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DEPENDANSE OF STORIES, TYPES OF FOUNDATION AND SOIL CONDITIONS ON SSI EFFECTS OF HIGH-RISE RC BUILDINGS

T. Mitsuda[(1)], X. Wang[(2)], M. Nagano[(3)]

[(1)] *Graduate student, Tokyo University of Science, 7115128@alumni.tus.ac.jp*
[(2)] *Assistant Professor, Tokyo University of Science, wangxin@rs.tus.ac.jp*
[(3)] *Professor, Tokyo University of Science, nagano-m@rs.tus.ac.jp*

Abstract

In recent decades, many high-rise RC buildings have been constructed on the soft soil including coastal area of Tokyo and Osaka Bay in Japan. Seismic response and dynamic characteristics of these buildings are different from those based on the fixed-base models due to swaying and rocking responses of foundations, i.e., the well-known soil-structure interaction (SSI). Although we can use sway-rocking (SR) models to incorporate the SSI effects into the earthquake response analyses of high-rise RC buildings, evaluation of dynamic impedance functions requires large computational efforts with complex calculations with many parameters. Therefore, rough estimation of the SSI effects for various types of combination of the building foundation and soil conditions will be helpful in the structural design with a small amount of labor.

This study investigates the SSI effects for various types of combination of the buildings, foundations and soil conditions. First, we collect the documentation on the structural design of the 52 high-rise RC buildings over 60 m height including foundations and soil conditions to determine parameters of soil models to calculate dynamic impedance functions by axisymmetric finite element method. Then we constructed the generic SR model, in which superstructures were modeled using the generic bending-shear multi-degree-of-freedom (GBSM) model proposed in previous studies (Murata et al., 2018) based on the averaged structural property of the 78 vibration analysis models.

As the result of eigenvalue analysis, the generic SR models with 20 to 50 stories showed that the natural period with the SSI effects became longer for smaller foundation, shallower embedding depth, deeper depth of engineering bedrock. Natural periods of the generic SR models are 3 to 13% longer than those of the fixed-base models, when level of the earthquake motion is small. Effect of the SSI increases as the story number becomes larger. The swaying ratio decreased with the increase of story number while rocking rate increased in proportion to the story number. The rocking rate is approximately 4 to 20% which is about 10 times larger than the swaying rate. The SSI effects for high- rise RC buildings is mostly dominated by the rocking rate. Next, we compared the analyzed results using generic SR models and vibration analysis models of the 4 existing high-rise RC buildings in Tokyo metropolitan area. Their structural models are referred from the documentation on the structural design and dynamic impedance functions are evaluated using soil models in their sites. It is found that the SSI effects of the 4 existing high-rise RC buildings can be roughly estimated by those from the generic SR models.

Keywords: soil-structure interaction, high-rise RC building, finite element method, eigenvalue analysis

1. Introduction

In recent decades, many high-rise residential buildings have been constructed on the soft soil including coastal area of Tokyo and Osaka Bay in Japan. It is well-known that the seismic response of buildings on the soft soil differ from those with fixed bases due to the soil-structure interaction (SSI). Furthermore, the SSI depends on the number of stories, soil conditions, and sizes of foundations [1, 2]. Similarly, for high-rise RC buildings, it is necessary to predict the earthquake response and investigate the influence of these factors to SSI. Although we can use sway-rocking (SR) models to incorporate the SSI effects into the earthquake response analyses of high-rise RC buildings, evaluation of dynamic impedance functions requires large computational efforts with complex calculations with many parameters. Therefore, rough estimation of the SSI effects for various types of combination of the building foundation and soil conditions will be helpful in the structural design with a small amount of labor.

In this study, using the generic bending-shear multi-degree-of-freedom model with sway-rocking spring (hereafter generic SR model), the dynamic characteristics including the effects of the SSI on structural response were examined. The SR model used in this study was constructed by attaching the sway and rocking springs at the bottom of the foundation of the generic bending-shear multi-degree-of-freedom (GBSM) model, which was proposed based on the statistic of design parameters of existing RC buildings [3]. Based on the result of the eigenvalue analysis, the influence of the number of stories, soil conditions, and sizes of foundations on the natural period, swaying and rocking displacement at top have been discussed.

2. Construction of analysis model

2.1 Data base of foundations and soil conditions

To investigate the SSI effects of high-rise RC buildings using realistic data, first we compiled the buildings' information related with the SSI from documents used in the structural design of the 52 existing high-rise RC buildings. Buildings scoped in this study are high-rise RC buildings over 60 m height constructed in Japan. Most of them are located in the highly urbanized area, e.g., Kanto, Kansai, and Chukyo, in Fig.1. All of them are supported by pile foundations on bearing strata. Some of them are constructed on soft ground in the coastal area, which could be influenced by the SSI effect.

