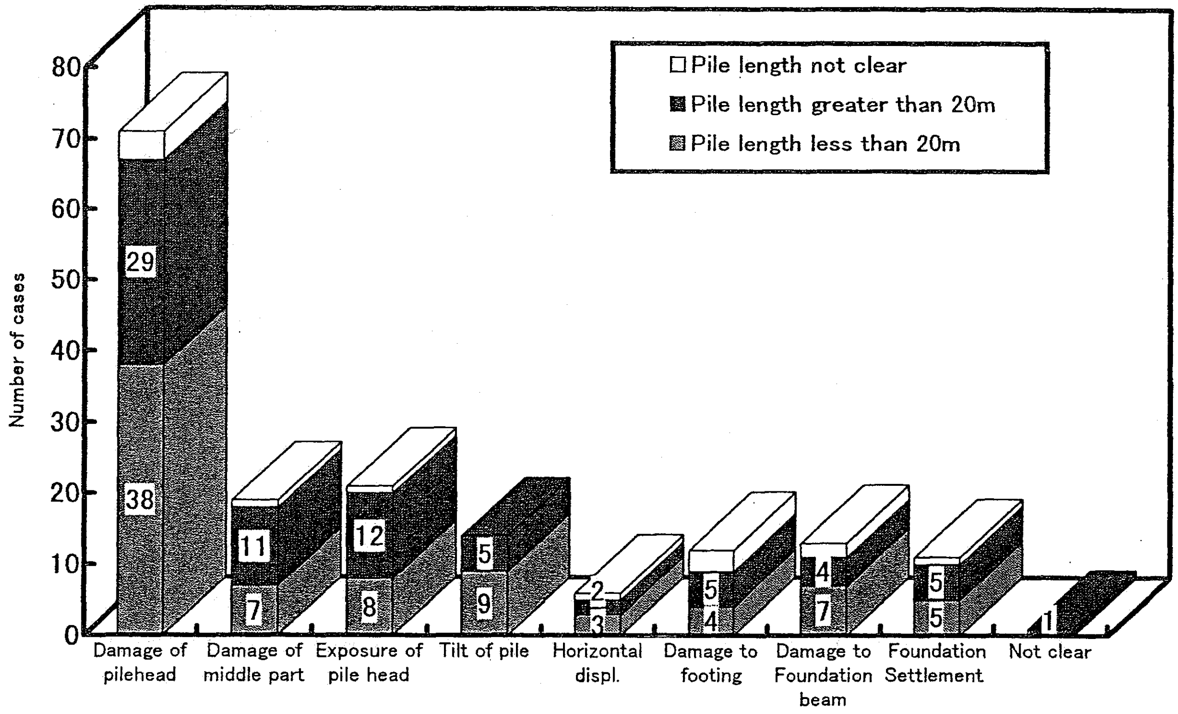
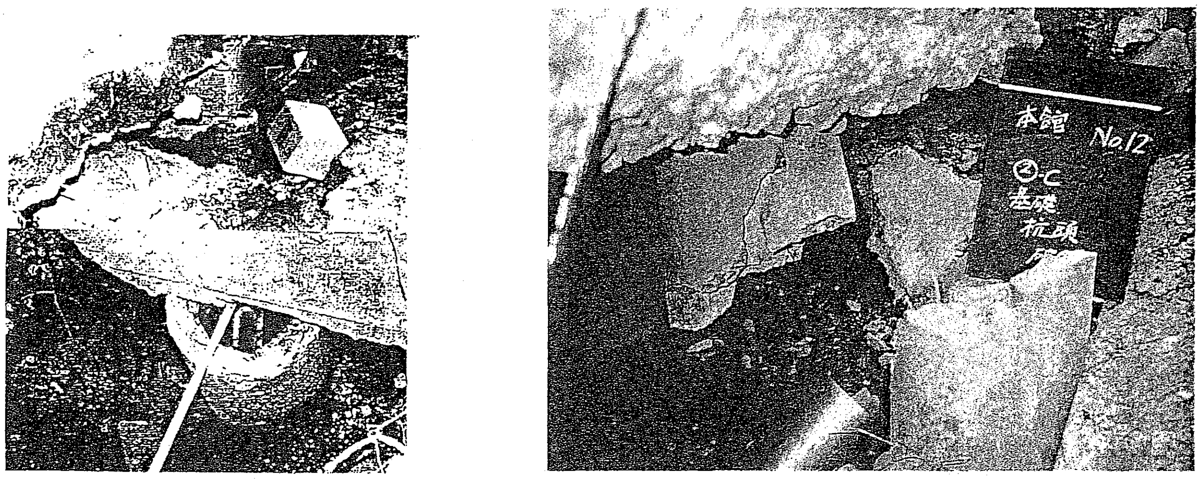


Fig. 5 The nature of pile foundation damage and the pile length.

