The effect of flexural stiffness of piles on the damage evolution of multi-story buildings supported on liquefiable soil foundation

AHMED M YOUSSEF M AND KOICHI MAEKAWA

Department of Civil engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
mohammed@concrete.t.u-tokyo.ac.jp

Abstract
This paper is to discuss the nonlinear seismic responses and damage evolution & control of multi-story buildings supported by group piles in liquefiable soil foundation. Here, group piles driven in dry and fully saturated soft sands are considered. The engineering focus is directed to the effect of axial-flexural pile stiffness on the pile-curvature, induced shear force in piles, and the base shear transmitted to the on-ground building structures. The results indicate that piles with low reinforcement ratio have higher safety margin against flexural failure. The structural damage and the induced base shear are clearly decreased by reducing the amount of axial reinforcement (Rft) of piles in the case of dry soil under severe earthquake, but no significant effect is found in case of liquefied soil. Piles with less Rft are preferably accepted due to higher deformability and less induced shear even on liquefiable soil foundations.

1. Introduction

The soil-structure interaction and liquefaction of soil foundation has become one of urgently important research issues in civil engineering after the serious structure damages due to soil liquefaction during Nigata Earthquake (1964, M=7.5) and Alaskan earthquake (1964, M=9.2) [1, and 2]. During Hyogoken-Nanbu Earthquake (1995 in Kobe, M=7.2), the liquefaction was the primary cause of damage to some piles supported structures and bridges. The onset of liquefaction may reduce the inertia force to the superstructures, and damage to the superstructure was less frequent even when damage to piles was observed. These facts indicate the importance of considering soil-pile-superstructure system in a seismic design even in liquefied ground.

After Nigata Earthquake and up to now, a number of research works have been carried out to understand the soil-pile-superstructure interaction, for example, analytically and experimentally investigating the effect of inertial and kinematic interaction on pile failure mechanism [3] The observations of pile foundations during past earthquakes have shown that piles in firm soils generally perform well, while the performance of piles in soft or liquefied ground can range from excellent to poor [2]. Most of the researchers have simplified the models of superstructure and/or the models of the pile foundation in their experiments to be elastic materials like steel or aluminum. Thus, the high nonlinearity of superstructure and rocking-mode effect were hardly considered, when the superstructure is simplified as a mass of concrete or steel rested on the piles heads [3,4, and etc].

In the past decades of research, the effect of the axial-flexural RC-pile stiffness on the damage of both piles and super structure was less discussed in view of the damage control. Under this situation, Okhovat and Maekawa tried to study the nonlinear seismic responses of underground reinforced concrete ducts [5] in terms of both structural damage and stability.

In this paper, seven-story building supported by nine columns/piles in a soft sandy soil foundation is analytically studied. Under different levels of earthquake PGA from low to sever ones, the effect of axial-flexural pile stiffness on the pile-curvature, induced shear force in piles, and the base shear transmitted to the on-ground superstructure is investigated. Here, both cases of dry and fully saturated soft sandy-soil are considered to discuss the effect of liquefaction on the pile damage and base shear transmitted to the superstructure under different levels of earthquake excitation. The results show that large amount of longitudinal Rft in piles causes higher flexural and shear failure risk in both piles and on-ground buildings. The full three-dimensional finite element analysis of soil-structure-pore water systems used in this study is also examined and verified by the past shaking table tests of top-heavy piles embedded in model foundation [6].

2. Finite element model

A seven story building with 12m in width and 24.5m in height is supported by nine columns (70cm x70cm) and these columns are extended through 16.5m of soft sandy soil to bear on the base soil (very dens sand) to act as pile foundation with massive concrete mat on the soil surface. For simplicity, all concrete slabs and foundation mate are considered as 3D elastic solid elements (density=2.5t/m^3, E_c= 2800 KN/cm^2, and Poisson's ratio = 0.2) with 50 cm in thickness, and the column-pile elements are considered as lineal Timoshenko frame elements (fiber cross section) (see figure.1). The soft soil is considered as 5 layers from very soft layer at the surface to compacted one at the bottom and deposited on very dense sandy soil to act as an engineering base on which the ground acceleration is defined. The soil layers properties are described in Table 1.