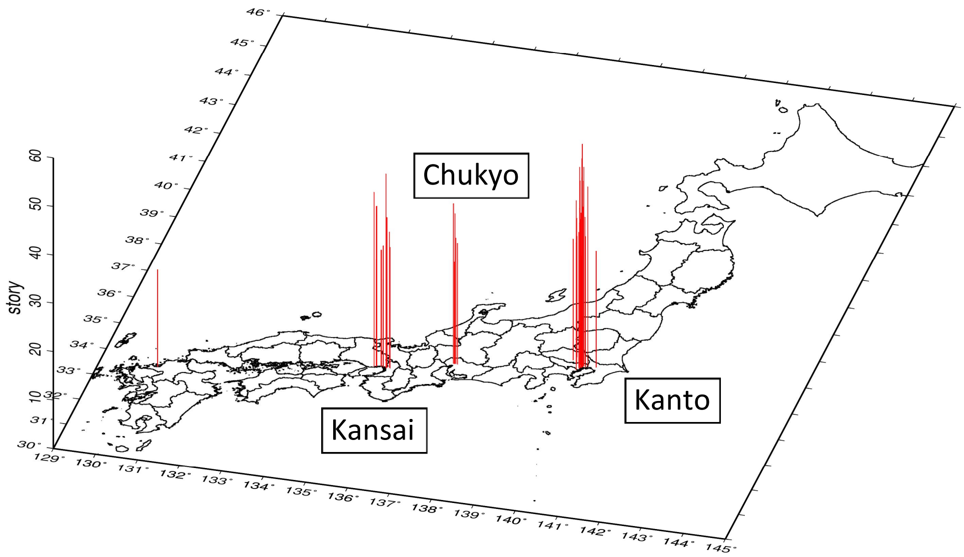


Fig.1 – Location of the 52 existing high-rise RC buildings in Japan

We aggregated data of planar widths and embedding depths of foundations, pile tip depth, the surface depth of engineering bedrock, and the average shear-wave velocity of soil over the engineering bedrock, shear-wave velocity of engineering bedrock. The X- and Y-direction widths of foundation were defined as the length of long and short span, respectively. The average shear-wave velocity of the surface strata was derived from total traveling time and thickness based on the quarter wavelength rule.

Compiled results are plotted in Fig.2 for (a) the relation between embedding depth of foundation and pile tip depth, (b) the widths of foundation in X- and Y-directions, (c) the relation between the depth of engineering bedrock and average shear-wave velocity of soil on the engineering bedrock, and (d) the relation between the average shear-wave velocity and shear-wave velocity of engineering bedrock. The medians of those data are also drawn with broken lines.

To roughly estimate the SSI effects for various types of combination of the building foundation and soil conditions, we set parameters for width of foundation, embedding depth, and bedrock depth, in Tables 1 and 2 for the SSI analysis, based on medians of above data. Total number of calculation cases are 27 as combination of three parameters. We assume square shape of building with width of 30 m and pile span of 6 m. Diameter of pile is 2 m. Shear-wave velocity of surface layers on the engineering bedrock in Table 3 is set as 150, 250, 350 m/s so that average value is 222 m/s.

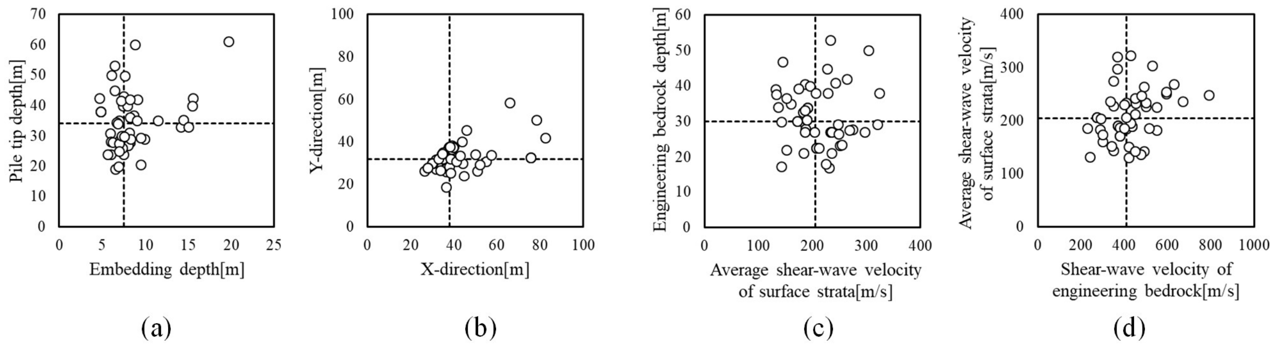


Fig.2 – Compiled results of soil and foundation information of existing RC buildings. (a) Relation between the pile tip depth and embedding depth, (b) Distribution of the widths of foundation, (c) Relation between the depth of engineering bedrock and average shear-wave velocity of surface strata, (d) Relation between the average shear-wave velocity of surface atrata and shear-wave velocity of eingineering bedrock.

Table 1 – Parameters of foundation

Case	Width of foundation [m]	Length of pile [m]	Embedding depth [m]	Shape of foundation	Span of pile [m]	Diameter of pile [m]
1	30, 36, 42	18	6	square	6	2
2		33	8			
3		48	10			

Table 2 – Parameters of thickness of soil

Case	Average shear-wave velocity of surface strata [m/s]	Thickness of each layer surface strata [m]	Depth of the engineering bedrock [m]	Shear-wave velocity of the engineering bedrock [m/s]
1	222	5	15	400
2		10	30	
3		15	45	

Table 3 – Soil profile

	Shear-wave velocity [m/s]	Density [t/m^3]	Poisson's ratio	Damping constant
1st layer	150	1.70	0.45	0.05
2nd layer	250	1.70	0.45	0.03
3rd layer	350	1.80	0.45	0.02
Engineering bedrock	400	1.90	0.40	0.01