Figure 5 shows the relationship of the pile length with the type of pile foundation damage. Damage near the pile head, including cracking and other modes of failure, is seen to be clearly dominant. Other types of damage are more or less evenly distributed. It is not clearly evident what portion of the damage near the pile head can be attributed to the inertial forces of the superstructure under the earthquake excitation, but it may be quite significant particularly in case of relatively shorter piles. The ductility of pile material is important in seismic design. But the high instances of the damage at or near the pile head clearly indicate particularly predominant importance of the ductility demand near the top of piles. Damage at middle part of the piles, which is indicated by Fig. 5 to be more frequent in case of longer piles, could be due either to the ground response effects emanating from uneven ground profile [3] or to the ground failure effects noted above.

GROUND CONDITION AND PILE FOUNDATION BEHAVIOR

The local ground condition affecting the foundation response under the action of strong ground shaking can be considered to manifest in two distinct ways: *ground shaking* and *ground failure*. Large scale differential ground settlement and lateral spreading are generally the result of ground failure due to different reasons such as soil liquefaction, slope failure, cracking etc., or their combinations. The ground shaking effect includes the inertial effect of the superstructure and the ground response effect unique to the local site condition. Both of the two types of effects can be noted in the behavior of pile foundation during the Hyogoken-Nambu earthquake. The examples below illustrate the typical cases of damages incurred by ground failure and ground shaking.



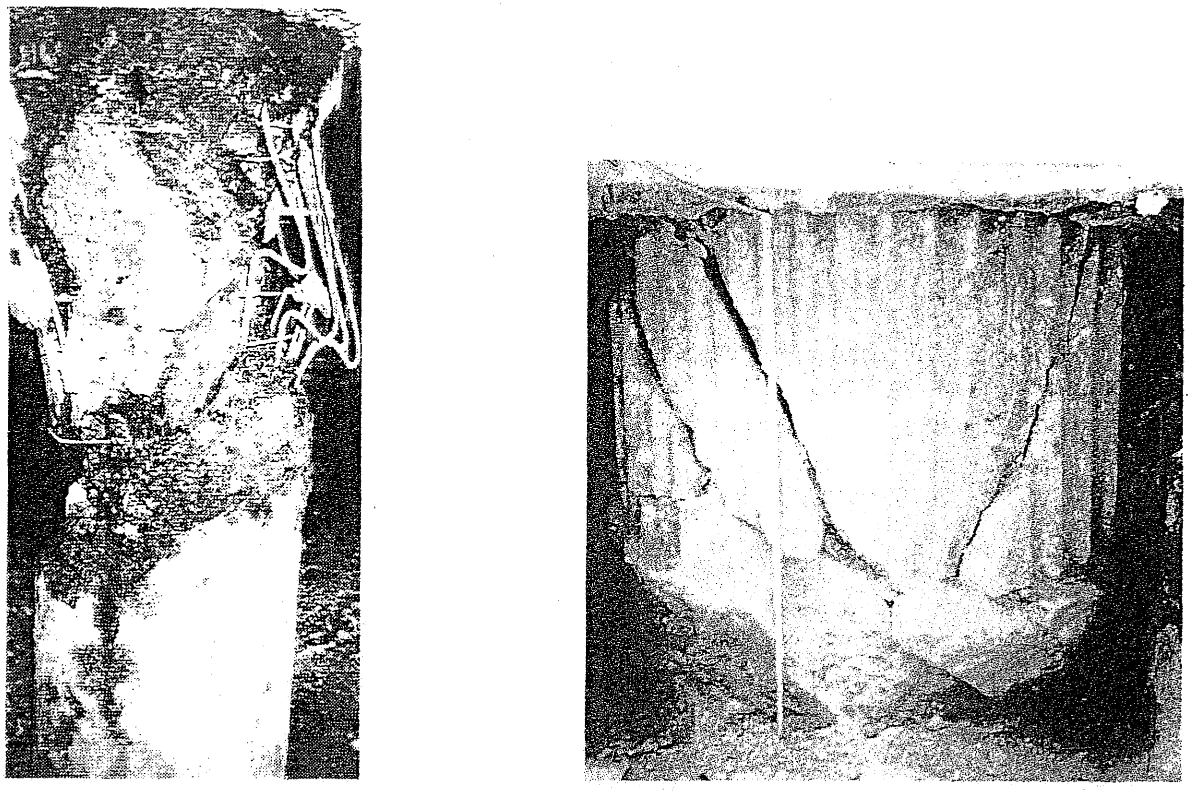
(a) Diameter 350mm RC pile at a reclaimed site with liquefaction and lateral spreading.

