17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

SEISMIC RESPONSE EVALUATION OF A PILE FOUNDATION STRUCTURE SUPPORTED BY INCLINED BEDROCK BASED ON CENTRIFUGE MODEL TESTS

M. Shoji[(1)], H. Kojima[(2)], T. Fujimori[(3)]

[(1)] *Research Engineer, Obayashi Corporation, shoji.michito@obayashi.co.jp*
[(2)] *Research Engineer, Obayashi Corporation, kojima.hiroaki@obayashi.co.jp*
[(3)] *Senior Engineer, Obayashi Corporation, fujimori.takeshi@obayashi.co.jp*
…

Abstract

Centrifuge model tests and analytical studies by 3-dimensional finite element method were conducted to evaluate the seismic response of a structure with piles of different lengths supported by inclined bedrock.

In the centrifuge model tests, it was confirmed that the ground amplification characteristics differed depending on the thickness of surface soil layer, and then the torsional response of the structure occurred. In addition, the distributions of bending moment of pile and the pile stresses under earthquakes differed depending on the pile length, and the piles were also subjected to seismic load in the orthogonal direction.

In the analytical studies by 3-dimensional finite element method, it was shown that the proper modeling of the piles and the setting of the soil properties considering the confining pressures were important to fully simulate the nonlinear structure-soil-interaction response under earthquakes. For the pile modellings, it was necessary to consider the volume of the piles in addition to the stiffness and weight of the piles. For the soil properties, it was necessary to set up the distributions of shear wave velocity measured under the confining pressures same as the tests and the numerical model representing the dynamic deformation characteristics obtained by the laboratory tests.

The series of tests and analyses were conducted under the limited condition concerning structures, pile foundations and soil. However, the major findings on seismic design obtained are summarized as follows: i) When short piles and long piles are used in combination, the short piles are greater subjected to the horizontal force than the long piles, and the toughness of the whole pile foundation becomes lower. Therefore, it is important to consider the distribution of seismic load between the piles. ii) Under earthquakes, a torsional response of structure occurs by the eccentricity and the torsional response center moves around between the side of short piles and the side of long piles. Therefore, it is important to pay attention to the pile stresses in the orthogonal direction of seismic load in addition to the pile stresses in the direction of seismic load.

Keywords: Inclined Bedrock; Pile Foundation; Seismic Response; Centrifuge Model Test; Finite Element Method

1. Introduction

Where the bedrock is inclined, the pile-foundation structure is constructed using piles of different lengths. The characteristics of the ground amplification differs depending on the thickness of surface soil layer, and then the torsional response of the structure occurs (Watanabe 2011, Shoji 2019). The torsional rsponse of the structure have been studied by seismic observation, static and dynamic analyses (Tobita 2017, 2019, Yamada 2000, Seki 2003), but there are few experimental studies.

Therefore, in order to evaluate the seismic response of the pile-foundation structure where the bedrock is inclined, centrifuge model tests and analytical studies by the 3-dimensional finite element method are conducted.

2. Centrifuge model test

2.1 Test outline

Shaking table tests were conducted in a 50G centrifugal field using a reduce model of a pile-foundation structure. Table 1 shows the test properties and Fig. 1 shows the test equipment. The model was composed of a superstructure, a foundation slab, piles and a ground. The properties of the superstructure were determined assuming a six-story apartment building. The superstructure was made of steel and its bottom was bolted to the foundation slab. The foundation slab was made of steel and was arranged where the long side of the slab was parallel to the inclined direction of the bedrock. The properties of the pile were determined assuming its bending stiffness equivalent to that of a PHC pile (type A) which diameter was 800 mm. The piles were made of stainless and those lengths were corresponded to the depth of the inclined bedrock. The pile heads were bolted to the foundation slab and those tips were embedded in the bedrock.

The ground was composed of a surface soil and a bedrock. The inclined angle of the bedrock was determined assuming the size of the rigid soil tank. The angle was one of the largest in comparison with the real case described in the AIJ publication (2015). The surface soil was made of dry silica sand No. 6 and its relative density was 60%. The bedrock was made of soil mortar which mixing the sand and cement.

The input wave was based on an earthquake motion in notification which had a random phase. The earthquake motion is adapted to the acceleration response spectrum of the extremely rarely occurred motion on the engineering bedrock defined in the notification of the Ministry of Construction. 20% of the motion was input at the reparability limit (L1), and 100% at the safety limit (L2). Furthermore, in order to confirm the change of the vibration characteristics of the model, the white noise was input before and after the above-described input.

Table 1 – Test properties (50G centrifugal field)

Superstructure	Form	I-shaped section
	Eigen value	1.73 Hz measured on base-fixed condition
Pile	Number of piles	8
	Length	4, 7, 10, 13 m
	Diameter	Equivalent to PHC pile 800ϕ (type A)
Surface soil	Vs	210 m/s on average in the depth direction
	Unit weight	15.6 kN/m^3

Bedrock	Vs	545 m/s
	Unit weight	17.9 kN/m^3
	Inclined angle	27 degrees
Shaking menu	Input wave	Earthquake motion in notification (random phase)
	Input direction	Orthogonal to inclined direction (NS)
	Input level	Reparability limit (Ll, acceleration at bedrock=80 cm/s^2) Safety limit (L2, acceleration at bedrock=400 cm/s^2)

