Dynamic Soil-structure Interaction of High-rise Building with Massive Foundation -Correlation Between Shear Forces of Building and Foundation-

K. Mitsuji
Yamagata Univeristy, Japan

K. Fujiwara
Suzuki Architectural Design Office, Japan

15 WCEE
LISBOA 2012

SUMMARY:
In this paper, in order to discuss correlation between shear forces of building and foundation, dynamic soil-structure interaction of pile-foundation high-rise building with massive foundation is studied. Numerical simulation is organized based on the Penzien type model that can consider soil-structure interaction of pile-foundation building. Eight types of building with different natural periods and two type of ground with different predominant periods. Numerical results show that shear forces at the lowest floor of building and foundation behave in-phase in case of TB<TG, and out-of-phase in case TB>TG, respectively. Cross correlation coefficients verify the results of time histories of shear forces of building and foundation. Results can be relevant to correlation coefficients of CQC method to superposition shear forces of building and foundation for practical structural design of pile foundation buildings.

Keywords: Soil-structure interaction, high-rise building, pile-foundation, cross correlation

1. INTRODUCTION

More and more high-rise buildings are being constructed in urban area. Pile foundations are generally adopted for those high-rise buildings on soft ground. Moreover, those high-rise buildings often have massive foundation such as basement to which pile foundations are connected. There have been a lot of discussions on the effect of foundation as countermeasure to strong shaking due to earthquake. However, the condition that foundation works effectively for total soil-structure system against earthquake is still being investigated. Therefore, it is important to estimate dynamic behaviour of super structure and foundation to design high-rise building on soft ground supported by pile foundations from the view point of dynamic soil-structure interaction.

Shear forces of building and foundation are superposed with weight coefficients related to seismic coefficients for practical structural design of soil-structure interaction system. Techniques to superpose shear forces of building and foundation have been proposed. The square root of the sum of squares method (SRSS) is mostly often applied to practical structural design. The effectiveness of adopting SRSS is discussing. In case of soil-structure interaction system, superposition technique is proposed according to combination of natural period of building and predominant period of ground. Assuming TB is natural period of building and TG is predominant period of ground, simple sum of shear forces of building and foundation is recommended for TB<TG, and SRSS is preferable for TB>TG in practical estimation of seismic stress in pile (Tokimatsu et al. 2005). However, simple sum technique may lead to the overestimate of synthesized stress of total system and SRSS may result in the underestimate in some specific cases according to combination of natural periods. For those cases, phase difference of shear forces of building and foundation in time history should be more paid attention.

In this paper, behaviours of shear forces of building and foundation are compared by numerical analysis of simple 1D soil-structure interaction model. Combination of natural period of building and predominant period of ground is discussed regarding phase difference in time history of those shear forces for structural design.

2. METHODOLOGY AND ANALYTICAL MODEL

As fundamental discussion of effective superposition, phase difference of shear forces of building and foundation is mainly investigated. Superposition concept regarding combination of natural period of building (TB) and predominant period of ground (TG) is illustrated in Figure 1. In case of TB>TG, subgrade reaction works against foundation. On the other hand, in case of TB<TG, subgrade reaction assists in phase with foundation.

Complete quadratic combination method (CQC) is proposed to superposition of shear forces of building and foundation. Figure 2 shows typical variation of correlation coefficient with different damping ratios. In CQC, procedure of SRSS is modified by use of correlation coefficient of Figure 2. Moreover, superposition technique that in the range of 0.65<TB/TG<1.5, simple sum technique is applied, in the range of TB/TG>1.5, weighted summation is recommended (Sugimura et al. 1997).

