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NUMERICAL SIMULATION OF PILE FAILURE IN LIQUEFIED SOIL OBSERVED IN LARGE-SCALE SHAKING TABLE TEST

Hideki FUNAHARA[1], Shunji FUJII[2] And Shuji TAMURA[3]

SUMMARY

Numerical analyses using an effective stress FEM, to simulate pile behaviours in a liquefied soil observed in a large-scale shaking table test, are presented. The soil is modelled using an elasto-plastic constitutive model "Stress-Density Model". Firstly, the model parameters are determined so that the 1D soil column analysis can reproduce the pore water pressure build-up and the ground deformations observed in the test. Then 2D FEM analyses of a soil-pile-structure model are performed, using the same model parameters for soil, which have been identified in the 1D analysis. The failure mechanism of piles and the interaction mechanism between the piles and the liquefied ground are studied through the analysis and the comparison with the test results. It is concluded that the pile failures at the pile heads are due to both the ground deformation and the inertial force of the superstructure. Also the pile failures at the middle parts are mostly due to a large ground deformation associated with liquefaction.

INTRODUCTION

During the 1995 Hyogoken-Nambu Earthquake, extensive liquefaction occurred widely around Kobe coast area, and many pile foundations were damaged because of the liquefaction. Many engineering researchers analyzed the case histories in details[1)], and it was realized that not only the inertial forces of the super-structures but also the deformations of the liquefied ground contributed to the damages. It has been recognized that establishing a design procedure for pile foundations considering the liquefaction induced ground deformation is necessary.

To establish a design procedure for pile foundations in a liquefiable ground, it is important to clarify what kind of interaction mechanism works between piles and a liquefied ground, and how the piles are damaged. To make clear the mechanism of the failure of piles in a liquefied ground, a large-scale shaking table test was conducted. A 5.8m-depth saturated soil model heavily liquefied in a large-scale laminar box, and four reinforced concrete piles (15cm in diameter) were damaged with flexural crushes at the pile head and at the middle part. The test results are reported precisely by TAMURA et al. (2000) [2)].

It is also important to establish a numerical technique that can properly evaluate the behaviour of the pile foundation during liquefaction. This paper describes numerical analyses by the 1D and 2D FEM using an effective stress method to simulate the shaking table test results.

1 TAISEI Research Institute, Taisei Corporation, Yokohama, Japan, hideki.funahara@sakura.taisei.co.jp
2 TAISEI Research Institute, Taisei Corporation, Yokohama, Japan, shunji.fujii@sakura.taisei.co.jp
3 National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Japan, tamura@eq-eng.bosai.go.jp

[1] TAISEI Research Institute, Taisei Corporation, Yokohama, Japan, hideki.funahara@sakura.taisei.co.jp
[2] TAISEI Research Institute, Taisei Corporation, Yokohama, Japan, shunji.fujii@sakura.taisei.co.jp
[3] National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Japan, tamura@eq-eng.bosai.go.jp

OUTLINE OF TEST

Figure 1 shows the schematic view of the test model and the measurement instrumentation. A large-scale laminar box is set on a shaking table (Photo 1). The inside measurement of the laminar box is 6m in depth, 11.6m in width, and 3.1m in thickness. Kasumigaura-sand (e_{max}=0.961, e_{min}=0.570, D_{50}=0.31mm, Fc=5.4%) is used for the saturated ground model. The ground depth is 5.8m. Four reinforced concrete pile models (15cm in diameter) are set in the ground model. The pile tips are connected to the bottom of the laminar box in pined condition. On the pile heads, a rigid structural model (14.1ton) is set in fixed condition. The axial stress in the piles is 1690kPa. Accelerations, pore water pressures in the ground, accelerations and displacements of the structural model, and strains of the piles are measured. Deformations of the laminar box are also measured. The input earthquake motion used in the test is an artificial earthquake "RINKAI wave (maximum acceleration 310m/sec2, Fig.2)" which is synthesized for the prospective Minami-Kanto Earthquake. The relative density of the sand measured