2.2 Evaluation of dynamic soil springs

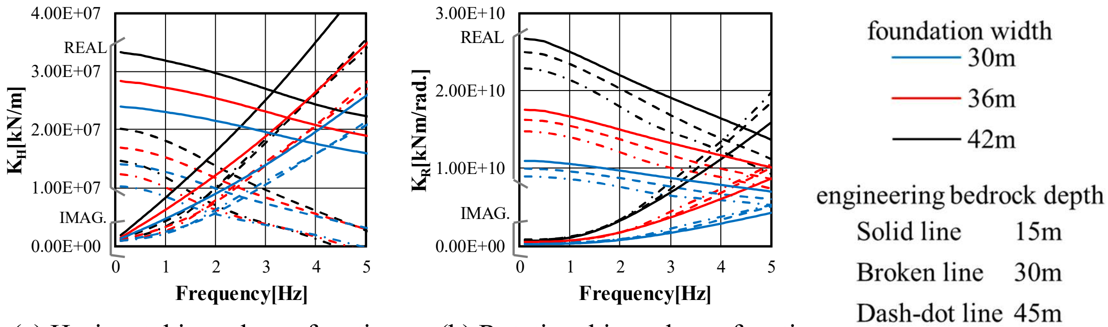
Based on the soil conditions and sizes of foundations, totally 27 dynamic soil springs were evaluated. Considering computational efficiency, the axisymmetric finite elements method (FEM) were employed as frequency domain analyses. Cylindrical embedded foundations were assumed for square or rectangular foundations, the radius r of which was determined from the equivalent area. Ring pile elements were used to model pile groups [4]. The energy transmitting boundary for side region and the viscous boundary for the bottom region are used to express half-space of soil. The impedance functions in the case where the embedding depth is 6 m are presented in Fig.3. Wider the foundation, shallower the engineering bedrock becomes, the real part of impedance functions taken as soil springs becomes larger. In addition, the influence of the depth of engineering bedrock is more dominant than the foundation width to the sway spring, and opposite influence to the rocking spring. Impedance functions are realized into constant soil springs, i.e., stiffness and damping coefficients, to be used in the SR models including the superstructure. The soil stiffness is taken as a value of the real part at 0.1 Hz, which is almost corresponds to static frequency, and the damping coefficients are taken as the smallest tangential value of imaginary part. The constant soil springs in Fig.4 increases in both stiffness and damping in proportion to the embedding depth.

2.3 Construction of the generic SR model

For the superstructure of the generic SR model, the GBSM model proposed in Murata et al. [3] is used. The GBSM model was constructed to reproduce the average seismic response characteristics of the existing high-rise RC buildings, and can easily estimate the eigenvalues and seismic response of the buildings simply by specifying the number of stories.

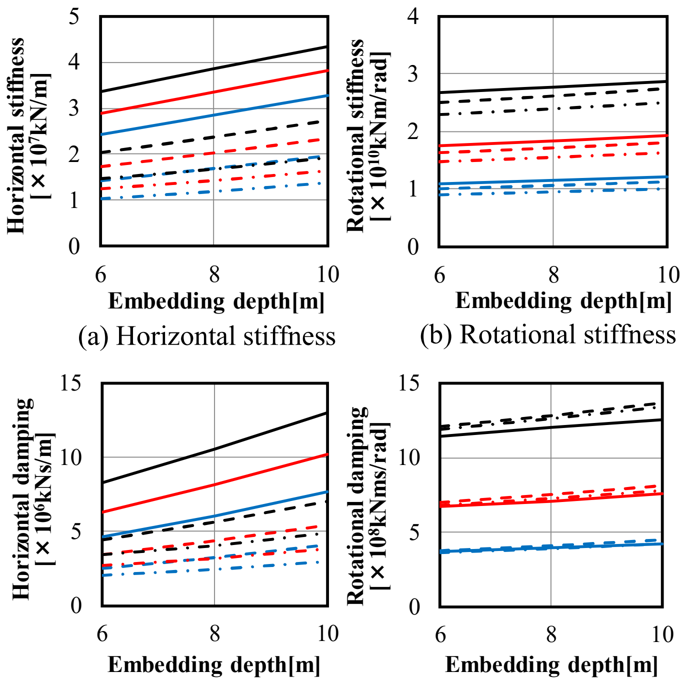
The fundamental natural period was determined from T_1(s)=0.02H, where building height H(m) is evaluated from the number of stories (N) and story height of 3 m. Normalized mass mn/A_0 (t/m^2) at the nth floor was determined from the following equations; m_n/A_0=-0.31Z_n+1.55 (Zn≥0.25), m_n/A_0=25.4Z_n^2-13.2Z_n+3.21(Z_n<0.25), where Z_n=3n/H is normalized height.

It is constructed by setting the restoring force characteristics as the nonlinear multiple-degree-of-freedom (MODF) model proposed by Hinoura et al. [5] based on the average distribution of the nonlinear parameters of the buildings, and then separating the deformation components into the bending deformation component and the shear deformation component. In the generic SR model in Fig.5, the embedded part and the soil springs were added to the bottom of the GBSM model. The upper structure with story height of 3m and 30m square planning were assumed. In this study, the eigenvalue analyses were performed for the generic SR model assuming the building of 20 to 50 stories, i.e. totally 31 cases of buildings. These buildings are assumed to be linear for simplify in this study.



(a) Horizontal impedance functions (b) Rotational impedance functions

Fig.3 – Impedance functions of soil (embedding depth 6 m).



(a) Horizontal stiffness (b) Rotational stiffness

(c) Horizontal damping (d) Rotational damping

Fig.4 – Constant soil springs.