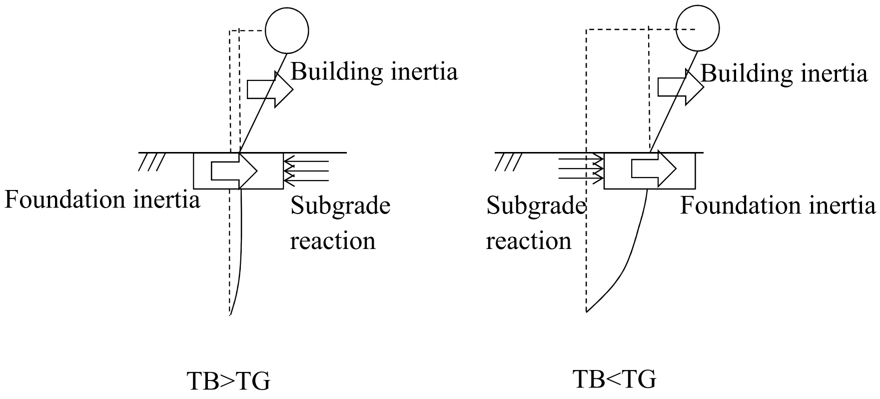

Figure 1. Superposition concept of building inertia and horizontal force acting on foundation

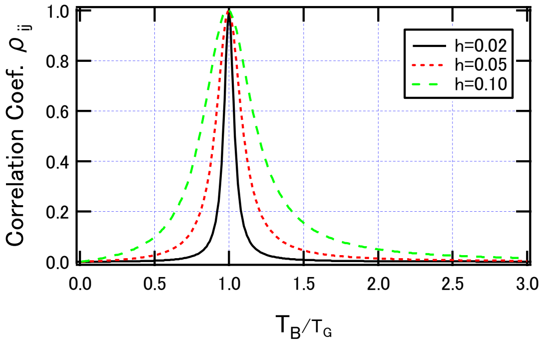

Figure 2. Example of correlation coefficients based on CQC (Wilson et al.1981)

Numerical analysis is carried out for the Penzien type model that can consider dynamic soil-structure interaction (Penzien 1964). Here, discussion on phase difference between shear forces of building and foundation is main objective. So, numerical analysis is focused on only linear case. Non-linear analysis is important, however, results of linear cases are expected to apply to non-linear cases. Schematic figure of numerical model of soil-structure interaction system and shear wave velocity of model ground are illustrated in Figure 3. Two different models of ground are prepared for numerical analysis. Predominant period of each ground is 0.56 for Case 1 and 0.96 for Case 2, respectively. Both ground models are assumed soft ground necessary adopting pile foundations to support superstructure. In Figure 4, schematic plan of model building is shown. Weight of each floor of building is assumed 12kN/m^2, and height of each floor is 3m. Shear stiffness of each floor is 3.23x10^{7}kN/m (X direction) and constant from the lowest floor to the highest floor. Building is assumed to be supported by 24 cast-in-place concrete piles with diameter of 1.6m. The length of pile is 30m reaching to base layer of ground. In order to express massive foundation, basement is assumed from GL-4m to ground surface. Numerical analysis is conducted for X direction in Figure 4. Eight kinds of building model are prepared according to natural period of building from 3F to 20F where low-rise building models are also prepared for comparison. The model having the longest natural period is assumed 20-storey building with base isolation at the foundation. Each natural period of building models is shown in Table 2.1. The ratios of natural period of building to predominant period of ground (TB/TG) are also shown for Case 1 and Case 2. Coloured cells mean the range of TB/TG<1. Building models of 8F and 15F have natural periods close to predominant period of ground for Case 1 and Case 2, respectively. That means those models are the cases of resonance of building mode and ground mode. Figure 5 shows Eigen modes of free ground and total system of soil-structure interaction for Case 1 and Case 2. Eigen mode shape of Case 1 and Case 2 are almost the same because predominant period of ground is the only different parameter. El Centro NS wave (1940) normalized by maximum acceleration 20cm/s^2 at the base layer is adopted as input motion. Maximum acceleration of ground response at the surface is 94 cm/s^2 for Case 1 and 69 cm/s^2 for Case 2, respectively.