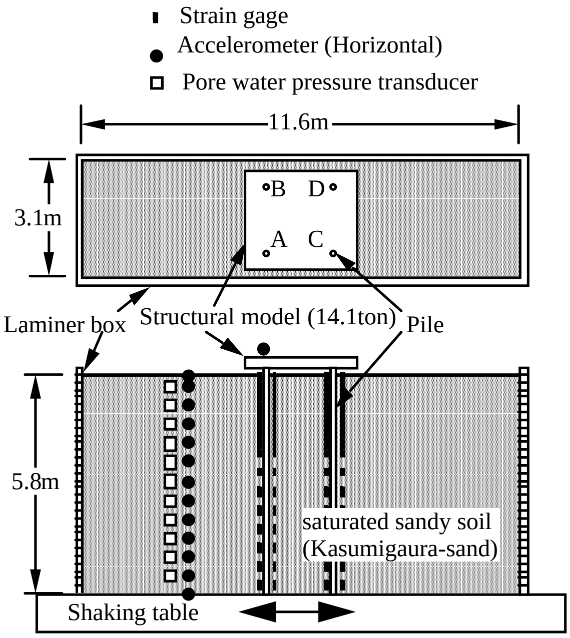

Fig.1 Test model

Photo 1 Large-scale Laminar Box

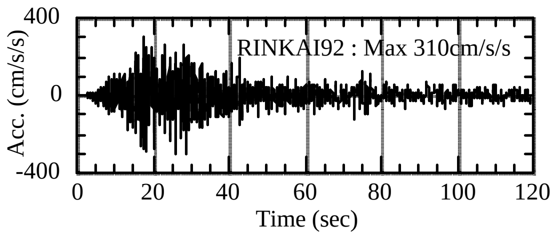

Fig. 2 Input motion

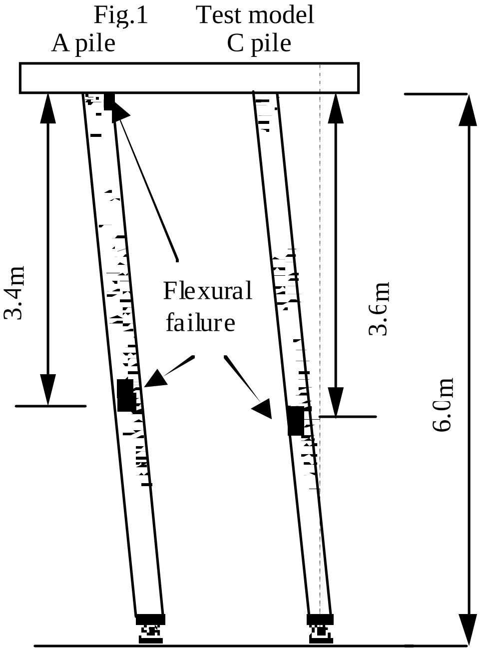

Fig. 3 Pile falure

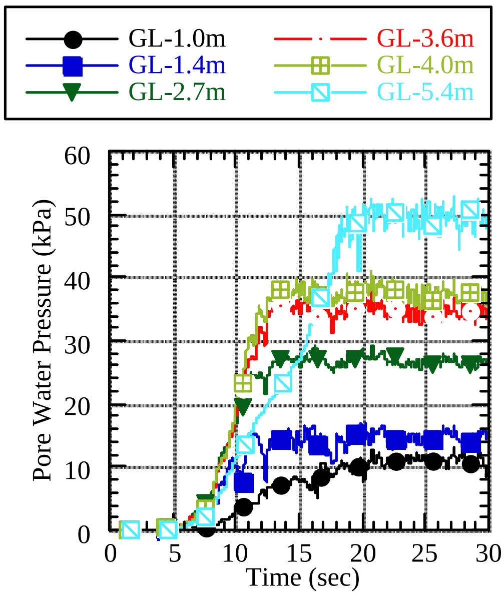

Fig. 4 Pore water pressure time histories in the test

before the test is about 60%, and the shear wave velocity is about 100 m/sec.