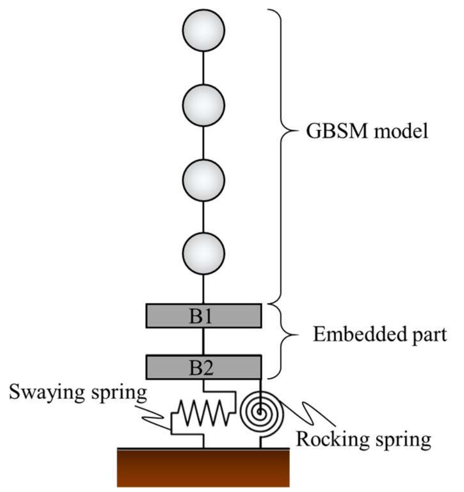


Fig.5 – The overview of generic SR model.

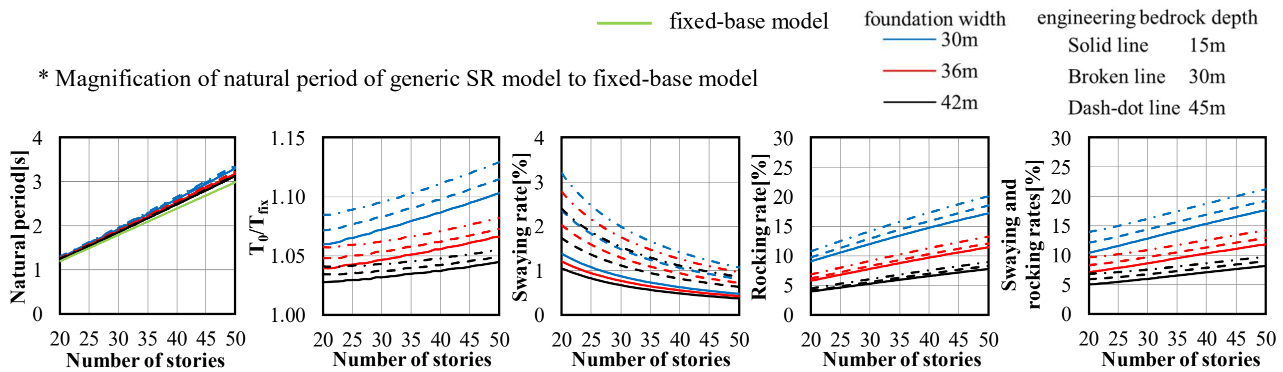
3. Variation of 1-st natural period, swaying and rocking rate

3.1 Case of linear condition

Variation of the first natural period, the swaying and the rocking rates with the increasing number of stories in Fig.6 (a) are discussed. The natural period (T_0) increase with the number of stories. Ratios of the natural period of the SR models to the fixed-base models in Fig.6 (b) indicate that the natural period becomes longer as the building is taller, the foundation is shallower, and the engineering bedrock is deeper. Natural periods of the generic SR models are 3 to 13% longer than those of the fixed-base models, when level of the earthquake motion is small. The ratios of the natural period tend to decrease as the number of stories decreases. This tendency becomes stronger as the foundation become wider. This is because the rotational stiffness is proportional to the third power of the width of the foundation.

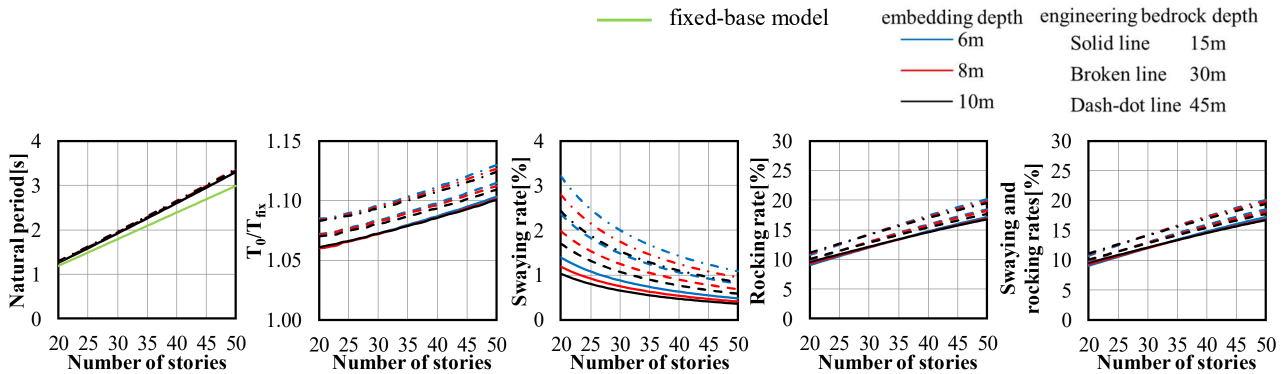
The swaying rate is defined as the ratio of the amplitude of the foundation bottom to that of the top of the building in the modal displacement of the 1-st mode. The rocking rate is the ratio of the amplitude due to the rotation of the foundation bottom to the modal displacement at the top of the building multiplied by the total value of the building height and embedding depth. The swaying rate decreased with the increase of story number while rocking rate increased in proportion to the story number. In general, the rocking rate is varied from 4 % to 20 %, which is much higher than the swaying rate. The SSI effects for high-rise RC buildings is mostly dominated by the rocking rate. As number of stories becomes large, the rocking rate increase because the overturning moment increase. The swaying rate in Fig.6 (c) is mainly influenced by the depth of the engineering bedrock and the rocking rate in Fig.6 (d) is mainly influenced by the width of foundation.

Eigenvalues and the swaying and the rocking rates of generic SR models with 30 m width foundation are plotted in Fig.7. As embedding depth is smaller, the SSI effect is larger. The effect of embedding depth is significantly smaller than that of the widths of foundation.