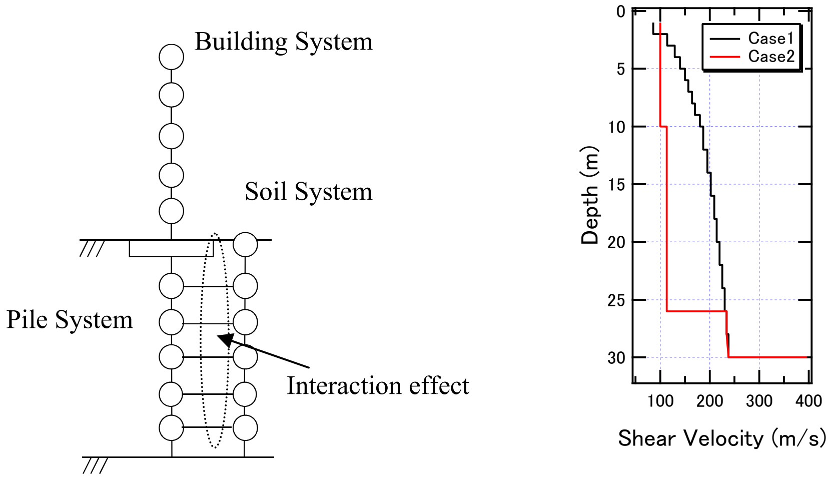

Figure 3. Numerical model of total structure and shear wave velocity profile of model ground

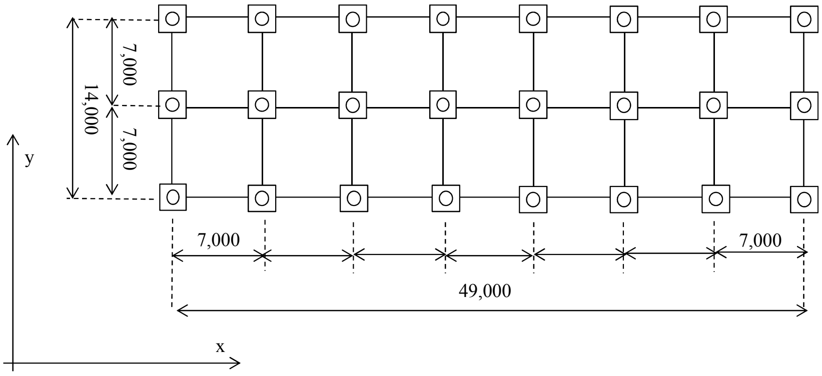

Figure 4. Schematic plan of model building

Table 2.1. Natural period of building model (TB) and its ratio to predominant period of ground (TB/TG)

	3F	5F	8F	10F	12F	15F	20F	20F B.I.
TB (s)	0.23	0.36	0.55	0.68	0.81	1.00	1.32	3.24
TB/TG (Case1)	0.41	0.64	0.98	1.21	1.44	1.79	2.36	5.79
TB/TG (Case2)	0.24	0.38	0.57	0.71	0.84	1.04	1.38	3.38

Case1: TG=0.56 (s), Case2: TG=0.96(s)
Coloured cells mean the cases of TB/TG<1

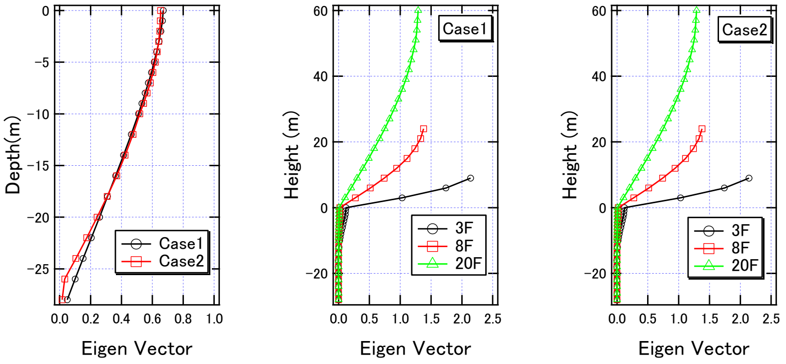

Figure 5. Eigen mode of numerical model

3. SHEAR FORCES OF FOUNDATION AND BUILDING

Results of shear forces of building and foundation in time histories are shown in Figure 6 for Case 1. Shear force of building means horizontal force calculated at the lowest floor of the building. In figures, "3F" means three-storey building for example of which natural period is shown in Table2.1.