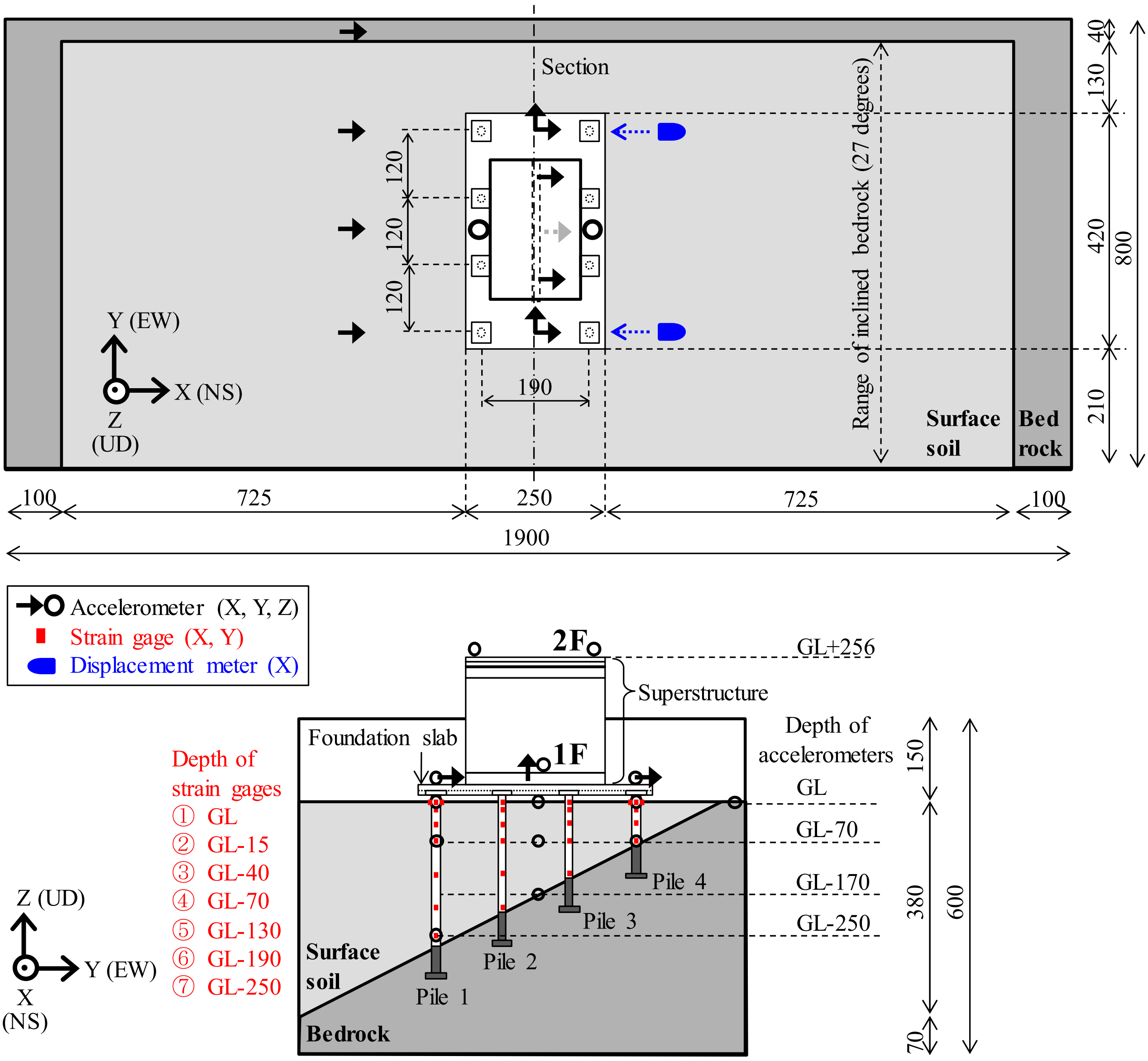


Fig. 1 – Test equipment (unit: mm, 1G centrifugal field)

2.2 Response of ground

Fig. 2 shows the acceleration waveforms of the ground surface at the reparability limit (L1) and the safety limit (L2). In the figure, the waveform at Pile 4 where the surface soil layer was thin overlay the waveform at Pile 1 where the layer was thick. As shown in the figure, the waveform at Pile 1 is larger.

Next, Fig. 3 shows the fourier spectra of the acceleration. In the figure, the spectra at Pile 1, the center of the foundation slab (between Pile 2 and Pile 3), Pile 4 and the bedrock are shown. As shown in the figure, ground amplification can be confirmed in 5-6Hz at L1, and in 3-6Hz at L2.

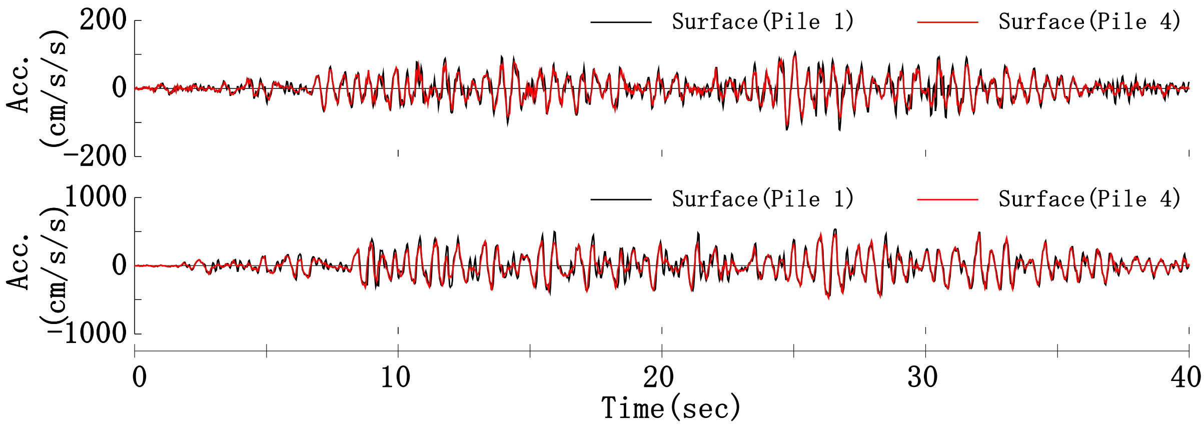


Fig. 2 – Acceleration waveforms of ground surface (upper: L1, lower: L2)

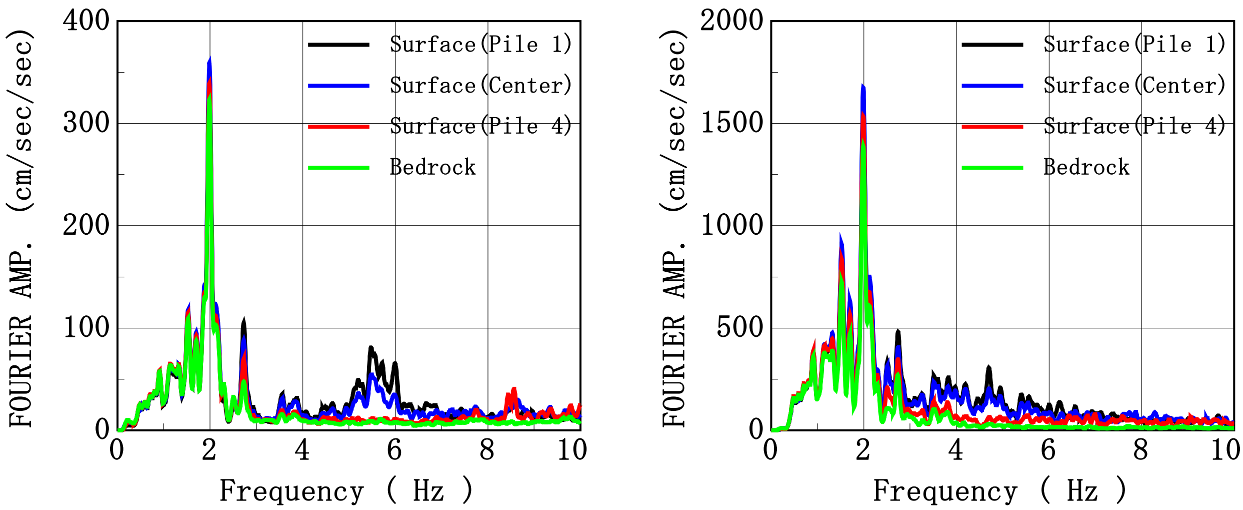


Fig. 3 – Fourier spectra of acceleration of ground surface and bedrock (left: L1, right: L2)