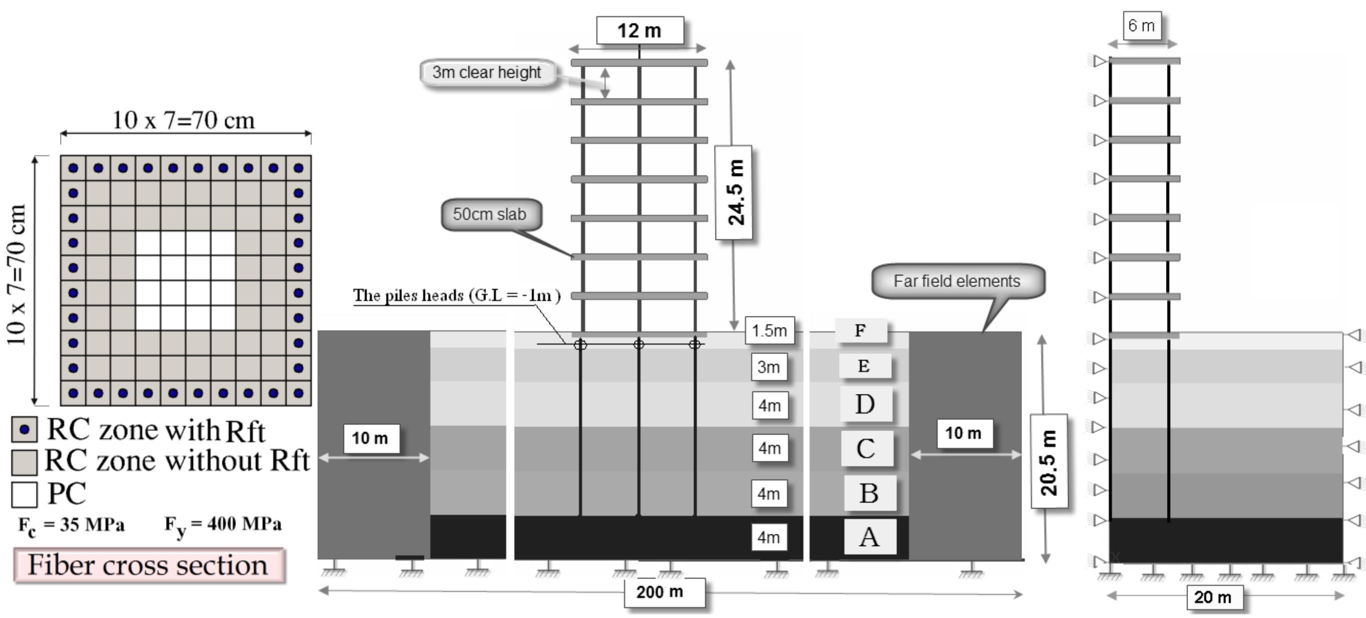

Figure 1: The model of the multi-story building, pile foundation and soil layers with far field elements

Table 1 : Soil properties used in analysis

Soil Layer	Initial shear stiffness Gs(MPa)	Relative density	Dry density (kg/cm3)	The internal friction angle φ
A	74	100	2.2	45
B	15	42	1.8	37
C	9	40	1.8	35
D	7	36	1.7	34
E	5	30	1.7	31
F	3	20	1.6	25

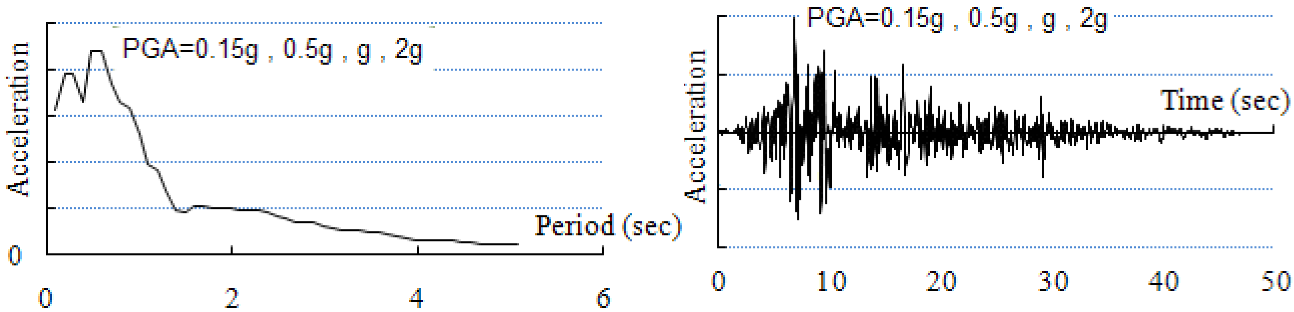

Figure 2: The earthquake record and its acceleration spectrum

3. Constitutive modeling

The finite element discretization was carried out by using 3D-nonlinear solid element, 3D-elatic solid element for RC slabs and Timoshenko frame elements for piles and columns [7]. A nonlinear path-dependent constitutive model for soil mainly depends on shear stress-shear strain relationship which is extended to three-dimensional generic condition and assumed to behave according to Masing's rule to fulfill the soil hysteresis. The soil is idealized as an assembly of a finite number of elasto-perfectly plastic elements connected in a parallel pattern. The nonlinear behavior of the soil system in liquefaction is assumed as undrained state, since its drainage time is much longer than the duration time of earthquake [8]. The soil undrained behavior is as shown in Figure 3. The Full details of the constitutive model of soil, RC-solid element, and frame element is explained by Maekawa et al [7].