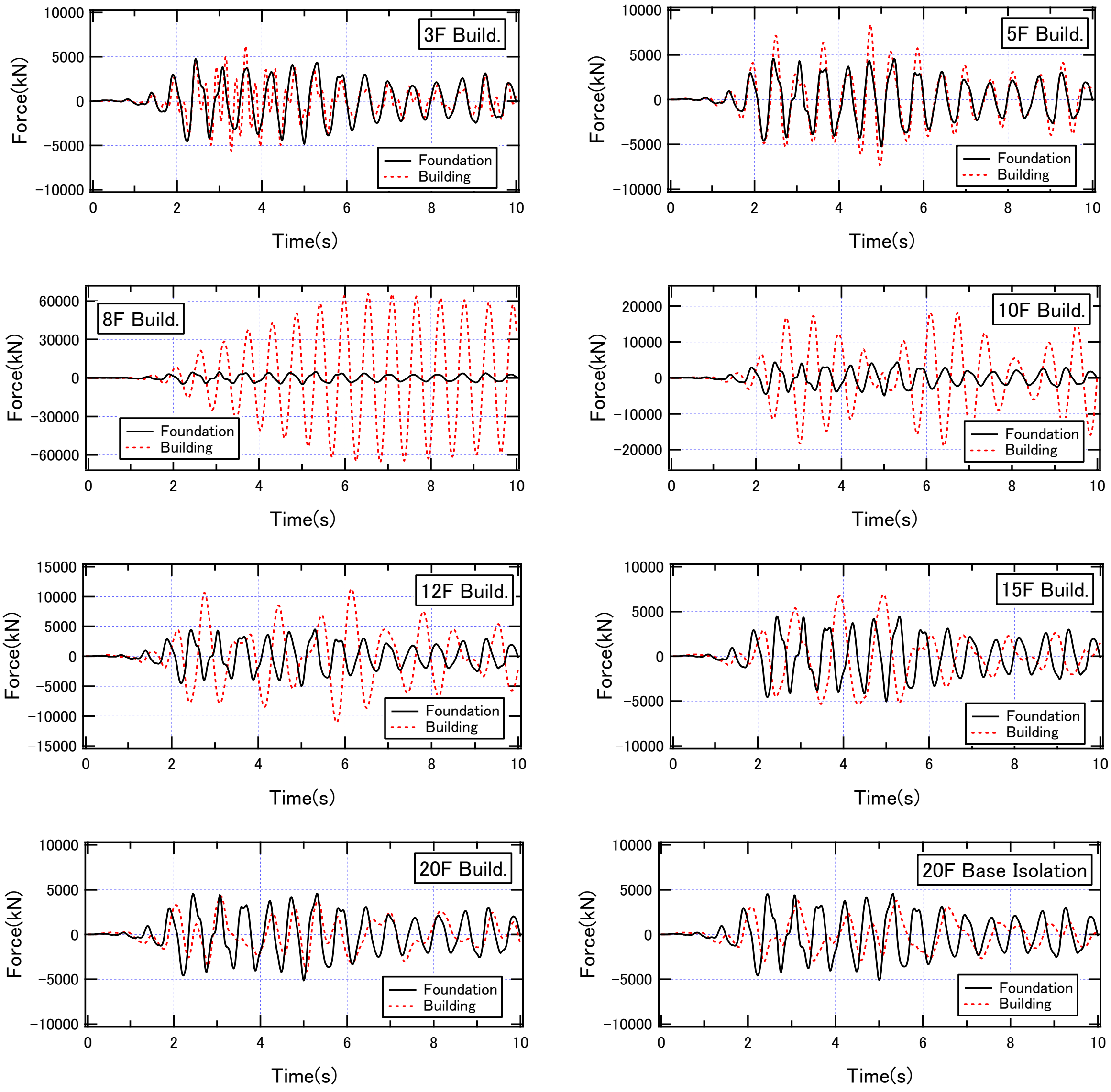

Figure 6. Shear forces of foundation and lowest floor of building (Case1)