2.3 Response of structure

Fig. 4 shows the acceleration waveforms of the structure-2F at the reparability limit (L1) and the safety limit (L2). In the figure, the waveform at Pile 4 where the surface soil layer was thin overlay the waveform at Pile 1 where the layer was thick. Similar to the response of the ground described in section 2.2, the waveform at Pile 1 is larger. Fig. 5 shows the fourier spectra of the acceleration of the structure-2F. Some peaks can be confirmed in 1Hz, 2Hz and 5.5Hz at L1 and L2 respectively.

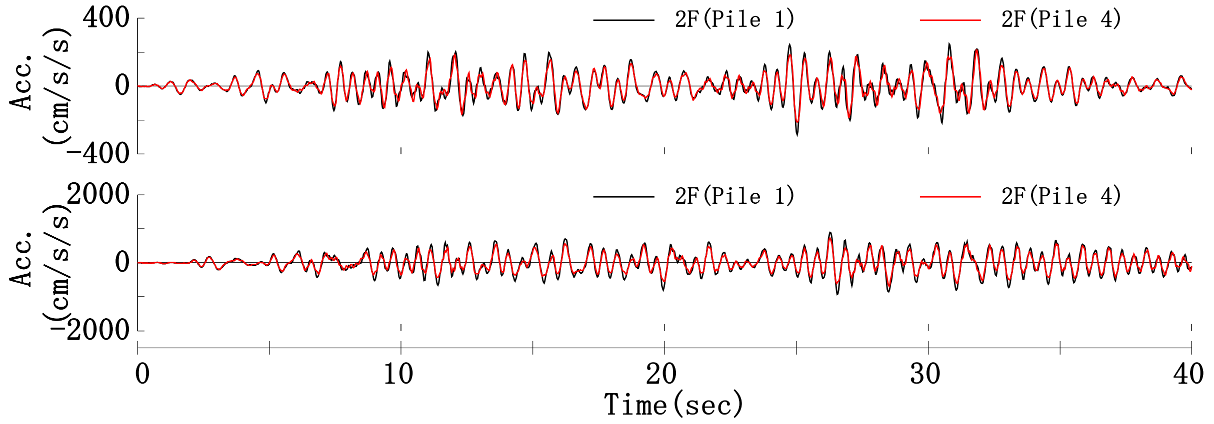


Fig. 4 – Acceleration waveforms of structure-2F (upper: L1, lower: L2)

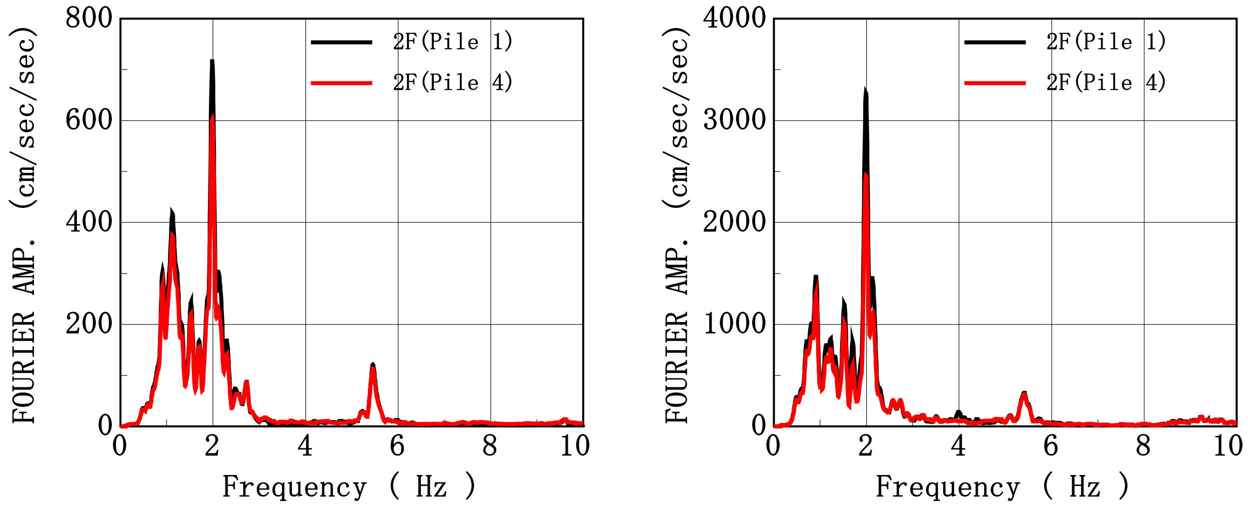


Fig. 5 – Fourier spectra of acceleration of structure-2F (left: L1, right: L2)

Next, by the method shown in Fig. 6, the translation and torsion of the structure are calculated using the acceleration of the structure-2F and 1F. As shown in the figure, the response in 1~2Hz is due to the translation. The response in 5.5Hz is due to the torsion and is considered to have been caused by the ground amplification described above.

Fig. 8 shows the ratio of the translation of the structure-2F to the response of the ground surface (2F/GL), the translation of the structure-1F (2F/1F), and the translation of the structure-1F with the deformation due to rocking (2F/(1F+Hθ)). At the reparability limit (L1), the peak of the response 2F/(1F+Hθ) is in 1.7Hz which indicate the elastic deformation of the structure, and the peak period (inverse of the frequency) becomes slightly longer considering the rocking response (see 2F/1F). Furthermore, considering the sway response, the peak period becomes longer to 1.1Hz due to the soil-structure interaction. The same tendency is observed at the safety limit (L2). These results indicate that the peak in 2Hz observed in the response of the ground and the structure is not due to the characteristics of the ground and the structure, but to the characteristics of the input wave and the shaking table.