During the test, the whole ground was heavily liquefied, and the piles were flexuraly failed with concrete crushing at the pile head and at the middle part (about 3.5m below the pile head). The schematic view of the pile damages sketched after the removal of the surrounding soils is shown in Fig.3. The excess pore water pressure time histories for several depths are plotted in Fig.4. The speeds of the pore water pressure build-up are different depending on the depth. At the middle part of the ground (GL-2.7~4.0m), the speeds of the pore water build-up are faster. Around 12~14 seconds, the pore water pressure at the middle part reaches the initial effective confining stress, which means the soil is liquefied. On the other hand, at the deeper part, the speed is slower, and the pore water pressure reaches the initial effective stress around 16~18 seconds. Near the ground surface, the speed is also slower. The ground model was made in the same way throughout the depth, but it is likely that the liquefaction strength differed depending on the depth.

The other test results such as the ground deformations, the accelerations, the pile deformations will be presented in the following sections in comparison with the simulation.

NUMERICAL MODEL

Outline of the numerical model

An analytical tool which is employed is an effective stress FEM code "DIANA-J" which includes "Stress-Density Model[3)]" as a constitutive model of soil. Figure 5 shows the schematic view of the analytical model for the soil-pile-foundation system. The soil is modeled by the plain-strain element, and is discretized into 12 elements in the vertical direction. The model parameters for soil are determined so that the 1D soil column analysis can reproduce the soil responses (such as the pore water pressure build-up, and the deformation time