In case of 3F and 5F, behaviour of shear forces of building and foundation indicate in-phase motion in time histories. Amplitudes of both forces are almost the same in 3F, but amplitude of building shear force is greater than foundation in 5F. The case of 8F indicates resonance of building and ground. Amplitude of building shear force is much greater than foundation because of resonance. Those two shear forces show lag time at times having each peaks. After the case of 10F, the ratios of periods, TB/TG are greater than 1. Direction of subgrade reaction to foundation is supposed to be opposite to cases of TB/TG >1. Amplitudes of building shear forces are also greater than foundation in 10F, 12F and 15F. It can be easily found out that phase of building shear forces in time histories are different from those of foundation. Especially, in case of 12F and 15F, phases of building shear forces indicate almost opposite to foundation. In case of 20F and 20F with base isolation, amplitudes of building shear forces still show lag time in phase to foundation, but compared to those of 12F and 15F, lag times are small and returns close to in-phase motion.

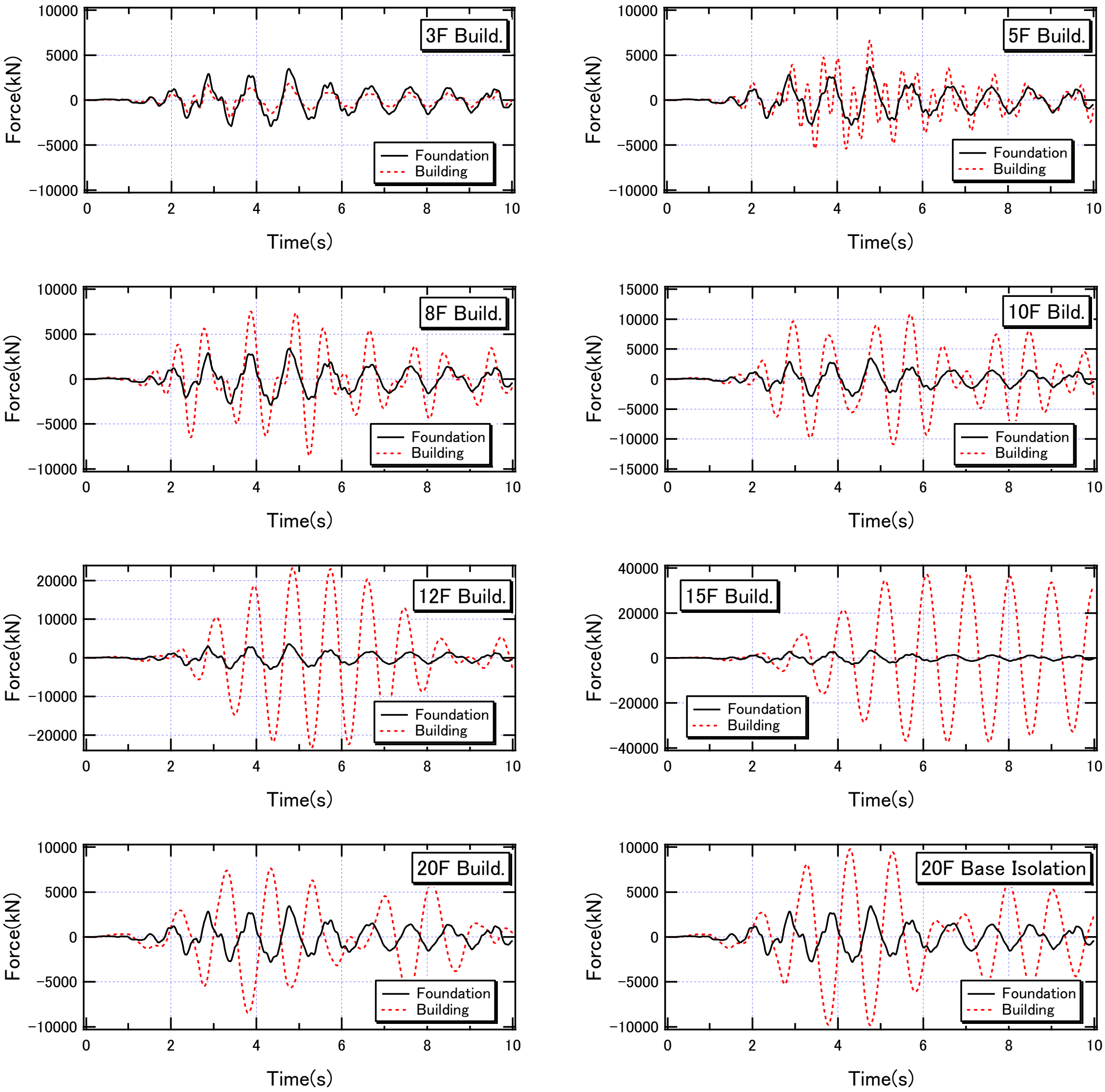

Figure 7. Shear forces of foundation and lowest floor of building (Case2)

Results of shear forces of building and foundation are shown in Figure 7 for Case 2. As well as Case 1, behaviours of shear forces of building and foundation indicate in-phase motion in case of 3F and 5F. It should be noted that short period component disappear in behaviour of 3F. In Case 2, predominant period of ground TG=0.96(s). It may be because TB is much smaller than TG (TB/TG is 0.24 in Table 2.1) and building behaves like a rigid body on ground. Results of 5F show the same tendency as Case

1. Namely, amplitude of building shear force is greater than foundation and motion in time history shows in-phase. In 8F and 10F, the ratios of periods TB/TG are less than 1.Amplitudes of building shear forces are greater than foundation and motions in time histories are in-phase as well as 5F. 15F is resonance model in Case 2. Result of 12F is close to that of resonance model of 15F. Amplitude of building shear force is much larger than foundation and motion in time history shows lag time. Results of 20F and 20F with base isolation show those amplitudes of building shear forces are greater than foundation and motions in time histories becomes out-of-phase, especially at times having peaks.