(a) Natural period (b) Magnification of natural period* (c) Swaying rate (d) Rocking rate (e) Total value of swaying and rocking rate

Fig.6 – Change of each eigenvalues in case of embedding depth of 6 m.



(a) Natural period (b) Magnification of natural period* (c) Swaying rate (d) Rocking rate (e) Total value of swaying and rocking rate

Fig.7 – Change of each eigenvalues in case of 30 m width foundation.

3.2 Effects of nonlinearity in soil and upper building

First, the nonlinear soil properties were obtained by step-by-step nonlinear analysis. The nonlinear characteristics of soil were sandy soil expressed by Hardin-Drnevich model [6]. The relations between the shear stiffness ratio and shear strain, damping coefficient and shear strain are presented in Fig.8. Input waves to the three soil models in Tables 2 and 3 are the artificial "Kokuji waves" with 10 types of random phase used in the structural design of super high-rise buildings in Japan, whose response spectra are defined as in Fig.9. Equivalent shear-wave velocity can be obtained from effective shear strain. The average values of the obtained equivalent shear-wave velocity are further averaged in the layer in Fig.10 and used for the axisymmetric FEM to calculate soil springs in the nonlinear soil case. The nonlinearity of upper structure is equivalently estimated from the secant stiffness at the yielding strength of the tri-linear skeleton curve. The natural period of fixed-base models considering nonlinearity of the building is about 1.60 times longer than that of the linear models.

In order to separate the effects of the nonlinearization of the soil and the building, the 4 cases of eigenvalues and the swaying and the rocking rates are evaluated as combination of linear and nonlinear cases for soil and building. The results for the embedding depth of 6 m are presented in Fig.11 and the results when the foundation width are 30 m in Fig.12. Variation of dynamic properties are large when the building is linear and soil is nonlinear, indicating that the SSI effect is clearly seen. The SSI effects becomes small when considering nonlinearity of both soil and building compared with those for linear case.

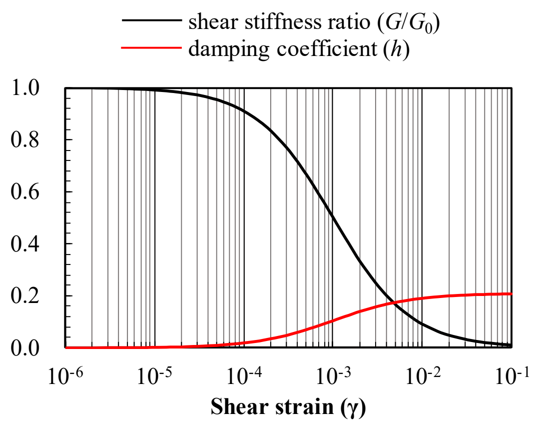


Fig.8 – G-γ, h-γ curve.

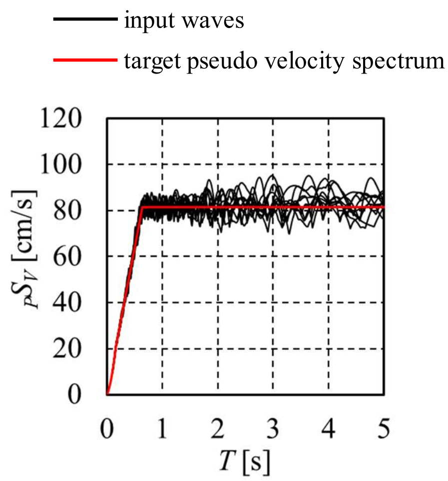


Fig.9 – Pseudo velocity spectra (*h*=5%)of 10 input waves for "Kokuji waves".