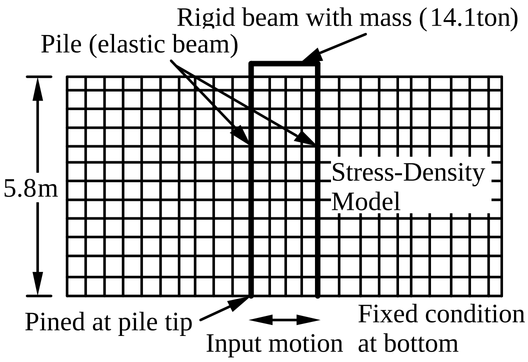

Fig. 5 Analytical model

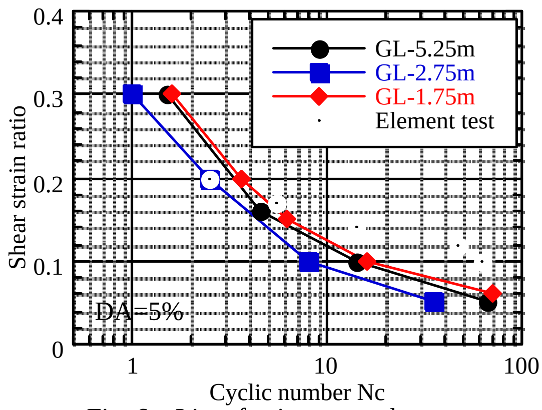

Fig. 6 Liquefaction strength curve of the model

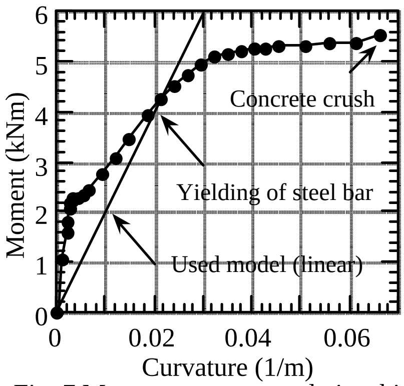

Fig. 7 Moment-curvature relationship of the pile

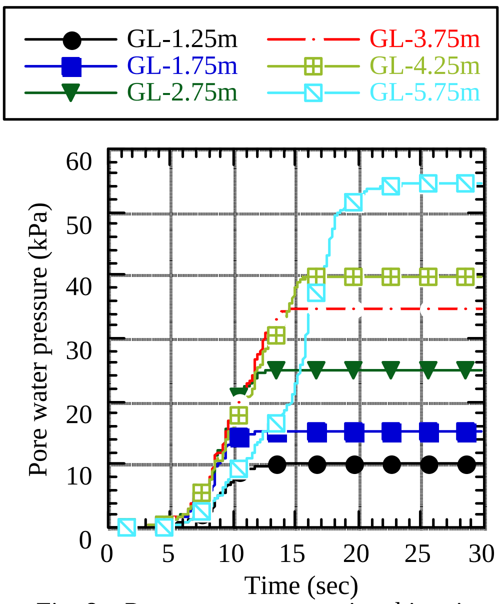

Fig. 8 Pore water pressure time histories in the 1D soil column analysis

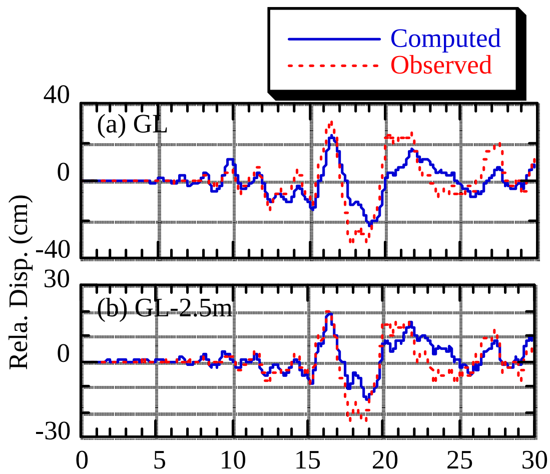

Fig. 9 Comparison of ground displacement time histories

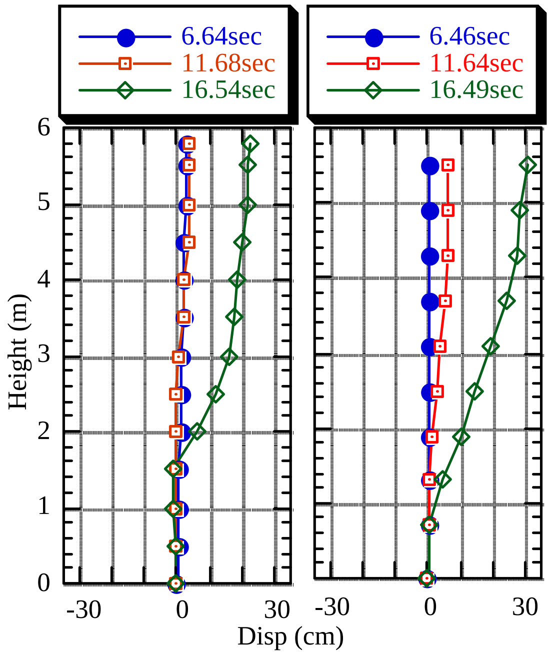

Fig. 10 Comparison of the vertical distribution of the ground displacement

histories) observed in the test. As the result, the model parameters for soil around the middle depth are selected to have relatively weak liquefaction strength. Figure 6 shows the relationship between the cyclic numbers and the shear stress ratio to achieve the 5% axial strain in double amplitude in the cyclic triaxial test, comparing the model and an element test result. Figure 7 shows the computed bending moment - curvature relationship of the pile at the static axial stress condition. The reinforcing bar yields at the curvature 0.018 (1/m), and the concrete crushes at the curvature 0.065 (1/m). In the analysis, the elastic beam element is used to model the pile, and the straight line in the figure is the stiffness of the model. The structural model is modeled by a rigid beam that has mass property corresponding to the real mass (14.1ton). The boundary condition at the bottom of the ground is fixed, and the nodes on the side boundaries are specified to yield the same horizontal and vertical displacement. The measured acceleration at the shaking table is used as an input motion. The time increment in the analysis is 0.005 second.

1D soil column analysis

The pore water pressure time histories in the 1D analysis is plotted in Fig.8. At the middle part, the pore water pressure builds-up are faster than the other parts as intended, and by comparing Fig.4 and Fig.8 it can be seen that the liquefaction progress at each depth is reproduced in the analysis.