4. CROSS CORRELATION BETWEEN BUILDING AND FOUNDATION

Based on the results in the previous section, it can be pointed out that phase differences in time histories between shear forces of building and foundation may appear dependent on combination of natural periods of building and predominant periods of ground. Cross correlation coefficients are obtained to discuss behaviours of phase differences in time histories in each case. Cross correlation coefficients in time histories are shown up to 5(s) in Figure 8 for Case 1 and Figure 9 for Case 2, respectively.

Table 3.1 and Table 3.2 show cross correlation coefficients at specific lag times based on the results from Figure 8 and 9. Coloured cells mean the ranges of TB<TG. Results in the first rows are cross correlation coefficients without lag time (τ=0).

While cross correlation coefficients at τ=0 indicate “+” in case of TB<TG (3F, 5F and 8F) and 20F and 20F with base isolation, “-” in case of TB>TG (10F, 12F and 15F). Of course, positive sign of cross correlation coefficient means two shear forces are acting in the same direction. On the contrary, negative sign means they are opposite. Smaller and much larger TB/TG=1, correlation tends to increase. Building model of TB/TG>1 that is close to resonance state indicate poor correlation. Positive cross correlation coefficients basically appear in the range of TB/TG<1, but when TB/TG is much larger than 1, cross correlation coefficient tends to return positive again.

Table 3.1 and 3.2 show also cross correlation coefficients Cij(τ) of the first and second peak and their lag times τ. Resonance models don’t always indicate high correlation. It is interesting that time lags between each first and second peak are almost the same as predominant period of ground. Namely, time lag for Case 1 is about 0.5s, and that for Case 2 is about 1.0s.

