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SIMULATION ANALYSES FOR 3-D RESPONSES OF PILE-SUPPORTED STRUCTURE IN LIQUEFIABLE SAND SUBJECTED TO BLAST-INDUCED GROUND MOTION

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SUMMARY

Simulation analyses were conducted for vibration tests on a pile-supported structure in a liquefiable sand deposit at a large-scale mining site, in order to understand three dimensional (3-D) responses of soil-pile-structure interaction systems under severe ground motions and to confirm the applicability of the response analysis method to non-linear response including liquefaction. This paper describes the simulation analysis results for the vibration tests. Firstly, site responses of the test pit were simulated using a 3-D finite element model. Next, the soil-pile-structure responses were analyzed by a beam element model with nonlinear springs taking into account the soil-pile interaction. Analysis results of the structure responses and the pile stresses showed good agreement with the test results, and it was confirmed that this analysis method was applicable for evaluating non-linear behaviors of soil-pile-structure systems during liquefaction.

INTRODUCTION

Vibration tests of a pile-supported structure in a liquefiable sand deposit were conducted at a large-scale mining site [1]. These tests yield the 3-D responses of the pile-supported structure under the test conditions as well as those during an actual earthquake. It is well known that pile stresses, especially axial forces, are greatly affected by 3-D dynamic behavior of the superstructure, and that they vary with location in the pile arrangement [2]. It is very important to evaluate how the responses of the superstructure affect the pile stresses and to incorporate those effects into seismic design of the pile foundation. This paper shows simulation analyses using a beam-interaction spring model for the 3-D dynamic behaviors of the soil-pile-structure system. The goal of this study is to achieve a better understanding of dynamic nonlinear behaviors of soil-pile-structure interaction systems under severe

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ground motions and to confirm the applicability of the nonlinear response analysis method to evaluate pile stresses.

OUTLINES OF VIBRATION TESTS

Outlines of the vibration tests using ground motions induced by mining blasts are shown in Figure 1. Vibration tests of pile-supported structures in a liquefiable sand deposit were conducted at Black Thunder Mine of Arch Coal, Inc. Black Thunder Mine is one of the largest coalmines in North America and is located in northeast Wyoming, USA. At the mine, there is an overburden (mudstone layers) over the coal layers. The overburden is dislodged by large blasts called "Cast Blasts" and the rubble is removed by huge earthmoving equipment. The ground motions caused by Cast Blasts were used for vibration tests conducted in this research. Photo. 1 shows the situation of vibration tests.

Figure 2 shows the outline of the pile-supported structure. The test structure was supported on four piles made of steel tube. The pile tips were closed by welding and embedded 70cm into the mudstone layer. The top slab and the base mat were made of reinforced concrete and were connected by H-shaped steel columns. The instrumentation is shown in Figure 3. Accelerations were measured of the structure and one of the four piles. Accelerations in the sand deposit and in the free field were also measured in array