The ground displacement time histories at two depths in the 1D analysis are plotted in Fig.9 comparing with the displacements of the laminar box in the test. Three time sections of the ground displacement are compared with test results in Fig.10. The ground is not liquefied around 6.5 sec and partly liquefied around 11.6 sec. Around 16.5 sec, pore water pressure is almost the initial effective stress, and the deformation of the ground reaches the maximum value. Although the computed displacements are slightly smaller, the overall behaviours are reproduced in the simulation.

2D FEM SIMULATION

Acceleration and displacement of structural model

The acceleration time history at the structural model computed in the 2D FEM is compared with the test result in Fig. 11. The numerical result matches the test result with reasonable accuracy, so it can be assumed that the effect of inertial force of the structural model to the pile is properly evaluated in the simulation. The

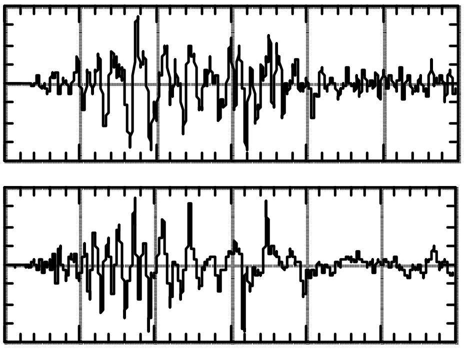

Fig : 11

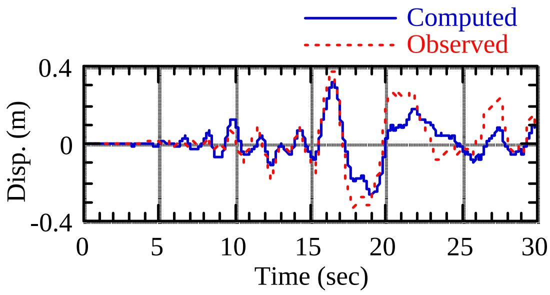

Fig. 12 Comparison of displacement of structural model

displacement time history of the structural model is also reproduced accurately as shown in Fig. 12.

Pile deformation

The time histories of the pile curvature at four heights in the analysis are shown in Fig. 13, in comparison with the test results. As several strain gages in some piles were dead in the test, the curvature time histories, which are successfully measured, are selected. There is some scattering in the measured curvatures, still the averaged tendencies can be seen.

At the pile head, the curvature exceeds the yielding point of the steel bar (0.016/m), in the earlier stage (5 to 15