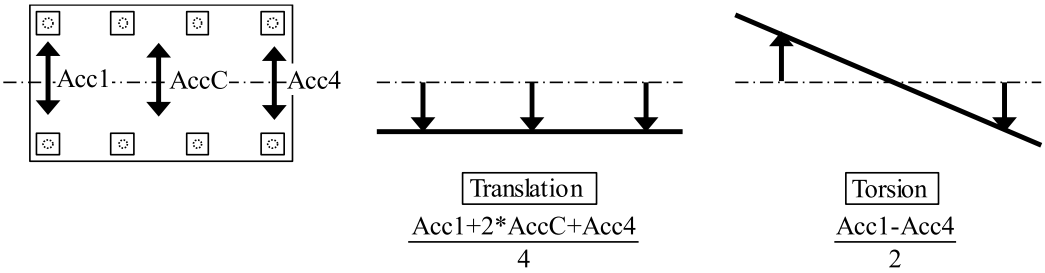


Fig. 6 – Calculation method of translation and torsion of structure

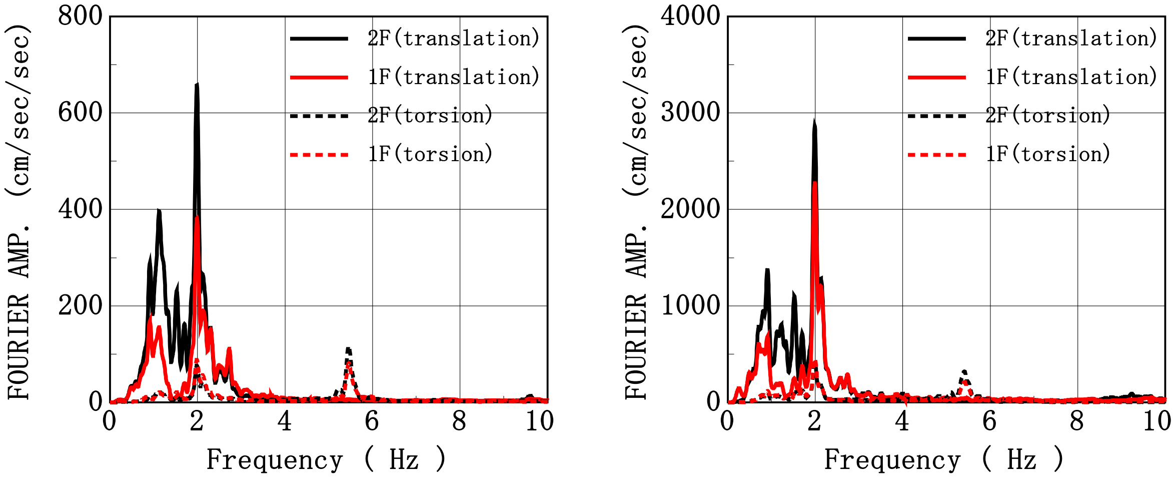


Fig. 7 – Fourier spectra of translation and torsion of structure (left: L1, right: L2)

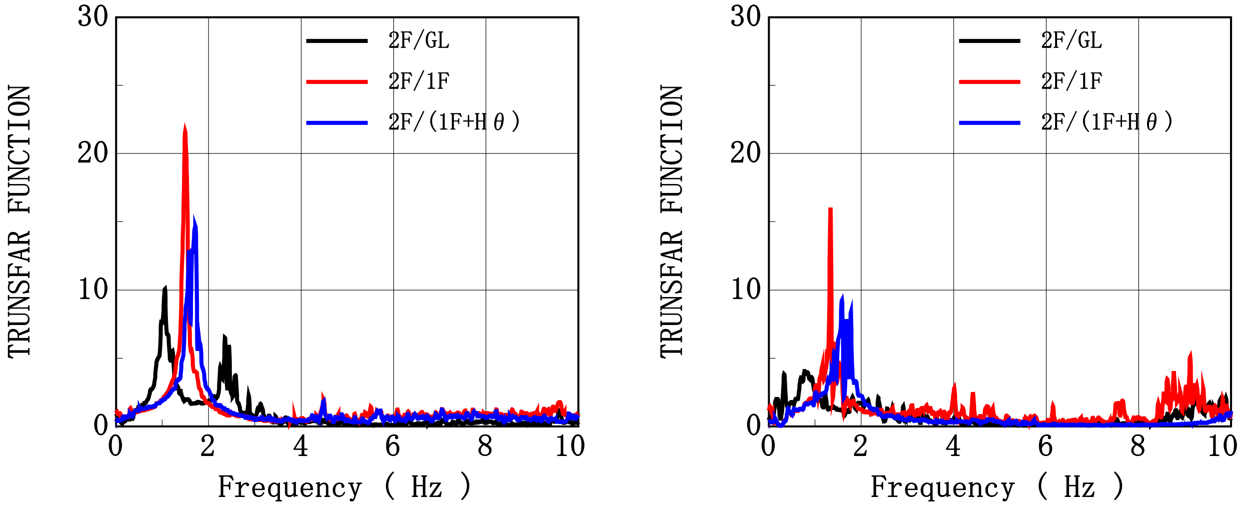


Fig. 8 – Transfar function of translation of structure (left: L1, right: L2)

2.4 Pile stresses

Fig. 9 shows the distributions of the maximum bending moment of pile at the reparability limit (L1) and the safety limit (L2). Pile 1 is the longest pile where the surface soil layer was thick. Pile 4 is the shortest pile where the surface soil layer was thin. In the figure, the moment in the parallel direction (NS) and the orthogonal direction (EW) to the shaking direction are shown.

As shown in Fig. 9, Pile 1, 2, and 3 have large moment at the pile head and the middle part of the pile in the parallel direction, which indicates the distribution of so-called 'long pile'. Pile 4 has large moment at the pile head and the pile tip respectively, which indicates the linear distribution peculiar to so-called 'short pile'. The moment at the pile head in the orthogonal direction is small at L1, but at L2, the moment becomes larger to about half of the moment in the parallel direction.