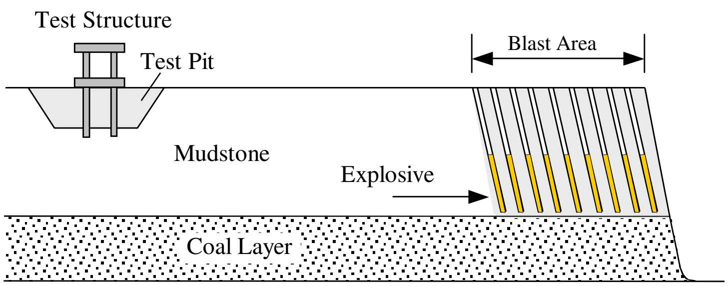

Figure 1 Vibration Test Method at Mining Site

Photo. 1 Situation of Vibration Tests

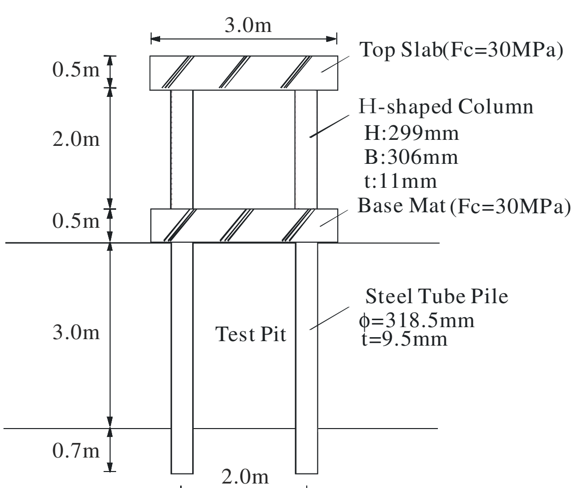

Figure 2 Pile-Supported Structure

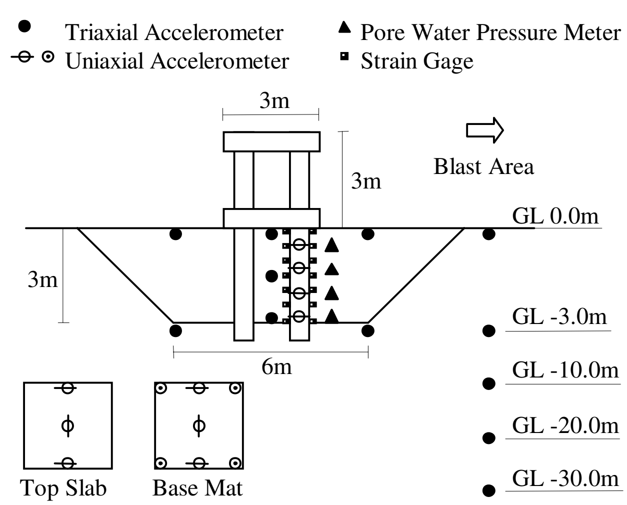

Figure 3 Instrumentation

configurations. Axial strains of the pile were measured to evaluate the bending moments. Excess pore water pressures were measured at four levels in the test pit to investigate liquefaction phenomena. Vibration tests were conducted six times. In this paper, Test-3 was chosen for detailed investigations. In Test-3, the distance was about 140m between the blast area and the test pit and the maximum acceleration at the ground surface was 579 Gals in the EW direction [3].

ANALYSIS METHOD

Figure 4 shows the analysis model for 3-D response of soil-pile-structure system. The soil response analysis is conducted by a 3D-FEM effective stress analysis method [3]. The analyses were performed by a step-by-step integration method and employed a multiple shear mechanism model for the strain dependency of soil stiffness and Iai-Towhata model for evaluating the generation of excess pore water pressure [4]. Table 1 shows the soil constants. The shear wave velocity was measured by PS-Logging and the density of the saturated sand was measured by a cone penetration test. Soil nonlinearity was taken into account for all layers and Table 2 shows the nonlinear parameter for this simulation analysis. Figures 5 and 6 show the nonlinear properties and the liquefaction curve for the reclaimed sand, respectively. These curves are based on laboratory tests.

The super-structure is idealized by a one-stick model and the pile foundations are idealized by a four-stick model with lumped masses and beam elements. The lumped masses of the pile foundations are connected to the free field soil through lateral and shear interaction springs. A nonlinear vertical spring related to the stiffness of the supported layer is also incorporated at the pile tip, as shown in Figure 7. The initial values of the lateral and shear interaction soil springs of the pile groups are obtained using Green's functions by ring loads in a layered stratum [5] and they are equalized to four pile foundations. The soil springs are modified in accordance with the relative displacements between soils and pile foundations and with the generation of excess pore water pressures.

ANALYSIS RESULTS

3-D Responses of Liquefied Sand Deposits

Figure 8 shows the calculated time histories of the ground surface accelerations and the pore water pressure ratios. The amplitudes of the horizontal motions became smaller due to the generation of pore water pressure at time 2.5 seconds. However, the amplitude of the vertical motion was still large after 2.5 seconds. The analysis results are in good agreement with the test results.