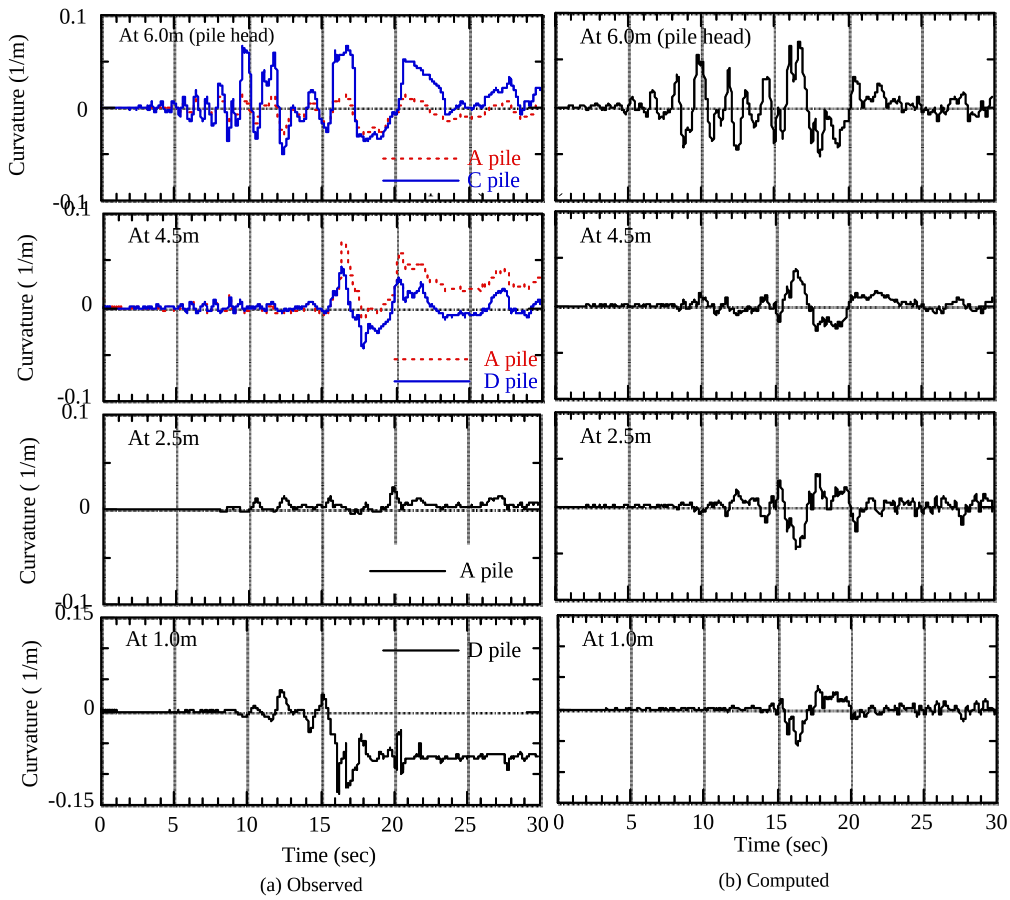

Fig. 13 Comparison of pile curvature time histories

seconds), when the pore water pressure does not reach the initial confining stress. Around 16 seconds, the curvature exceeds the concrete crush level (slightly over 0.065/m), both in the analysis and in the test. These results are consistent to the fact that the concrete crushes were observed at two pile heads in the test.

Around the middle heights of the piles (at 2.5m and 4.5m), the curvatures stay relatively small, until the pore water pressure reaches the initial confining stress at around 15 seconds, both in the analysis and in the test. Then at around 16 seconds, the curvature increases suddenly. The sudden deformation is likely to be caused by the large ground deformation at around 16 seconds. The deformation at around 16 seconds can be considered to have made the four piles failed at the middle parts finally.

The vertical distributions of the curvatures at three time sections are compared in Fig. 14. In the analytical results, before liquefaction (around 6.5sec), the peak of the curvature in the ground is around 4 or 5 m from the bottom. During the liquefaction process (at 11.04sec), the peak is around 3.5m from the bottom. When the deformation of the ground is largest (around 16.5sec), the peak is around 2 m from the bottom. In the analysis, the peak of the curvature moves downward in the liquefaction processes. In the test results, the tendency mentioned for the analytical results is not so clear. Especially the observed damages at the middle part of the piles, which are also represented in the analysis, are not clearly justified in the measurement. It is assumed that this discrepancy is mainly due to the dead strain gages.

Subgrade reaction

The vertical distributions of the computed shear forces and the subgrade reactions are shown in Fig. 15. At 6.64sec, before the liquefaction, the shear forces and the subgrade reactions are observed mainly near the pile top. It can be said that the inertial force of the structural model is the dominant factor for generating the pile stresses at this stage. At 11.04sec, when the liquefaction is in progress, the shear stresses and the subgrade