(b) Diameter 350mm PC pile in ordinary ground with liquefaction and lateral spreading.

Fig. 6 Examples of the severe effects of ground failure on precast concrete piles.

Figure 6 shows the effect of significant lateral ground movement on the piles. Figure 6a shows the case of a 14 m long RC (reinforced concrete) pile supporting a 2 storied steel structure in a reclaimed site about 20 m from the quay wall. There was extensive settlement and lateral spreading due to liquefaction. Ground settlement of the order of 0.6 m to 1.0 m was observed. The RC pile was completely broken off due to the lateral ground movement. Similarly, Fig. 6b shows the failure of a PC (prestressed concrete) pile of unknown length supporting a six-storied concrete building in ordinary ground. The building was located about 10 m from the quay wall. The ground settlement was of the order of about 2 m, primarily caused by the seaward movement of ground. As can be noted in Fig. 6, pile damage at location with ground failure can be very severe indeed.

Figure 7 shows the typical cases of pile foundation damage in fairly firm natural ground where there was no clear evidence of ground failure. Figure 7a 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, most likely due to severe ground shaking followed by the action of inertial forces from the superstructure. The building structure had tilted by about 1 in 120 but otherwise was quite intact, and was designated to be only slightly damaged.



(a) Diameter 500 mm and 13 m long PHC pile.

(b) Diameter 1200 mm and 12.5 m drilled shaft supporting a 11 storied SRC building structure.

Fig. 7 Examples of pile foundation damage due to ground shaking effects.

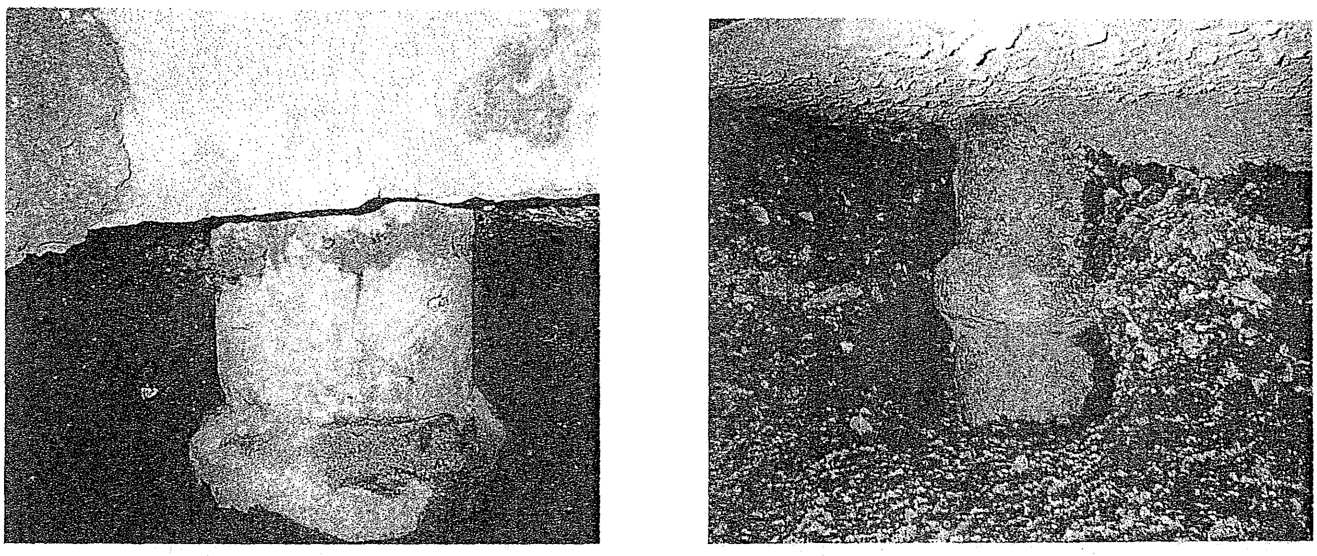
Figure 7b shows some cracking near the top of a drilled shaft in similar situation. Some of the drilled shafts supporting the SRC (steel and reinforced concrete composite) building structure had severely cracked near the top. As can be noted in Figure 7b, concrete spall off was also seen in heavily cracked shafts. The building structure in this case was found to suffer severe damage accompanied by a rather precarious tilting of about 1 in 30. All the columns in this building had single drilled shafts under them. Examples in Fig. 7 clearly illustrate the severity of the damage to piles that can result from ground shaking effects of earthquake.