Figure 9 shows the relationship between the shear stress and the shear strain at GL-1.5m in the sand. The left figure shows the results for the EW direction and the right one shows those for the NS direction. The blue lines show the 3-D analysis results and red ones show the 1-D analysis results. The symbols show the occurrence time of maximum shear strain in each direction. Both occurred at almost the same time. The maximum shear stresses of the 1-D results are higher than those of the 3-D results. This shows that the 1-D analysis under-estimated the soil nonlinearity due to liquefaction.

Figure 10 shows the acceleration response spectrum of the ground surface in the EW direction. The blue line and the red line show the 3-D and 1-D analysis results respectively, and green line show the test results. All spectra have a first peak at 0.6 seconds, and the 3-D results are good agreement with the test result. Figure 11 shows the acceleration response spectrum of the ground surface in the UD direction. All spectra have a first peak at 0.3 seconds, and both of the 3-D and 1-D analysis results are in good agreement with the test result.

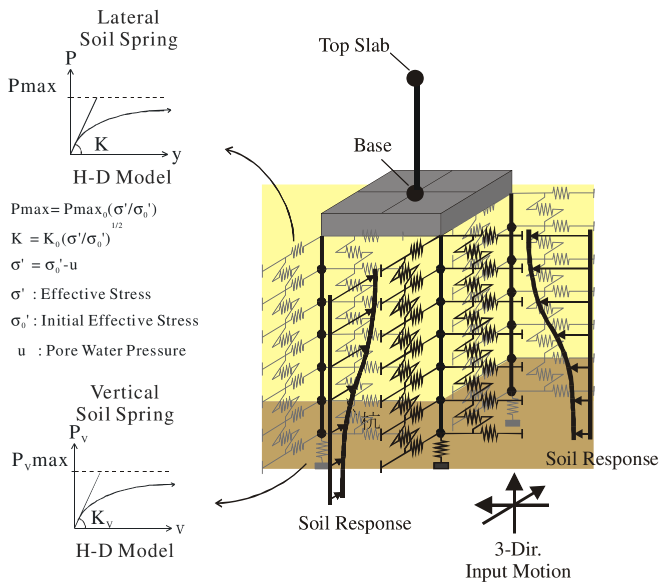

Fig. 4. Three-dimensional analysis model for soil-pile-structure system

Table 1: Soil Properties for simulation analysis

Soil type	Thickness (m)	Unit Weight (kN/m^3)	Vs (m/s)	Vp (m/s)
Sand (Test Bed)	3.0	18.9	80	1530
Clay	2.0	16.7	200	400
Mudstone	5.0	18.6	320	1240

Table 2: Nonlinear Parameters

Reclaimed Sand

Reference Strain : 0.034%

Maximum Damping Factor : 28%

Liquefaction Parameter

W1=1.15, S1=0.005, P1=0.5,

P2=1.12, C1=1.6,

Phase Transformation Angle=28deg.