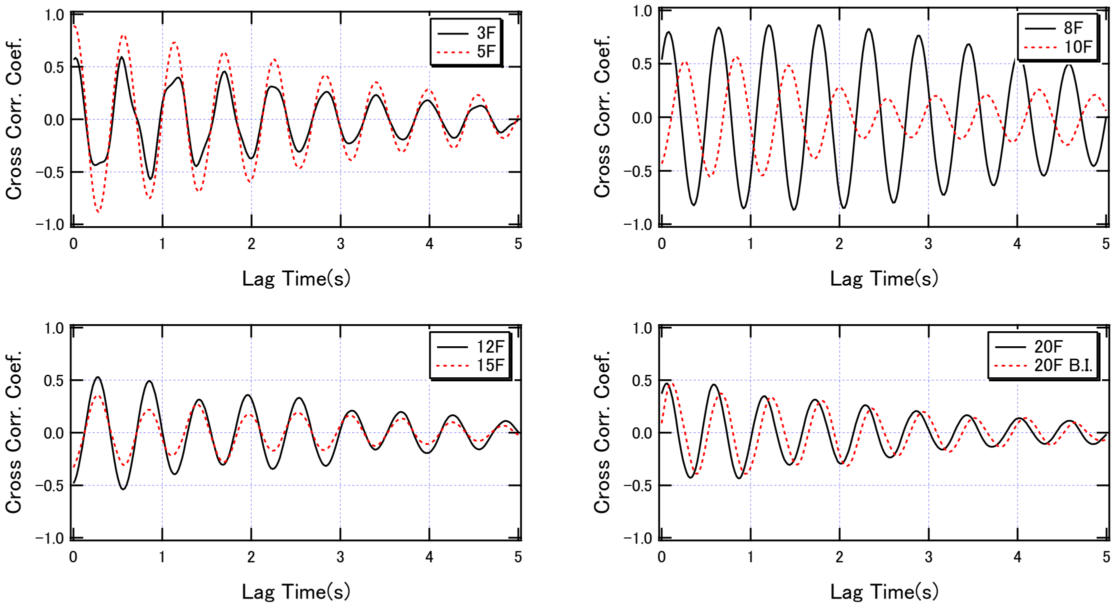

Figure 8. Cross correlation coefficient with lag time (Case1)

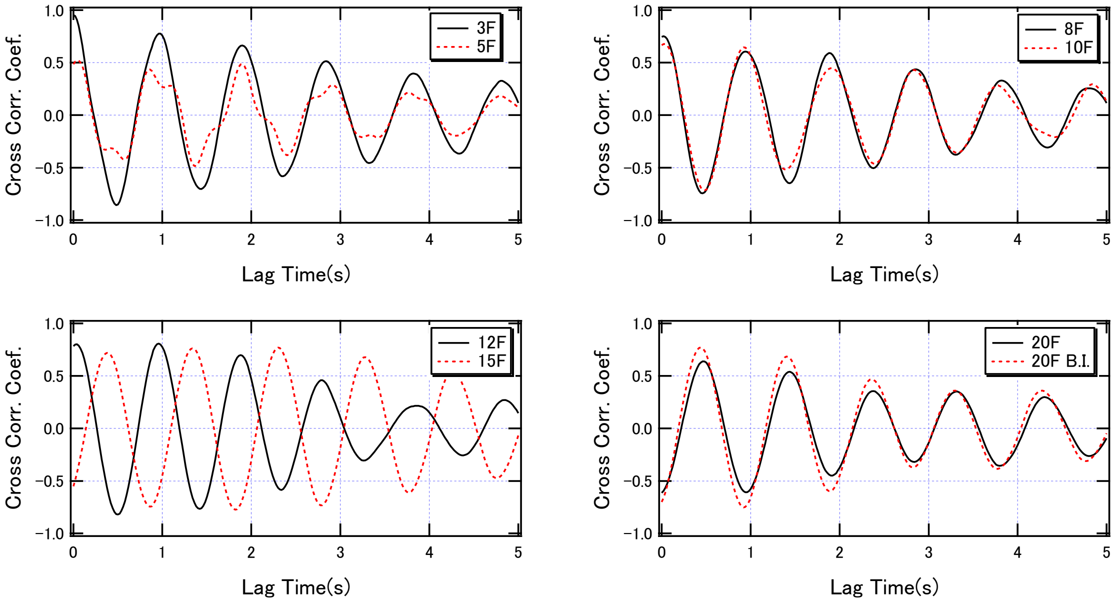

Figure 9. Cross correlation coefficient with lag time (Case2)