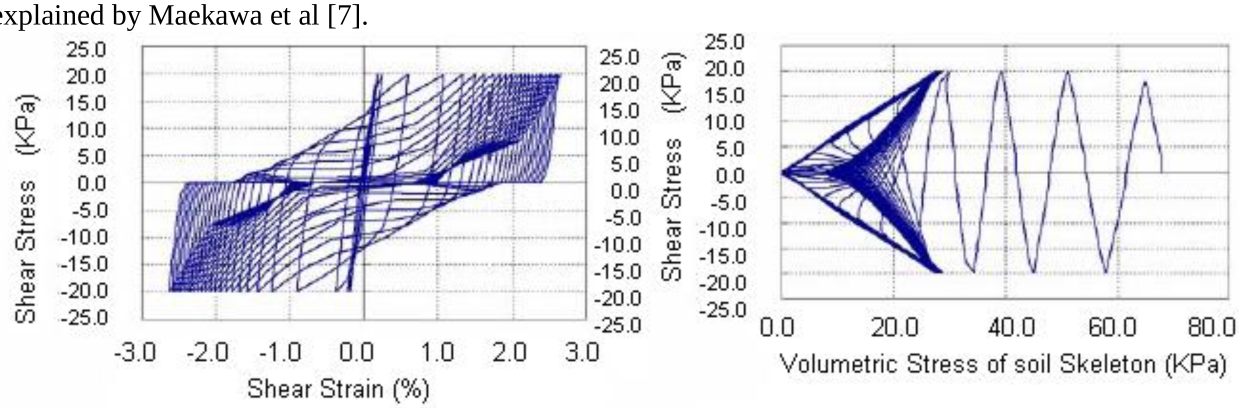

Figure 3: Confinement dependent soil model under undrained condition

4. Analytical Results

The flexure stiffness of the superstructure columns is kept constant (Rft=2.8%), and the piles Rft ratio varies from 0.5% up to 6% to investigate its effect on the whole structural performance under different seismic levels.

4.1 superstructure damage

The pile Rft ratio has no significant effect on the normalized base shear (max base shear/whole superstructure weight, 7500KN) induced to the superstructure at liquefaction even under severe seismicity as illustrated in figure 4. In the dry case, the pile Rft ratio strongly influences on the structural damage while the vulnerability to severe EQ exists. It implies that the soil liquefaction is mostly less hazardous in terms of human life because the base shear is about 50% of the dry soil case (Figure 4), and actually this result looks consistent to the past experiences.

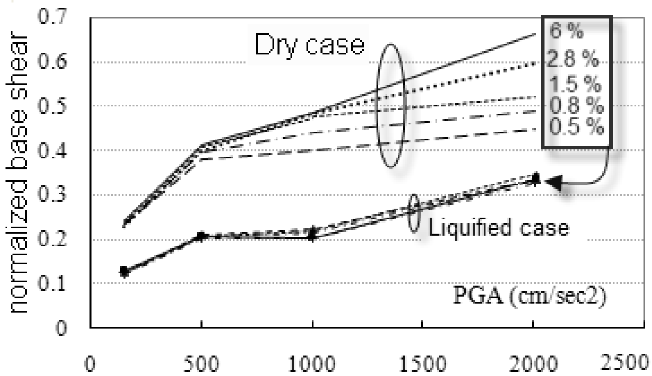

Figure 4: The effect of the Rft ratio and the PGA on the base shear induced to superstructure

4.2 piles damage

The influence of the pile Rft ratio on the pile performance has two opposite faces. While the pile is strengthened with higher longitudinal Rft and under the risk of a severe seismicity, the pile curvatures decreases, but on the other hand, the pile curvature capacity (Φ_c, the start of concrete crushing and moment capacity reduction) decreases (see Figure 5 and Figure 7). Figure 5 shows the average curvature (normalize to yield curvature) at the pile-heads with considering different levels of earthquake record. After and during the earthquake, the pile with flexural damage may survive and possibly carry the superstructure stably. The shear in piles significantly increases in case of dry soil as illustrated in Figure 6. The shear failure of an axially loaded member like piles or columns is more significant on the pile carrying mechanism than flexural failure