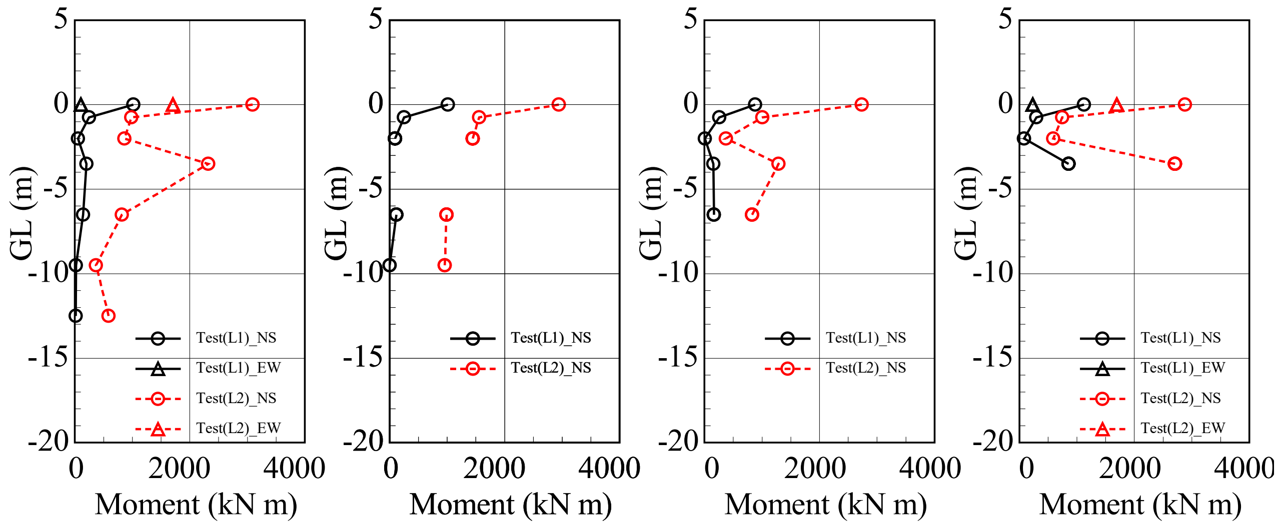


Fig. 9 – Distributions of maximum bending moment of pile (L1, L2)

3. Numerical analyses

3.1 Analyses outline

Fig. 10 shows the outline of the analytical model using the 3-dimentional finite element method. The superstructure and the foundation slab were modeled with linear solid elements. The piles were modeled with beam elements, which had the bending moment-curvature curve shown in Fig. 11. The tri-linear curve was determined along the bending test result of the pile. In order to consider the effect of the pile volume, the ground around the pile was withdrawn in an octagon shape of the same diameter as the pile diameter. The pile and ground were jointed with rigid elements each horizontal section.

The ground composed of the surface soil and the bedrock was modeled with solid elements. The shear stiffness of the surface soil was set to correspond to the stiffness under micro strain in the dynamic deformation tests of sand and differed depending on the constraint pressure in the depth direction. As shown in Fig. 12, using general hyperbolic equation model (GHE model, Murono 1999), the strain-dependent characteristics of the surface soil were determined along the results of the dynamic deformation tests. The shear stiffness of the bedrock was determined using the deformation modulus E_{50} obtained from the uniaxial compression tests of the soil mortar which was the secant modulus at half the compressive strength.

As for the boundary conditions, the side and the bottom of the ground were fixed according to the centrifuge model tests using the rigid soil tank. The superstructure, foundation slab and piles had a Rayleigh damping of 2% at 1Hz and 10Hz. The acceleration waveforms on the bedrock obtained from the centrifuge model tests were used as the input wave of the analyses.