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 mostly 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. Based on the survey of buildings in and around Kobe area that are supported by PHC nodular piles, it is reported [4,5] that there were relatively fewer instances of damage even at locations where liquefaction, settlement and lateral spreading were apparent to some extent.

Figure 8a 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 400 mm 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 the piles for possible damage. There was reportedly no evidence of undue distress to the 11m PHC nodular piles supporting the building.

Figure 8b shows another example of excavation inspection of PHC nodular pile. In this case, a five-storied RC building was supported on 13 m long nodular piles in a filled ground. Originally the site was a pond. The ground was found to have settled by about 100 mm 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 Fig. 8b, there was no damage in the PHC nodular piles supporting the building.

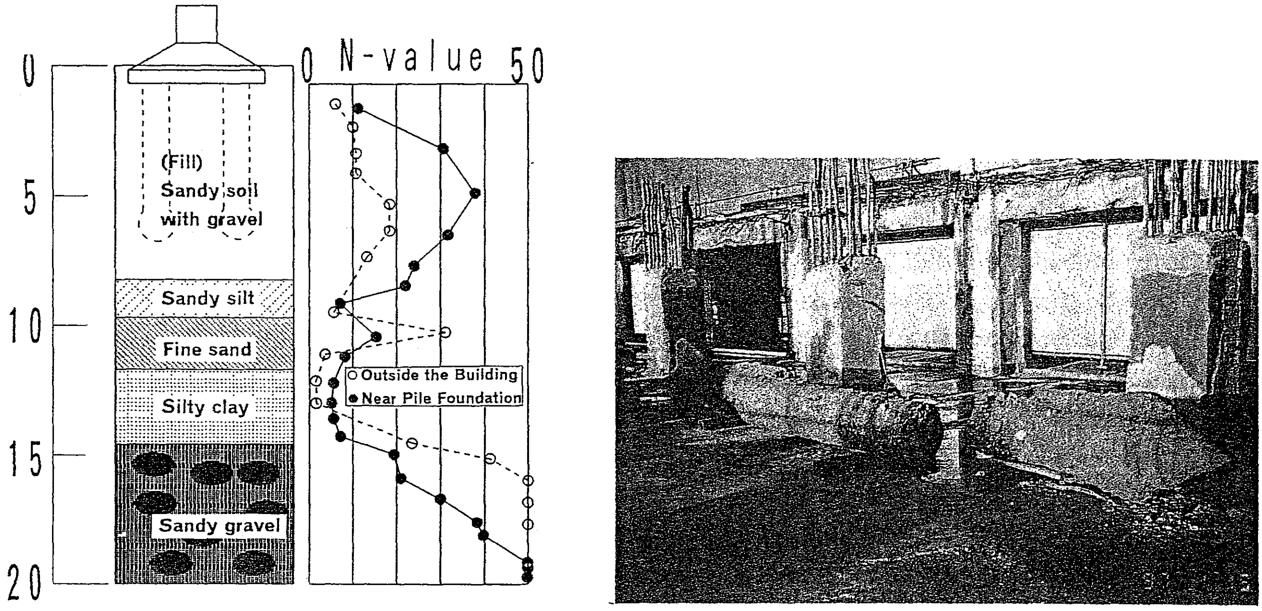


a) Location where the ground moved laterally by about 150 mm.