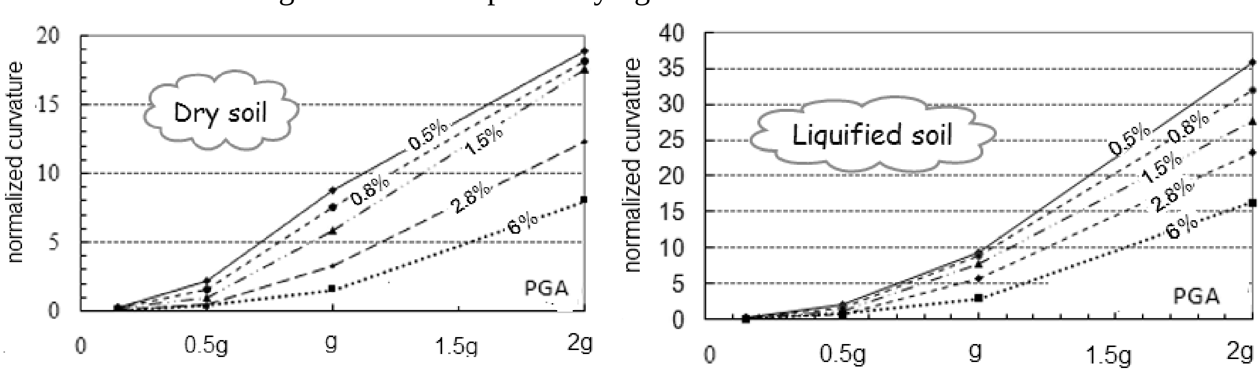

Figure 5: The average normalized peak curvature at the pile-heads w.r.t PGA and Rft ratio

The author has defined a factor of safety (F.S = Φ_C / Φ_R) as a ratio of the pile curvature capacity (Φ_C) to the pile peak curvature response (Φ_R). In case of dry soil, the F.S is higher at both upper and lower applicable limits of the Rft ratio(0.5%~3%) as shown in figure 7, but the upper limit of Rft causes more transmitted shear force to the superstructure (see figure 4) and higher shear failure risk in piles. In case of liquefaction, the F.S decreases with increasing the Rft ratio in piles (see figure 7) and that shows the significant effect of the kinetic force caused by liquefied soil movement.

The liquefaction induces more damages (curvature) to piles than in dry case as indicated by the F.S in Figure 7. Liquefaction has an aggressive effect to piles. The shear in piles is significantly influenced by the pile Rft ratio in the case of dry soil from moderate to severe earthquake. In case of the liquefaction under severe seismicity, and due to the soil cyclic mobility (see Figure 3), the pile Rft ratio increases the shear in piles significantly, but the effect is less than the one in the dry case, as shown in Figure 6.

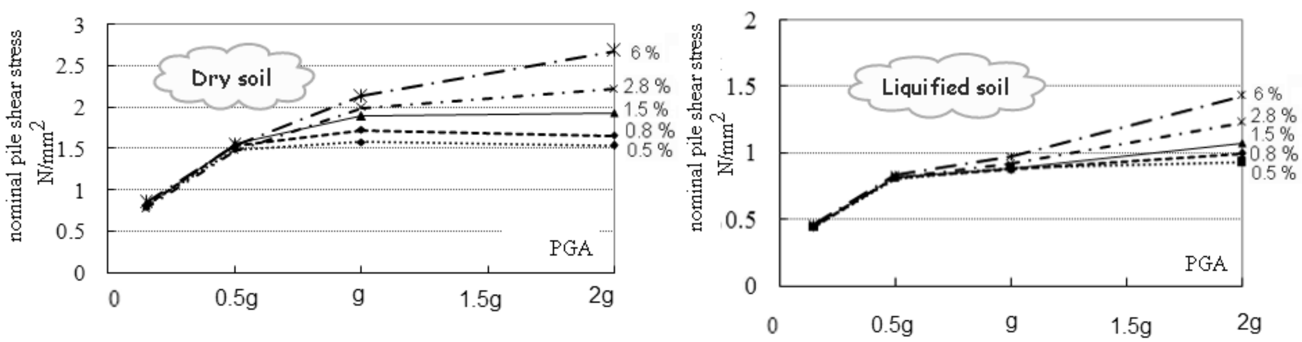

Figure 6: The effect of the PGA and Rft ratio on the average nominal shear stress at piles heads