17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

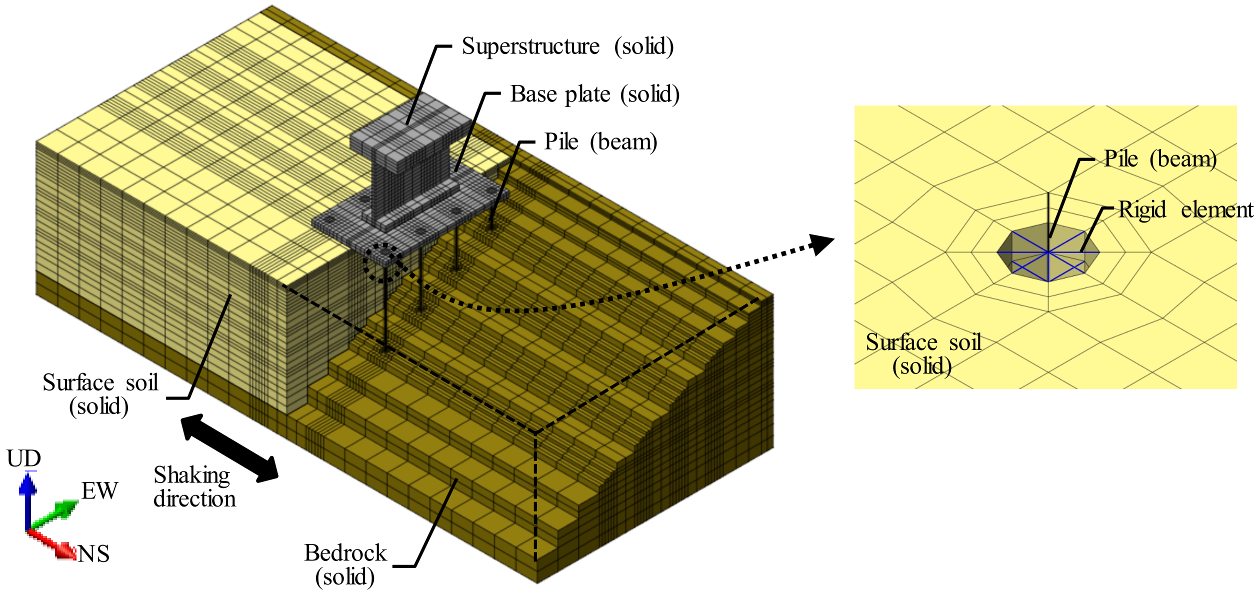


Fig. 10 – 3-dimentional finite element model

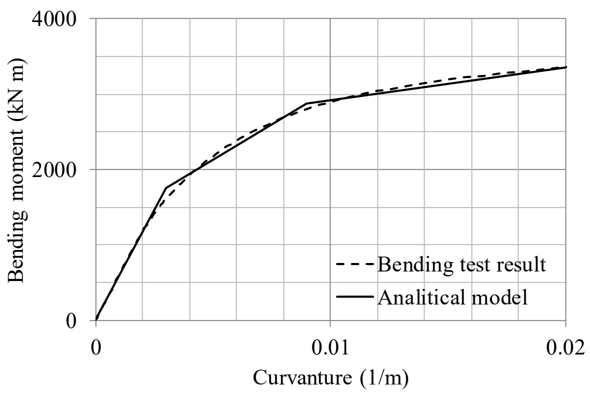


Fig. 11 – M-ϕ curve of pile

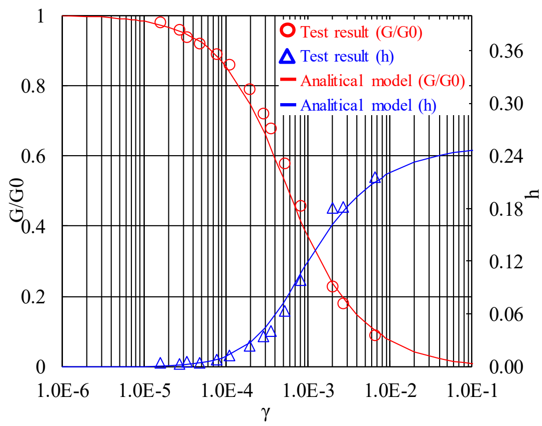


Fig. 12 – Dynamic deformation properties of surface soil

3.2 Response of ground and structure

Fig. 13 shows the acceleration waveforms of the ground surface and the structure-2F at Pile 1 where the surface soil layer is thick. In the figure, the waveform obtained from the analysis overlay the waveform obtained from the test. As shown in Fig. 13, the analytical results correspond well to the test results.

Next, Fig. 14 shows the fourier spectra of the acceleration. For the ground surface, both the magnitude of the amplitude and the frequency range of the amplitude increasing obtained from the analysis generally correspond to the test result. For the structure, the peak in 5~6 Hz due to the torsion is slightly different between the analysis and the test, but the response in 1~2Hz due to the translation obtained from the analysis generally correspond to the test result.

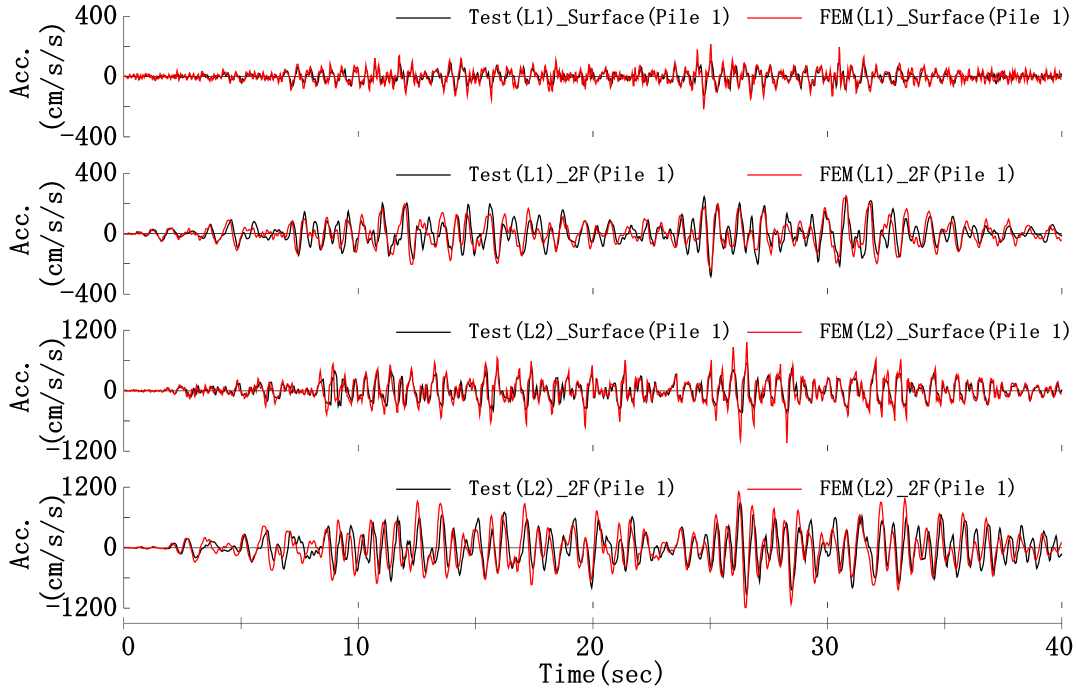


Fig. 13 – Acceleration waveforms of ground surface and structure-2F (Test vs. FEM)

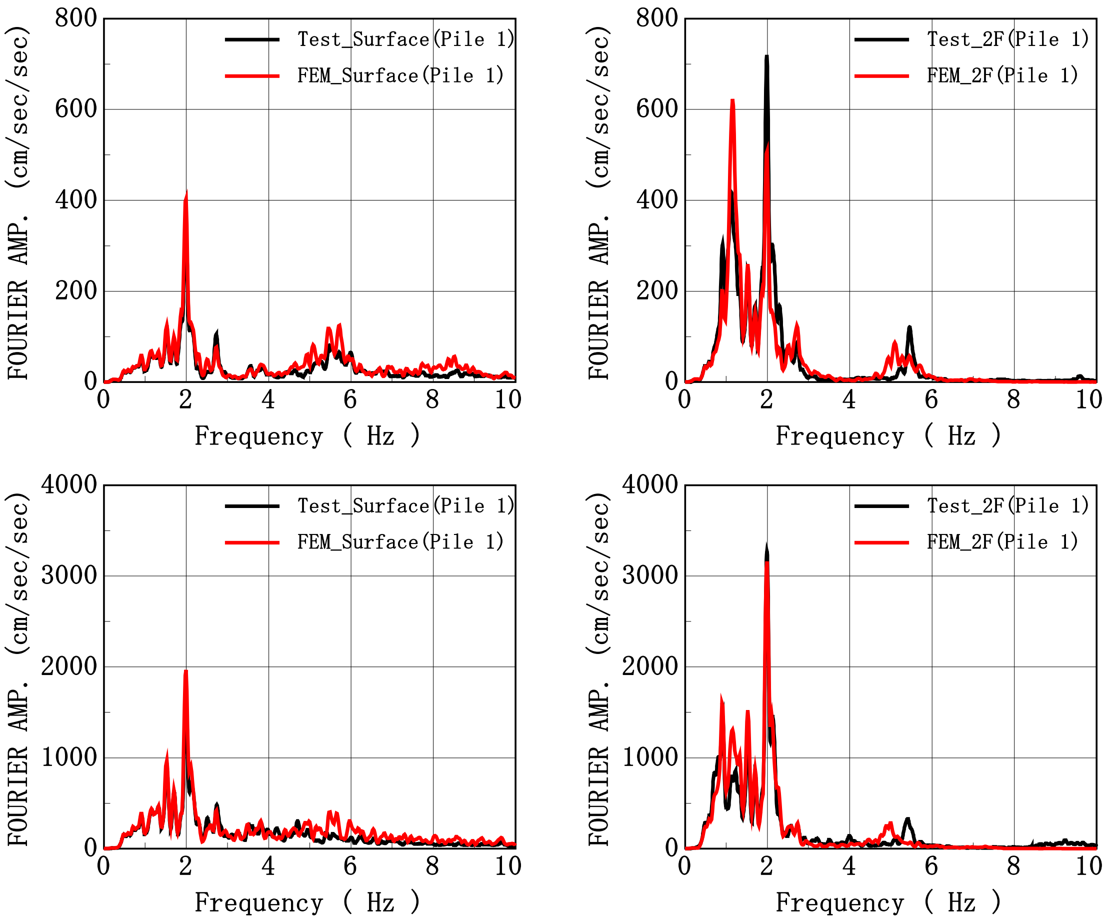


Fig. 14 – Fourier spectra of ground surface and structure-2F (Test vs. FEM, upper: L1, lower: L2)