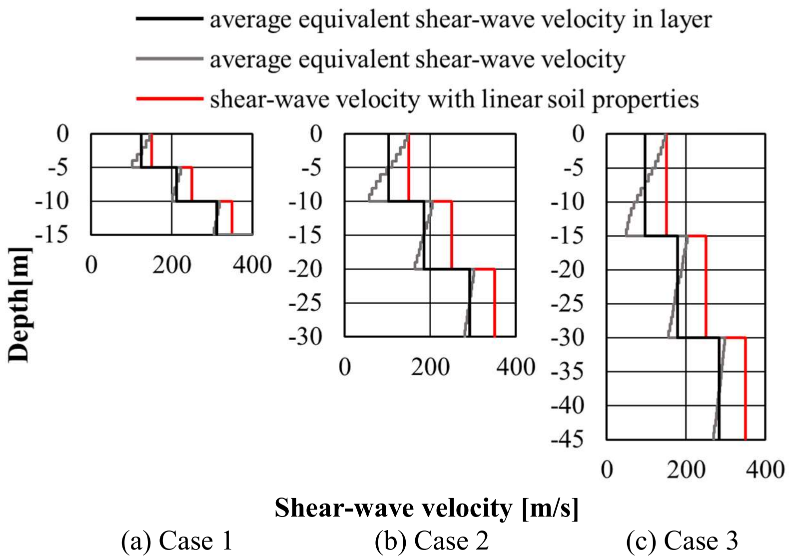
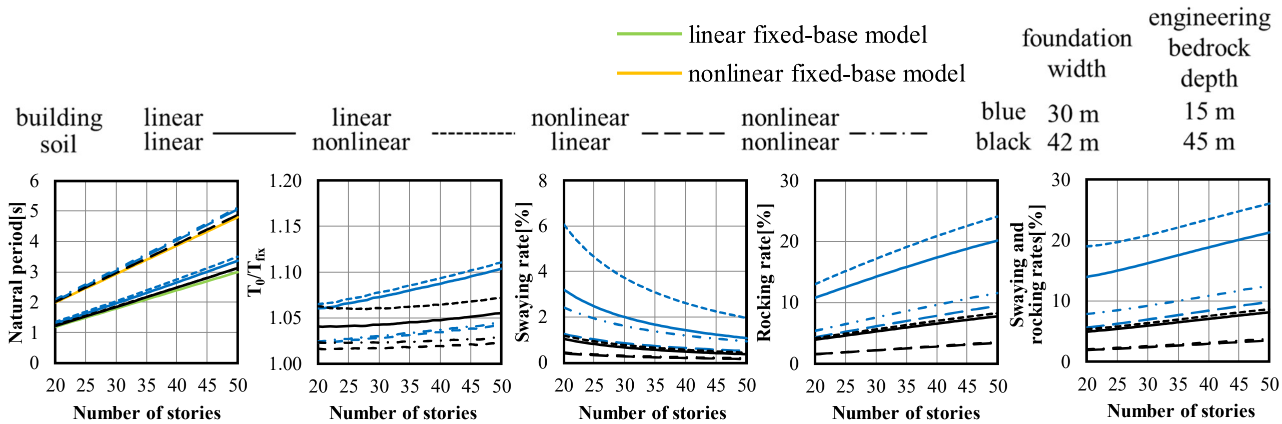
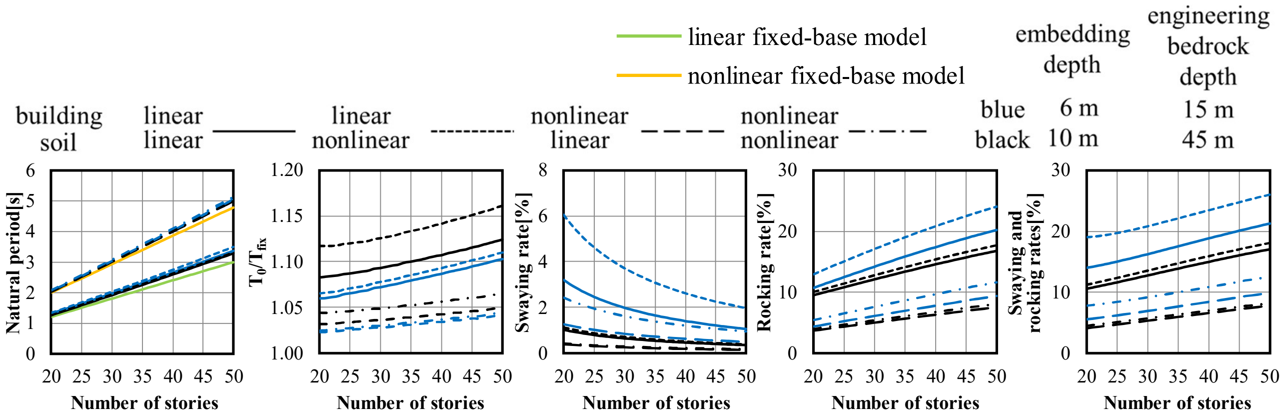


Fig.10 – Equivalent shear-wave velocity considering soil nonlinearity.



(a) Natural period (b) Magnification of natural period* (c) Swaying rate (d) Rocking rate (e) Total value of swaying and rocking rates

Fig.11 – Variation of eigenvalues due to the nonlinearization of the soil and the building in case of embedding depth 6 m.



(a) Natural period (b) Magnification of natural period* (c) Swaying rate (d) Rocking rate (e) Total value of swaying and rocking rates

Fig.12 – Variation of eigenvalues due to the nonlinearization of the soil and the building in case of foundation width 30 m.

* Magnification of natural period of generic SR model to fixed-base model

4. Validation of SSI effects using analyses for four existing buildings

4.1 Buildings scoped in this study

In order to examine the validity of the generic SR model, the effects of the number of stories, soil and foundation conditions on the SSI are examined for 4 existing RC buildings in the Tokyo metropolitan area (hereinafter, building A, G, C, H) in Table 4. The locations of buildings are plotted in Fig.13. The plans of pile arrangement are presented in Fig.14. The building G has composite foundation with piles surrounded by diaphragm walls.

4.2 Evaluation of soil springs

The dynamic impedance functions are evaluated using soil models with the shear-wave velocities in Fig.15. Soils in the buildings A and G are relatively soft. Diameters of piles are set 2m for simplify. The soil springs are calculated by axisymmetric FEM. The foundation width and the embedding depth are referred from the documents from the structural design of buildings. Soil nonlinearity is considered in the same manner as Section 3.2, where the equivalent soil properties were obtained by step-by-step nonlinear analysis.

Constant soil springs of existing building sites are plotted in Fig. 16. The horizontal stiffness in Fig.16 (a) is the largest in building C and is about 6 times larger than that of building G, which is smallest. The rocking stiffness in Fig.16 (c) is also largest in building C and is about 3 times larger than that of building G. The stiffness is decreasing due to soil nonlinearity while the damping tend to increase.