Clay and Mud Stone

Reference Strain : 0.17%

Maximum Damping Factor : 25%

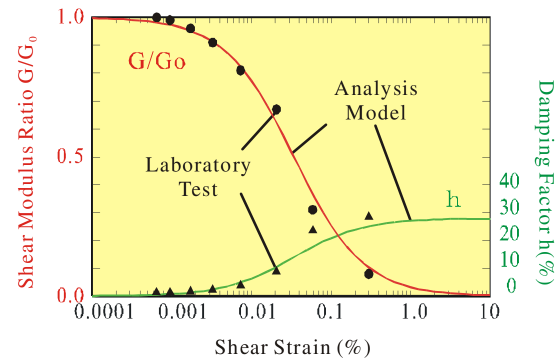

Fig. 5. Nonlinear properties of reclaimed sand

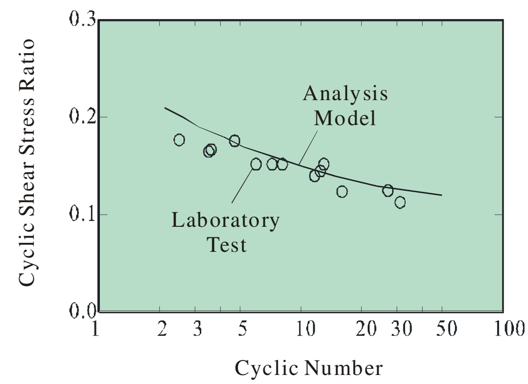

Fig. 6. Liquefaction curve

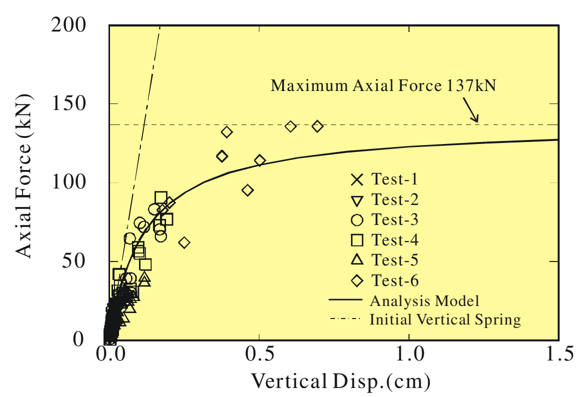

Fig. 7. Relationship between vertical displacements and axial forces at pile head

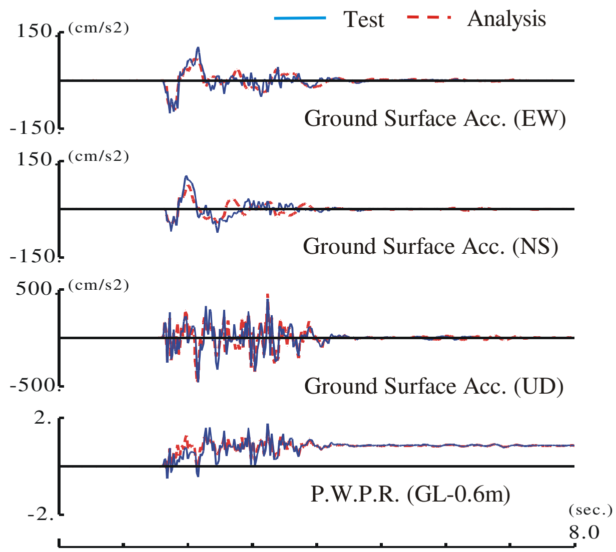

Fig. 8. Comparisons of time-histories of ground surface accelerations and excess pore water pressure ratios at GL-0.6m for Test-3

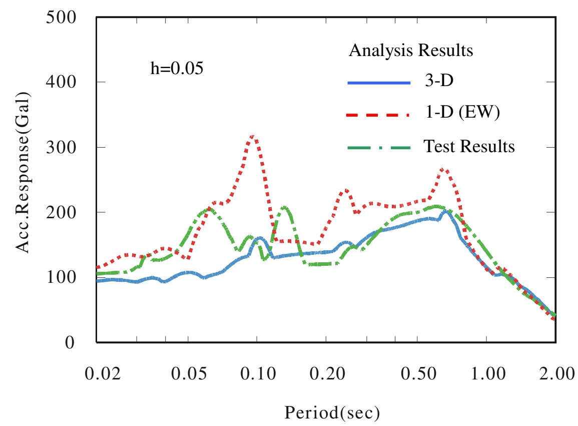

Fig. 10. Comparisons of acceleration response spectrum of ground surface in EW direction