(b) Filled site with clear evidence of ground settlement.

Fig. 8 Examples of PHC nodular piles as typical behavior of friction piles.

Another interesting example of a good behavior is that of a 70 year old and about 5 m long plain concrete pedestal piles supporting a four storied building in Kobe. The details are reported by Numakami et al. [6]. The pile foundation outline along with the ground condition and the photograph of a dug-out pile are shown in Fig 9. It is reported that the plain concrete piles, whose compressive strength was found to vary from 26 Mpa to 69 MPa, were imbedded within the 7 m to 10m thick fairly uniform filled layer consisting of gravel mixed coarse sand. Evidently the area was reclaimed from the sea around 1923, and the ground water level at 1.5 m below ground surface is practically same as the sea level.



(a) Ground condition and pile layout.

(b) Photograph of a dug-out pedestal pile.

Fig. 9 70 years old plain concrete pedestal pile that suffered no damage.

There was no noticeable damage to the pile foundation due to the Hyogoken-Nambu earthquake. In fact the load test conducted on two of the piles at the demolished portion of the building indicated a yield load of about 1.6 MN. Another interesting feature is that the SPT N-value closer to the pile foundation was found to be significantly larger than that measured outside the building plinth area. The difference is particularly noticeable in the filled portion. The improvement in N-value may be attributed to the installation of closely spaced pedestal piles 70 years ago and the surcharge loading of the filled layer through transfer of building load by friction over the years. It is possible that the pedestal pile foundation and the surrounding ground acted together to effectively behave as a thick raft, rather as individual piles. Such characteristically unique behavior under the severe shaking due to the Hyogoken-Nambu earthquake may have spared the foundation from damage.

DISTINCTIVE FEATURES OF FRICTION PILES

Damage investigation seems to indicate somewhat consistently favorable behavior of friction piles during the Hyogoken-Nambu earthquake. The observation can be considered to have some relevant implications for pile foundation design practice and research needs. For one thing, it might provide the foundation designer with a dose of confidence on the earthquake resistance of friction piles, partly helping to dispel the apprehension that the frictional resistance may all but vanish during strong ground shaking. It should, however, be noted that a rational explanation for the favorable behavior is not readily evident from the damage investigation alone. Further research is needed for the identification and substantiation of the distinctive feature of friction piles that might have lead to the favorable behavior during the Hyogoken-Nambu earthquake. Some possible features considered unique to the friction pile foundations, that may have been responsible for the favorable behavior, may be pointed out at this stage.

1. 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 the piles during ground shaking. The stresses at the intermediate part of the piles due to response of soil deposit as well as the stresses near the top of the 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.

2. The load from the building structure may act as the surcharge over the upper layer of the ground where the major part of the load is transferred by skin friction to the surrounding soil medium, resulting in some sort of pressing down effect. This phenomenon cannot be expected in case of a point bearing pile where the major part of the load is transmitted directly to a competent stratum down below, without any surcharge effect on the surficial layer. The function of the possible surcharge on the soil directly below the structure can be two fold: one to help improve the ground over the time and the other to restrain the soil during ground shaking.

3. As the bearing capacity of individual friction piles is comparatively small, use of the friction piles results in the installation of closely spaced piles to transfer the load. Closely spaced piles of small diameter can provide stiffening and confinement of the ground directly under the structure such that the soil and the piles embedded in it may behave as a unit. This may result in the overall foundation behavior that is closer to a thick flexible raft, rather than the individual piles and pile groups usually considered in practice.

4. Use of the friction pile normally means the use of larger number of piles to transfer a given load to the ground. Having larger number of elements to transfer the load to the ground in case of the friction pile foundation is additionally favorable in that it results in increased structural redundancy against failure under extreme seismic events.