3.3 Pile stresses and torsional response of structure

Fig. 15 shows the distributions of the maximum bending moment of pile obtained from the analyses. In the figure, the moment in the parallel direction (NS) and the orthogonal direction (EW) to the shaking direction are shown. The moment in the parallel direction of the analysis is larger than that of the test in the middle part of the pile, but the shape of the distribution that increases rapidly near the pile head corresponds well to the test result. The moment at the pile head in the orthogonal direction of the analyses is smaller than that of the tests. This is probably because in the analyses, the peak due to the torsion is slightly different from that of the ground amplification. Furthermore, the analytical results indicate that as in the parallel direction, the moment in the orthogonal direction becomes larger both at the pile head and in the middle part of the pile.

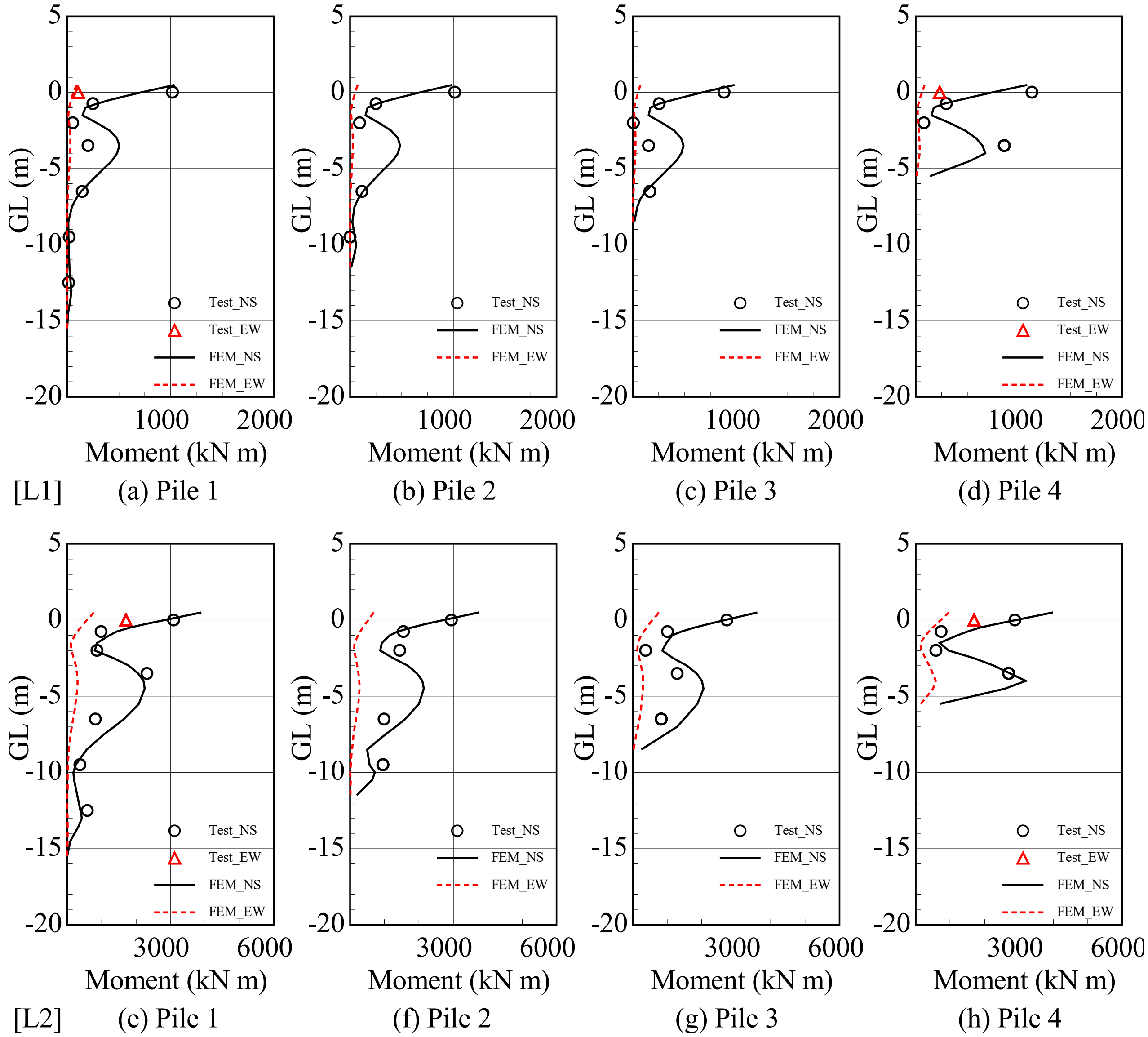
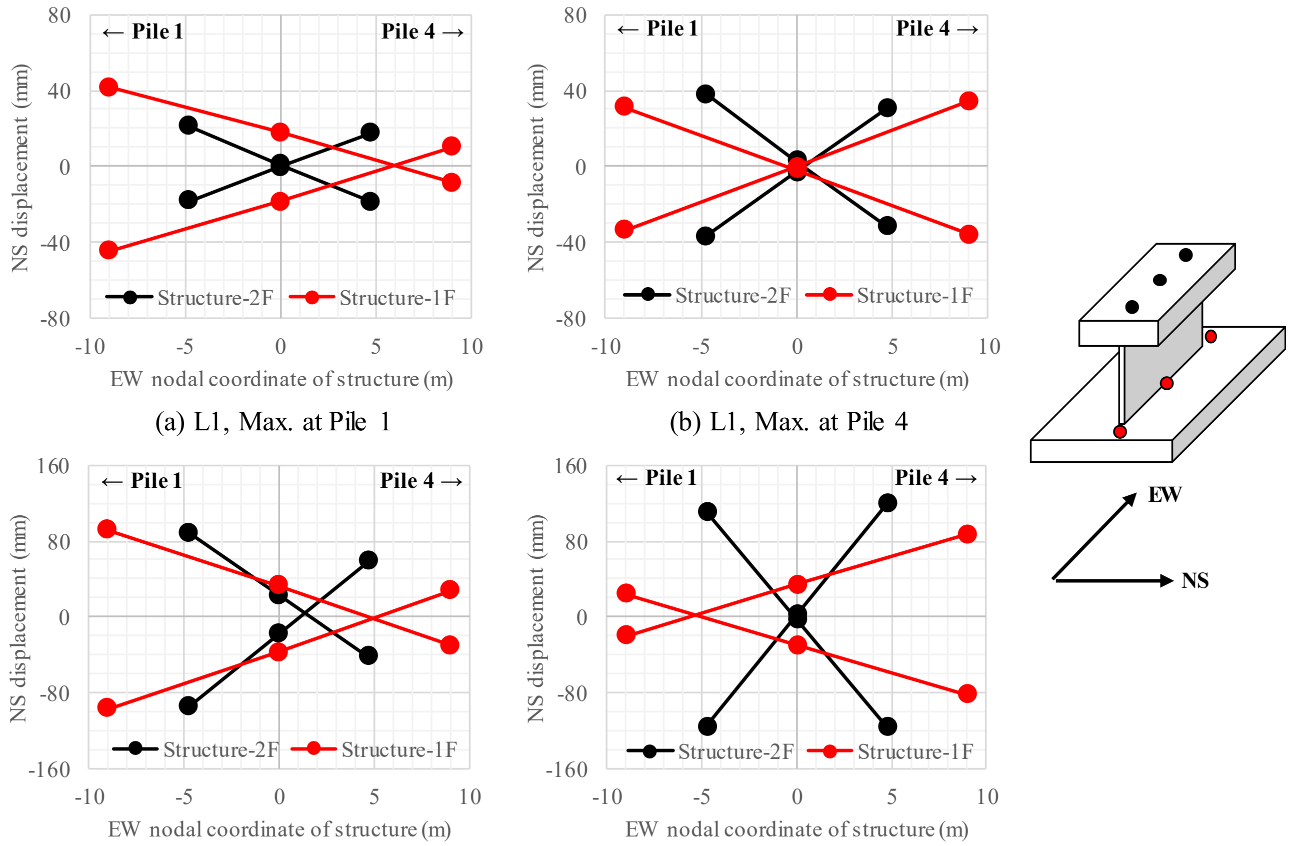