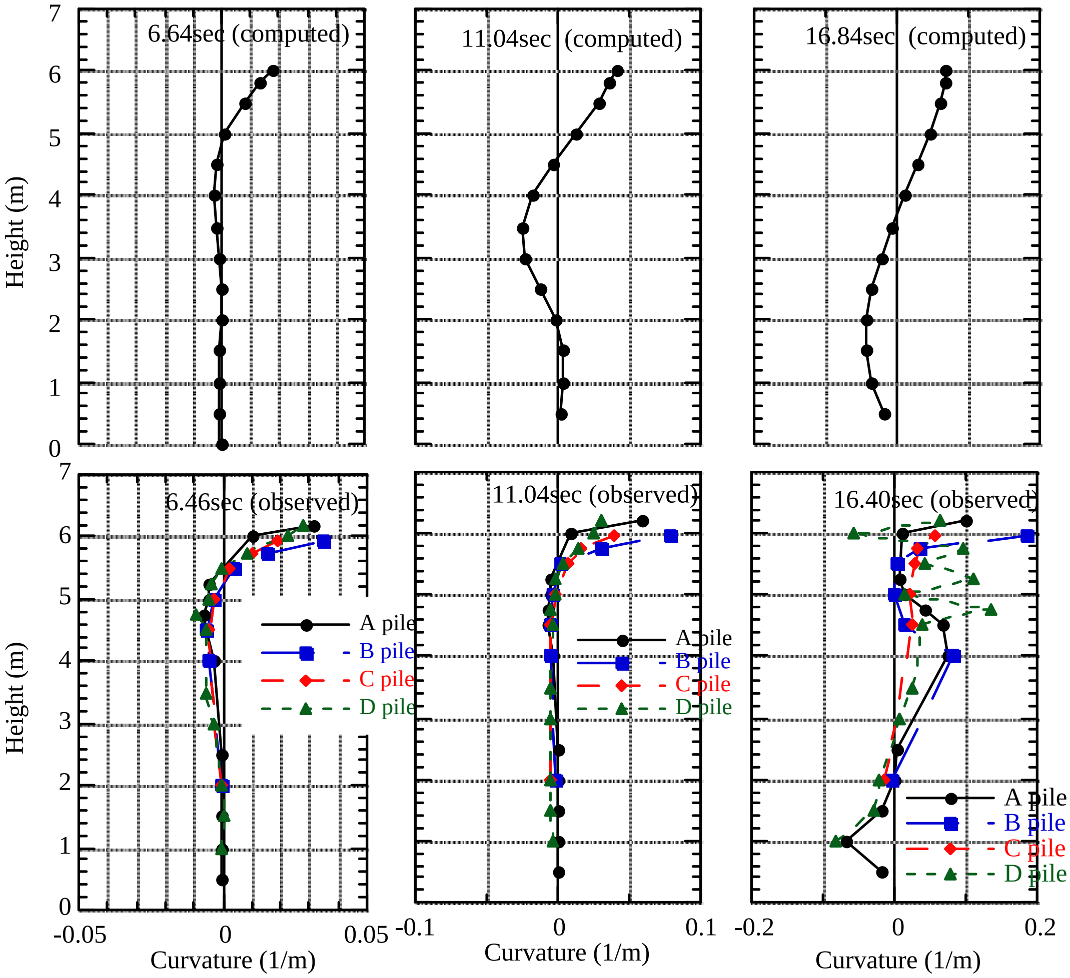

Fig. 14 Distributions of pile curvature

reactions around the middle part of the pile are becoming dominant. At 16.64 sec, when most of the ground is