The list of the possible features of friction piles contributing to their apparently favorable behavior during the Hyogoken-Nambu earthquake as mentioned above is far from complete and substantiated. In addition, there are aspects of apprehension about the sound behavior of friction piles during earthquake shaking that need to be investigated. For example, there is a persisting concern about the possible loss of frictional resistance, including the adverse effects of the rise in the pore water pressure. There might indeed be a risk in relying on the frictional resistance during earthquake shaking in certain soil conditions. Investigation of the features of friction piles contributing to their reportedly favorable behavior during the Hyogoken-Nambu earthquake, vis-a-vis the possible adverse effects on frictional resistance of soil during ground shaking, would go a long way towards better understanding and wider application of friction piles.

IMPLICATIONS FOR FRICTION PILE DESIGN PRACTICE

Aside from the general apprehension regarding the adequacy of frictional resistance during earthquake shaking, there does not seem to be a clear cut distinction in the design approach of friction piles from that of the other types of piles. Basically, the designation `friction pile' is simply taken to mean a pile that has significantly larger portion of the bearing capacity provided by skin friction rather than end bearing. However, features possibly unique to the friction pile foundation and pertinent to the overall load transfer mechanism, particularly in relation to the behavior observed during intense earthquake shaking, would require specific consideration for realistic representation in the analysis and design. Some of the possible distinctive features for such consideration are pointed out above.

There is substantial research initiative yet to be undertaken concerning the features responsible for the reported favorable behavior of friction pile foundation during the Hyogoken-Nambu earthquake. One of such initiative is reported by Hagino et al. [7], who have undertaken a parametric study on a 2-D FEM model under the action of earthquake excitation. They reported that the effective dynamic stresses induced by earthquake shaking is smaller in friction piles when compared to the end-bearing piles. In addition, they have found that the short period component of the earthquake motion transmitted to the superstructure becomes smaller in case of friction piles. These results indicate rather unique and favorable dynamic characteristics of friction piles, which need to be adequately represented in the design.

Considering that the ordinary buildings may sustain some damage under the action of extreme level earthquakes, it is imperative to think in terms of judicious provision of energy absorption mechanism to prevent collapse of the structure. It is also important to take into consideration the rehabilitation of the building structure after a major earthquake. One of the reasonable locations for the provision of energy absorption mechanism may be the interface between the structure and the friction pile foundation. For this, friction piles need to be designed to have high ductility near the top. While a long pile designed to take the load down to a deeper layer at a site may have even chances of failure anywhere along the length, friction pile is more likely fail at the top if and when it does fail. Kobayashi et al. [8] have reported on cyclic tests to failure on pile top footing connections to investigate the seismic capacity. In addition to providing some fresh information on the consideration of the degree of fixity at pile head, their test result also illustrates the importance of the ductility under reversible dynamic load. Developments towards the use of composite friction piles with upper portion consisting of ductile material connected to ordinary PHC nodular pile may provide a functional and economic solution in this respect.

CONCLUDING REMARKS

Beginning with an overview of the behavior of building foundations during the Hyogoken-Nambu earthquake, this report attempts to identify some pertinent features of friction piles based on their apparently favorable behavior. Overall statistics indicated fewer instances of foundation damage in buildings with medium to heavy structural damage. In contrast, there was only slight or no structural damage in buildings that had foundation damage. It indicates a possible trend of the absorption of incident earthquake energy in causing some damage in the foundation, resulting in lesser damage to the superstructure.

The pile foundation damage statistics clearly show that the other mode of cracking failure at or near the pile head was the dominant form of damage, while other types of damage was more or less evenly distributed. This is a clear indication of the need for provision of the ductility, particularly at the top portion of the pile.

Comparatively favorable behavior of friction piles is indicated by the post-earthquake survey reports. Further investigation is required to identify and confirm the possible beneficial features of friction piles contributing to the evidently favorable behavior. In addition, there is the concern of the possible loss of frictional resistance under earthquake shaking, including the effect of the rise in the pore water pressure, which requires adequate attention. It would seem logical to make distinctions between ground shaking effects and ground failure effects in pursuing research on seismic behavior of friction pile foundations.

The implication of the observed favorable behavior of friction piles to the pile design practice can be expected to be dictated by the pace of further research in this direction. Although recent research publications indicate distinctive dynamic characteristics of friction piles under earthquake loading, the results may be only preliminary. However, the ductility of friction piles near the top is an important consideration in the seismic design. Use of a composite friction pile, with the upper portion consisting of a ductile material connected to an ordinary PHC nodular pile may prove to be a functional and economic solution in this respect.

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