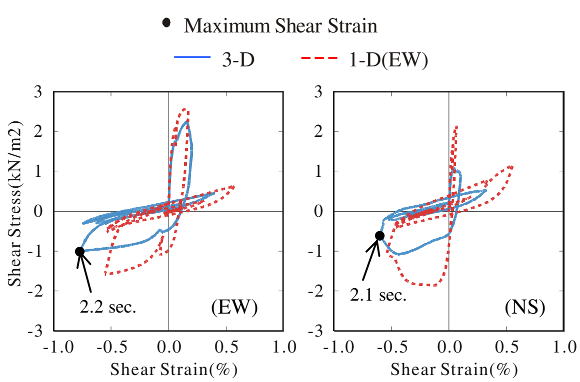

Fig. 9. Relationship between shear stress and shear strain at GL-1.5m in sand bed

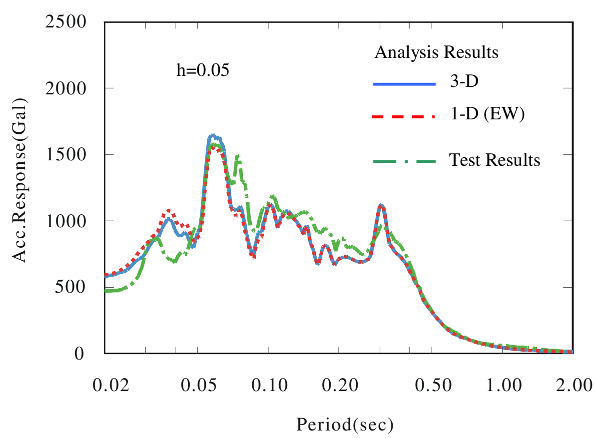

Fig. 11. Comparisons of acceleration response spectrum of ground surface in UD direction

Dynamic Responses for Test Structure

Figure 12 compares the calculated time-histories of acceleration for the test structure with the test results. The horizontal motions for the top slab of the test structure have almost the same amplitudes in the EW and NS directions, and are different from the records for ground surface shown in Figure 8. However, the vertical motion for the base mat of the test structure is almost the same as that for the ground surface shown in Figure 8. The analysis results are in good agreement with the test results not only in the horizontal directions but also in the vertical direction.

Figure 13 shows the displacement orbit in the EW and NS directions for the top slab and the ground surface. The horizontal motions of the ground surface had an almost circular orbit. On the other hand, the top slab had an elliptical orbit and amplitudes for the EW direction became larger than those for the NS direction due to the different vibration property of the test structure. The analysis results are in good agreement with the test results, and it is confirmed that this analysis method is applicable to evaluate the 3-D responses of pile-supported structures in liquefied sand deposits.