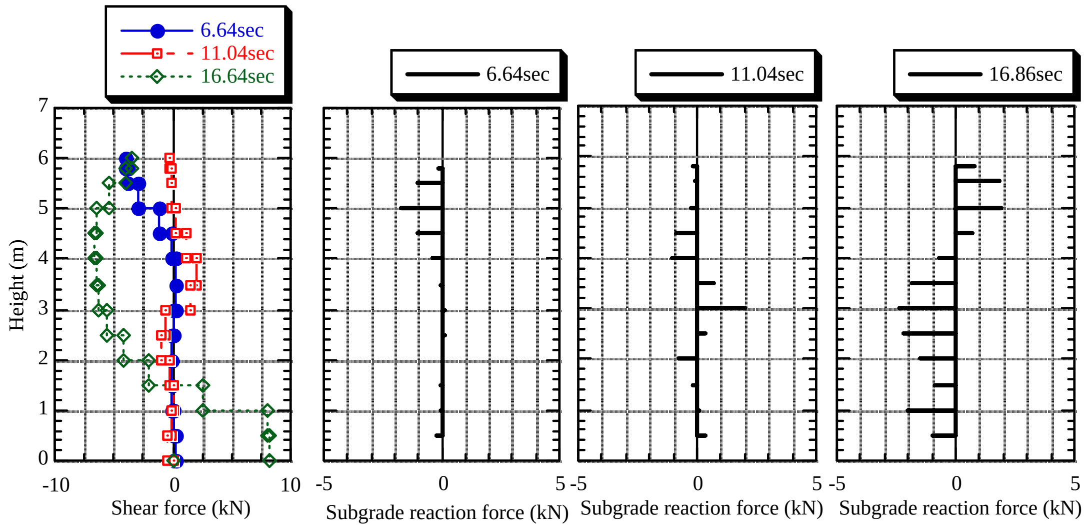

Fig. 15 Distributions of Shear force and subgrade reaction force

liquefied and the ground deformation is largest, the shear stress and the subgrade reactions are observed on all over the pile and become large.

From the analytical results, the subgrade reaction for the pile from the liquefied ground is not very small.

Effect of the inertial force at the pile head

A 2D FEM model without the mass of the structural model is also used, to see the effect of the inertial forces to the pile damage. Time histories of curvature on the pile are compared with the model with the mass in Fig.16, and the comparisons of the curvature distributions are shown in Fig. 17. Without the mass, the curvature at the pile head is reduced, and the maximum value is under the concrete crush criteria 0.065(1/m), which is inconsistent with the test results. On the other hand, no big effect of the mass is seen at the middle part of the pile. These results indicate that the pile failures at the pile heads are due to both the ground deformation and the inertial force of the superstructure, and the failures at the middle parts are mostly due to the large ground deformation associated with liquefaction.

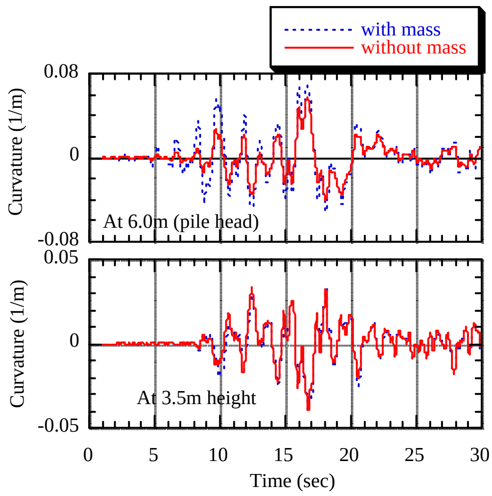

Fig. 16 Effect of pile-top mass on curvature time history

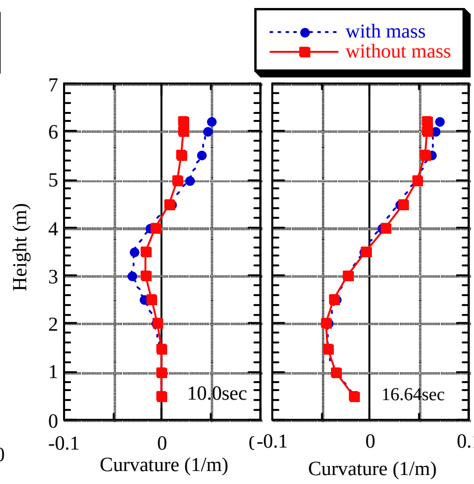

Fig. 17 Effect of pile-top mass on curvature distribution

CONCLUSIONS

Numerical simulations of the pile behaviours in a liquefied soil observed in a large-scale shaking table test lead to the following conclusions:

1) By determining the soil parameters so as to reproduce the soil response in the test, the analysis of the 2D soil-pile-structure system offers reasonably accurate simulation of the pile and the structural response.

2) As the liquefaction develops and the deformation grows, the interaction forces distribute widely on a pile. After the liquefaction is fully developed, the subgrade reaction of soil still exists and is not very small.

3) Through a parametric study on the effect of the inertial force at pile head, it is indicated that the causes of the pile failures at the pile heads are due to the combined effect of the ground deformation and the inertial force from the superstructure. The failures at the middle part are mainly due to the large ground deformation associated with liquefaction.

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