Fig. 15 – Distributions of maximum bending moment of pile (Test vs. FEM, upper: L1, lower: L2)

Next, we investigate the torsional response of the structure that caused the moment in the orthogonal direction to the piles. The displacements due to the torsion are extracted from the displacement waveforms in the parallel direction obtained from analyses. The displacements are calculated using band-pass filter (4~6 Hz) referring the response shown in Fig. 14. Fig. 16 shows the displacement of the three nodes per 1 floor including the center of the structure when the displacement at Pile 1 or at Pile 4 is the maximum. At the reparability limit (L1), the center of the torsional response of the structure-1F agrees with the center of the structure or is closer to the side of Pile 4 which has the center of rigidity. At the safety limit (L2), the torsional center moves back and forth between the side of Pile 1 and the side of Pile 4. The center of the torsion may deviate from the center of rigidity under a large earthquake, which requires attention in the seismic design.



(a) L1, Max. at Pile 1
(b) L1, Max. at Pile 4
(c) L2, Max. at Pile 1
(d) L2, Max. at Pile 4

Fig. 16 – Displacement due to torsional response of structure (NS, upper: L1, lower: L2)

4. Conclusion

Centrifuge model tests and analytical studies by 3-dimensional finite element method were conducted to evaluate the seismic response of a structure with piles of different lengths supported by inclined bedrock.

The series of tests and analyses were conducted under the limited condition concerning structures, pile foundations and soil. However, the major findings on seismic design obtained are summarized as follows: i) When short piles and long piles are used in combination, the short piles are greater subjected to the horizontal force than the long piles, and the toughness of the whole pile foundation becomes lower. Therefore, it is important to consider the distribution of seismic load between the piles. ii) Under earthquakes, a torsional response of structure occurs by the eccentricity and the center of the torsional response moves around between the side of short piles and the side of long piles. Therefore, it is important to pay attention to the pile stresses in the orthogonal direction of seismic load in addition to the pile stresses in the direction of seismic load.

5. Acknowledgements

This research was conducted as part of the promotional programs of sustainable building systems by Association for Sustainable Building Systems with the subsidy of Ministry of Land, Infrastructure, Transport and Tourism.

6. References

[1] Watanabe T, Iiba M, Kato K, Koshika N (2011): A fundamental study on effects of inclined engineering bedrock on amplification characteristics in surface layer. *The AIJ Journal of Technology and Design*, Vol.17, No.36, 455-459. (in Japanese)

[2] Shoji M, Fujimori T (2019): Evaluation of the input ground motion for a building located on an inclined bearing layer. *Report of Obayashi Corporation Technical Research Institute*, No.83. (in Japanese)

[3] Tobita Y, Nagano M, Kitamura H, Sato T, Suzuki K, Matsuda Y, Yamauchi T (2017): Study on torsional response of seismically isolated building on soil with inclined bedrock using strong motion records. *The AIJ Journal of Technology and Design*, Vol.23, No.54, 409-414. (in Japanese)

[4] Tobita Y, Nagano M, Kitamura H, Yamauchi T (2019): Seismic response analysis of seismically isolated building constructed on soil with inclined bedrock based on strong motion records and evaluation of pile stresses. *The AIJ Journal of Structural and Construction Engineering*, Vol.84, No.756, 149-159. (in Japanese)

[5] Yamada A, Miura K (2000): Nonlinear earthquake response of structure on composite foundation. *The AIJ Journal of Structural and Construction Engineering*, No.529, 113-119. (in Japanese)

[6] Seki T, Chatani F, Kazama S (2003): Lateral behaviour of composite foundation supported by dipping stratum part 2 lateral behaviour of composite foundation of a direction parallel to the slope, or the direction which intersects orthogonally with the slope. *The AIJ Summaries of Technical Papers of Annual Meeting*, B-1, 497-498. (in Japanese)

[7] Architectural Institute of Japan (2015): *Evaluation of foundation soil for design and construction of building foundations*. (in Japanese)

[8] Murono Y (1999): Study on the Seismic Design Method of Pile Foundations That Reflects the Non-linear Dynamic Interaction During Strong Ground Motions. *RTRI report*. (in Japanese)