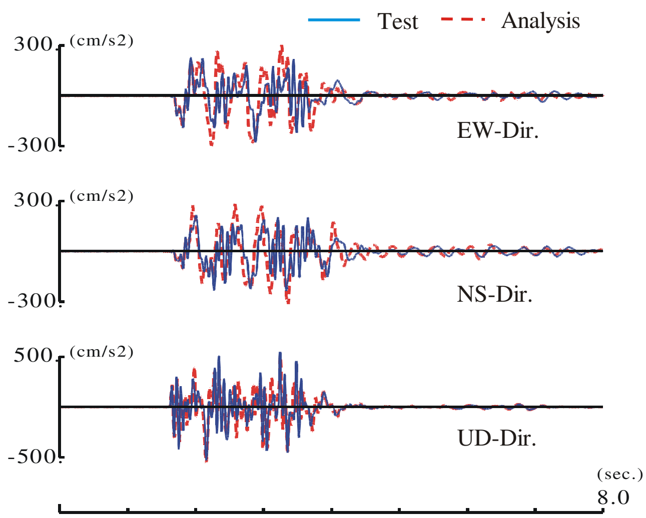

Fig. 12. Comparisons of calculated time-histories of accelerations for top slab

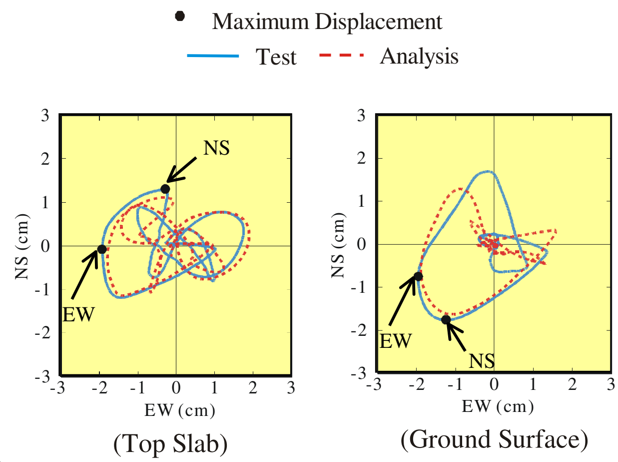

Fig. 13. Relationship between displacements in EW and NS directions of top slab and ground surface

Bending Moments and Axial Forces for Pile Foundation

The distributions of maximum pile stresses, bending moments and axial forces, are shown in Figure 14. Bending moments became larger at the pile head as well as at the interface between the reclaimed sand and the supporting layer. The calculated maximum bending moments at pile heads are almost the same in

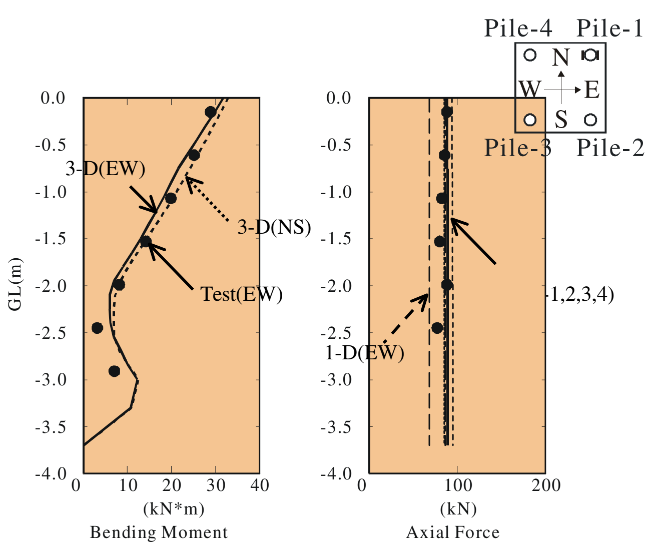

Fig. 14. Comparisons of the maximum bending moments and the maximum axial forces by the location in pile arrangement

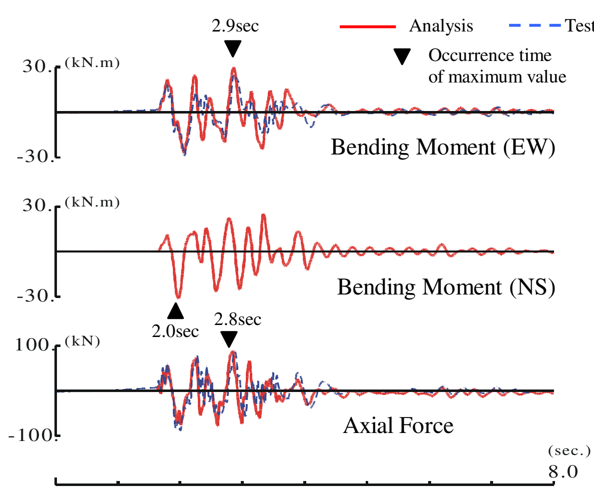

Fig. 15. Comparisons of calculated time-histories of bending moments and axial force at pile head of Pile-1
(Axial force : compression(+), tensile(-))

the EW and NS directions, since the maximum acceleration of the superstructure were almost the same in both directions, as shown in Figure 12. The calculated maximum axial forces in the four piles are almost the same and about 90kN. The 1-D analysis result became smaller than the 3-D analysis results.

The time histories of the pile stresses at pile heads are shown in Figure 15. The analysis results are in good agreement with the test results, which indicates that this analysis method is applicable to evaluate pile stresses during liquefaction. The maximum bending moments occurred at 2.9 seconds in the EW direction and at 2.0 seconds in the NS direction. These times correspond closely with the superstructure responses, as shown in Figure 12. The time history of axial force at the pile head is similar with that of the bending moment in the EW direction, and it is different with that of the superstructure response in the UD direction shown in Figure 12.