Table 4 – Profiles and natural periods of existing 4 buildings

Building Name	Number of stories	Building height [m]	Natural period [s]				Width of foundation [m]		Embedding Depth [m]	Engineering bedrock depth [m]
			Fixed-base model		SR model					
			X	Y	X	Y	X	Y		
A	30	95.90	1.56	1.68	1.75	1.90	38.10	32.40	7.60	47.20
C	30	88.35	1.82	1.80	1.87	1.88	31.80	27.30	8.00	29.90
G	28	81.50	1.48	1.47	1.62	1.62	26.00	26.00	4.90	47.90
H	24	69.95	1.31	1.17	1.36	1.23	35.00	32.00	6.00	22.50

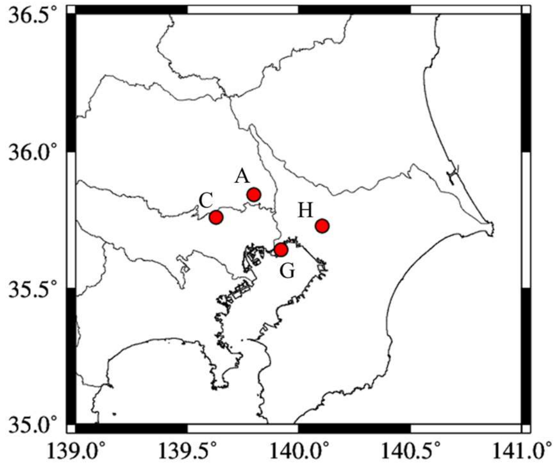
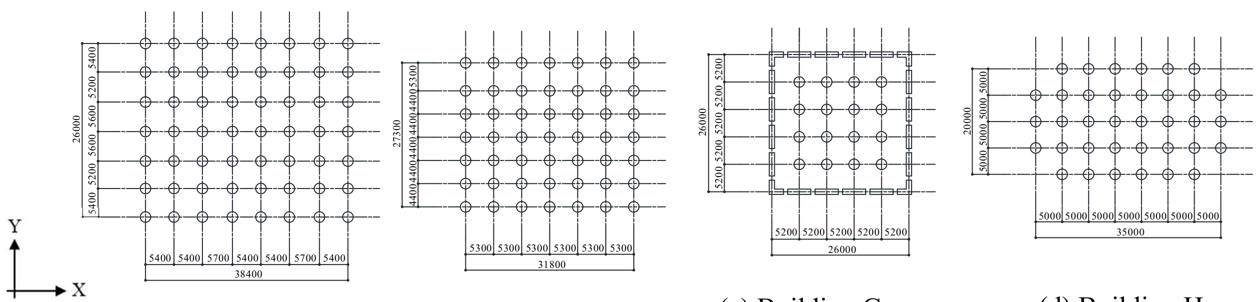


Fig.13 – Sites of buildings in Table 4



(a) Building A (b) Building C (c) Building G (d) Building H

Fig.14 – Plan of pile arrangements

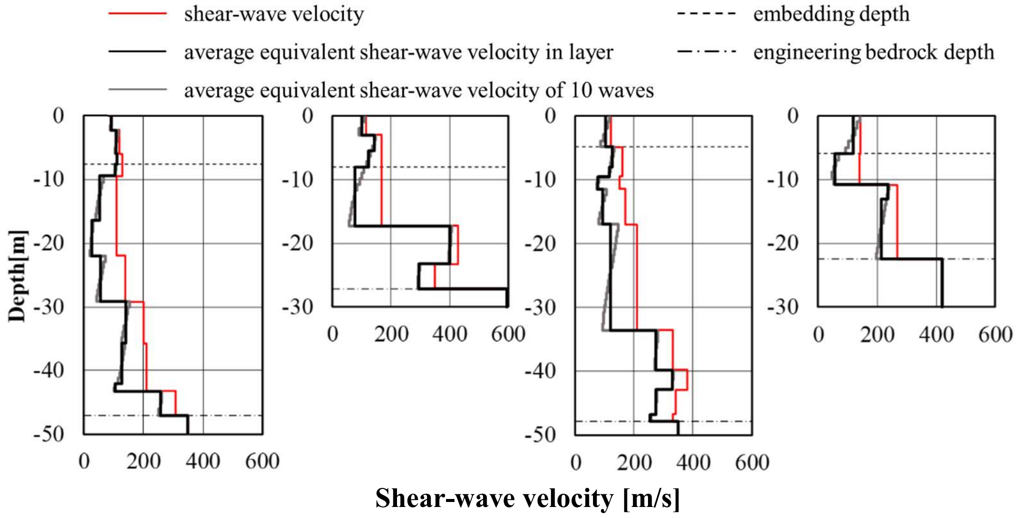


Fig.15 – Soil properties of existing high-rise RC buildings.