Table 3.1. Cross correlation coefficients (Case1)

		3F	5F	8F	10F	12F	15F	20F	20F B.I.
τ=0	Cij(0)	0.57	0.89	0.54	-0.43	-0.48	-0.33	0.37	0.09
1st	Cij(τ)	0.59	0.81	0.84	0.53	0.53	0.36	0.47	0.47
	τ(s)	0.54	0.56	0.64	0.26	0.28	0.28	0.06	0.10
2nd	Cij(τ)	0.40	0.73	0.86	0.57	0.49	0.22	0.46	0.37
	τ(s)	1.18	1.14	1.20	0.84	0.86	0.84	0.58	0.66

Table 3.2. Cross correlation coefficients (Case2)

		3F	5F	8F	10F	12F	15F	20F	20F B.I.
τ=0	Cij(0)	0.95	0.49	0.75	0.67	0.78	-0.55	-0.62	-0.70
1st	Cij(τ)	0.78	0.44	0.61	0.65	0.81	0.72	0.64	0.77
	τ(s)	0.96	0.86	0.94	0.92	0.96	0.38	0.46	0.44
2nd	Cij(τ)	0.66	0.49	0.59	0.45	0.70	0.76	0.54	0.68
	τ(s)	1.90	1.90	1.88	1.90	1.88	1.34	1.44	1.40

5. CONCLUSIONS

Correlation between shear forces of building and foundation of high-rise building with massive foundation is discussed based on the results from dynamic soil-structure interaction analysis.

In case of TB<TG, shear forces of building and foundation indicate in-phase motions in time histories. On the other hand, in case of TB>TG, both of shear forces tend to behave out-of-phase. However, when natural period of building is much longer than predominant period of ground, both of shear forces tend to behave in-phase again.
Cross correlation coefficients between shear forces of building and foundation verify the above results. In case of TB<TG, cross correlation coefficients at lag time τ=0 have positive sign. That means shear forces of building and foundation are acting in the same direction. On the contrary, in case of TB>TG, cross correlation coefficients at lag time τ=0 have negative sign. That means shear forces of building and foundation are acting in the opposite direction.

Lag times between peaks of cross correlation coefficients in time histories are corresponding to predominant period of ground.

While numerical analysis is focused on linear case here, physical interpretation will be able to apply to non-linear case. Numerical examples are also limited regarding building type, ground types and characteristics of input motion. Further investigation is expected.

REFERENCES

Tokimatsu, K., Suzuki, H. and Sato, M. (2005), Effects of inertial and kinematic interaction on seismic behavior of pile with embedded foundation, Soil Dynamics and Earthquake Engineering, **Vol. 25**, pp 753-762.

Sugimura, Y., Fujiwara, K., Ohgi, T. and Karkee, M. (1997), Seismic behaviour of piles supporting tall buildings and the consideration of ground response effects in design, Proc. 4th Conf. Tall Buildings in Seismic Regions, Los Angels Tall Buildings Structural Design Council and the Council on Tall Buildings and Urban Habitat, pp.303-317

Wilson E.L., Kiureghian, A.D. and Bayo, E.P. (1981), A replacement for the SRSS method in seismic analysis, Earthquake Engineering and Structural Dynamics, **Vol.9**, pp.187-194

Penzien, J., Scheffey, C.F. and Parmee, R.A. (1964), Seismic analysis of bridges long pile, J. of the Eng. Mech. Div., Proc. of ASCE, **Vol.90**, **No. EM 3**, pp.223-254.