Figure 16 shows the relationship between the bending moments and axial forces at the pile head for the Pile-1 and Pile-4. At the occurrence time of bending moments in EW direction, the time of 2.9 seconds, compression force (74kN) arose in Pile-1, and tensile force (37kN) was caused in Pile-4. The tilts of the loop became inversely in Pile-1 and Pile-4, it means that axial forces mainly caused by rotational displacement of super-structure and the effects by the vertical motion of the super-structure was small. An area of the loop by 1-D analyses became smaller than that of the loop by 3-D analyses. It suggests that a great care is needed in applying the 1-D analyses to evaluate pile stresses on seismic design.

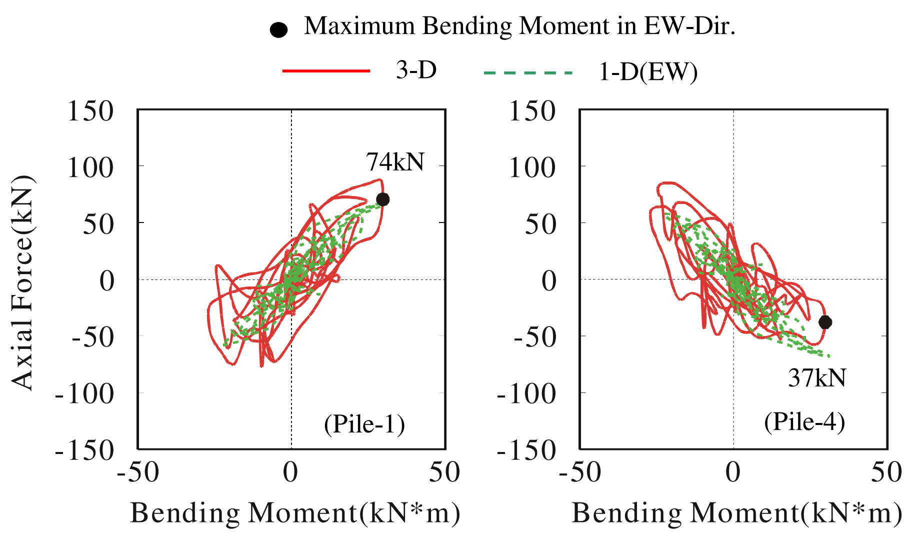

Fig. 16. Relationship between bending moments and axial forces at pile head of Pile-1 and Pile-4 (Axial force : compression(+), tensile(-))

CONCLUSIONS

(1) 3-D responses of a pile-supported structure in liquefied sand deposits have been obtained from vibration tests using ground motions induced by large-scale blasts. Simulation analysis results were in good agreement with the test results for the responses of the superstructure and pile stresses due to liquefaction.

(2) The maximum 1-D shear stresses and acceleration response spectrum in the horizontal direction were higher than the 3-D results. This shows that the 1-D analysis under-estimated the soil nonlinearity due to liquefaction.
(3) The horizontal motions for the top slab of the test structure were very different from those at the ground surface due to liquefaction. However, the vertical motion for the base of the test structure was almost the same as that for ground surface regardless of the liquefaction
(4) The pile bending moments became larger at the pile head and at the interface between the reclaimed sand and the supported layer. The bending moments at the pile head were greatly affected by the 3-D responses of the superstructure and the maximum bending moments occurred at almost the same time as the maximum acceleration of the superstructure.
(5) The pile axial forces varied greatly with the location in the pile arrangement, because they were caused by the rotational displacement of the superstructure, and because the effects of the vertical motion of the structure were small. For the bending moments and axial forces at the pile head, the area of the loop by 1-D analyses became smaller than that by 3-D analyses. This suggests that a great care needs to be taken in applying the 1-D analysis to evaluate pile stresses for seismic design.

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