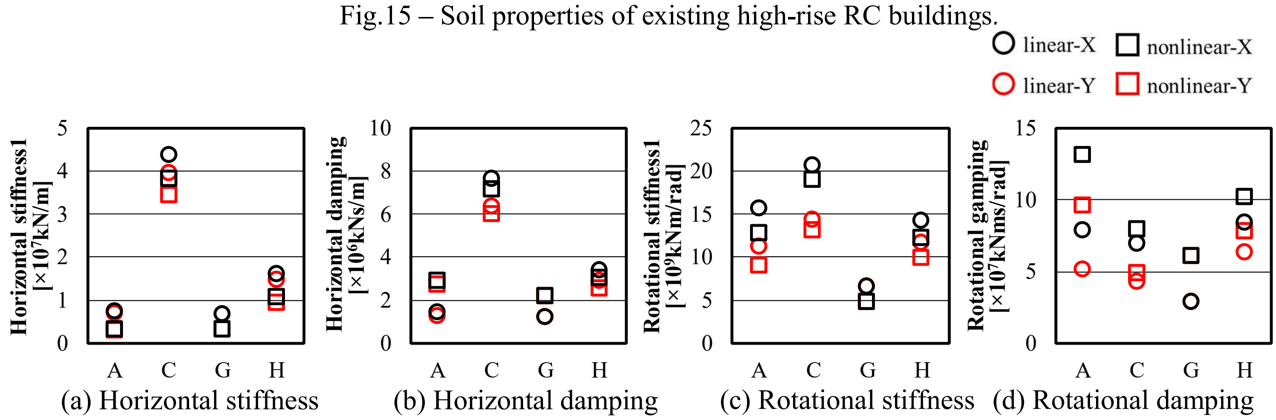
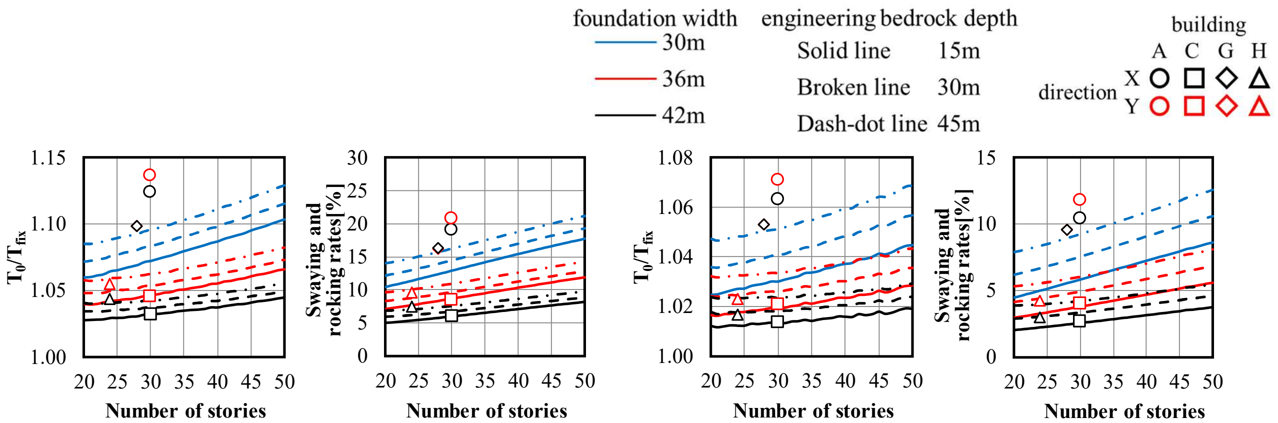


Fig.16 – Constant soil springs of existing building sites.

4.3 Eigenvalue analysis of four existing building models

Eigenvalues and modes were calculated for the SR models of the existing buildings. Comparison of eigenvalues between the SR models of existing buildings and the generic SR model are plotted in Fig.17 for the linear case. The magnification of natural period due to the SSI effect in Fig.17 (a) indicates that the effect of SSI is larger in Y direction which is short span direction. Magnification is large in the buildings A and G where depth of engineering bedrock is deep and shear-wave velocity is relatively small.

The variation of eigenvalues in case where both soils and buildings are nonlinear are presented in Fig.18. The nonlinearity of the existing building expressed by equivalent stiffness in the same way as the generic SR model. Magnification of the natural period and the swaying and rocking rates in the nonlinear case is smaller than those in the linear case, whose trend is similar to those of the generic SR models.



(a) Magnification of natural period of generic SR model to fixed-base model

(b) Total value of swaying and rocking rates

Fig.17 – Magnification of natural period and swaying and rocking rate of existing building models compared with generic SR models (linear, embedding depth 6 m).

(a) Magnification of natural period of generic SR model to fixed-base model

(b) Total value of swaying and rocking rates

Fig.18 – Magnification of natural period and swaying and rocking rate of existing building models compared with generic SR models (nonlinear, embedding depth 6 m).

5. Conclusions

In this study, using the generic bending-shear multi-degree-of-freedom model with sway-rocking spring (hereafter generic SR model), the dynamic characteristics including the effects of the SSI on structural response were examined for rough estimation of the SSI effects for various types of combination of the building foundation and soil conditions.

First, we collect the documentation on the structural design of the 52 high-rise RC buildings over 60 m height including foundations and soil conditions to determine parameters of soil models to calculate dynamic impedance functions by axisymmetric finite element method. Then, we constructed the generic SR model, in which superstructures were modeled using the generic bending-shear multi-degree-of-freedom model.

As the result of eigenvalue analysis, the generic SR models with 20 to 50 stories showed that the natural period with the SSI effects became longer for smaller foundation, shallower embedding depth, deeper depth of engineering bedrock. Natural periods of the generic SR models are 3 to 13% longer than those of the fixed-base models, when level of the earthquake motion is small. Effect of the SSI increases as the story number becomes larger. The swaying rate decreased with the increase of story number while rocking rate increased in proportion to the story number. The rocking rate is approximately 4 to 20% which is about 10 times larger than the swaying rate. The SSI effects for high- rise RC buildings is mostly dominated by the rocking rate. Next, we compared the analyzed results using generic SR models and vibration analysis models of the 4 existing high-rise RC buildings in Tokyo metropolitan area. Their structural models are referred from the documentation on the structural design and dynamic impedance functions are evaluated using soil models in their sites. It is found that the SSI effects of the 4 existing high-rise RC buildings can be roughly estimated by those from the generic SR models.

6. Acknowledgements

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7. References

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