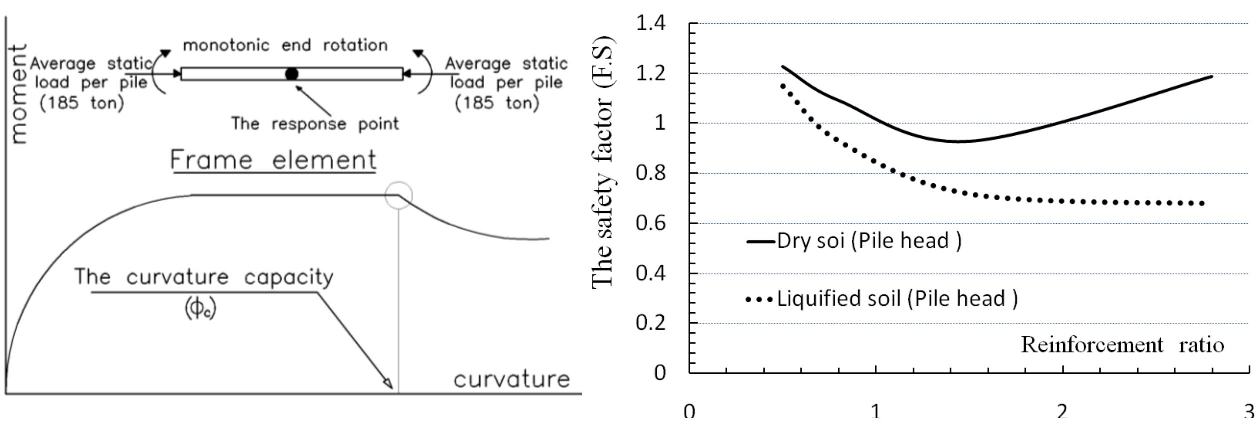

Figure 7: the piles Safety factor (F.S) against the concrete crushing in flexure failure

4.3 Rigid body motion

The rigid body motion of the superstructure and the pile response for liquefied soil are mainly governed by the swaying mode, but for dry soil, they are mainly governed by the rocking mode. The normal forces in all piles are mainly kept as compression in the case of liquefaction, but the ones for dry soil are varied from compression to tension. Figure 8 shows the response (normal force and moment) at the 6-piles heads cross section versus the pile cross section interaction diagram (Nu: ultimate axial capacity & Mu: ultimate moment) according to [9].

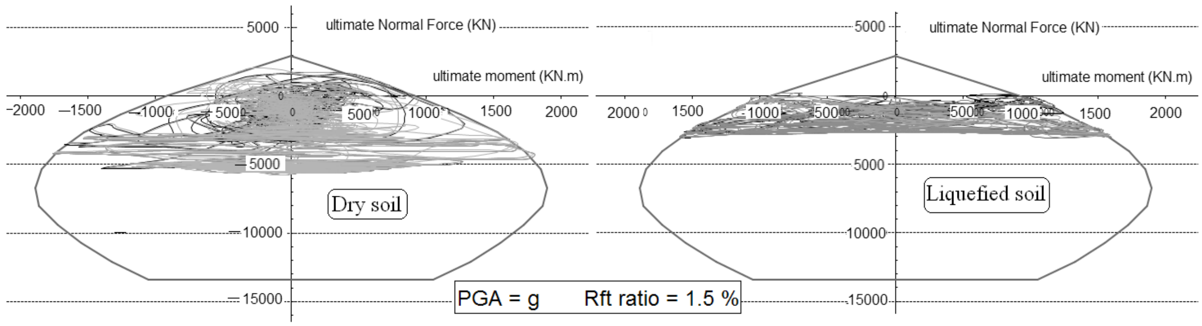

Figure 8: Pile-heads cross section response (N&M) versus the pile section capacity

5. Conclusions

1. The liquefaction is mostly welcome with some damage controls as considering raft foundation and sheet pile walls to help in improving the stability of the super structure and that coincide with the structure performance in the past history.
2. The liquefaction causes flexure damage to the pile more than the damaged caused by dry soil, but the induced shear is less than the one caused by dry soil.
3. Large amount of longitudinal Rft in piles causes higher shear failure risk in both piles and on-ground buildings in case of dry soil under moderate to severe EQ, and in case of liquefaction under the severe EQ due to the soil cyclic mobility.
4. The rocking mode of the super structure has a significant effect on the pile response, so it should be considered in design.
5. The piles with less Rft are preferably accepted due to the higher deformability, the higher safety against concrete crushing in flexure, and less induced shear to piles.

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