CENTRIFUGE TESTS FOR SINGLE-DEGREE-OF-FREEDOM(SDOF) FRAME STRUCTURE WITH SHALLOW FOUNDATION

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SUMMARY

Centrifuge tests were performed to study the SSI effect on the dynamic response of single-degree-of-freedom (SDOF) frame structure with shallow foundation. Four specimens with different number of columns and natural period (mass of frame) were tested. Before centrifuge tests, an impact hammer test was performed to estimate the dynamic properties (period and damping ratio) of the specimens with fixed base. In each centrifuge test, accelerations were measured at the frame, foundation and free-field, and the results of acceleration, Fourier transform, and transfer function were compared. The acceleration of the centrifuge test specimens was significantly less than that of the fixed base model as the soil did not resist the pull-out force of the foundation. The acceleration converged to a limit value as the free-field motion increased. In FE analysis, the specimens were modeled as flexible base models with soil springs. The results of numerical analysis agreed with the test results.

Keywords: *SEEBUS; soil-structure interaction (SSI); period lengthening; flexible base model.*

INTRODUCTION

Recently, soil-structure interaction (SSI) has been studied as an important field of earthquake engineering. In general seismic analysis, the boundary condition of the structure base is assumed to be fixed, but various studies show that incorrect boundary conditions (fixed base) may overestimate or underestimate the seismic load (Chopra and Gutierez, 1974; Stewart et al., 1999; Veletsos and Meek, 1974). Particularly, in buildings with shallow foundation, movements such as sliding, uplift, and rocking can occur in the foundation. Therefore, researchers have conducted analysis and experimental studies on SSI effects on buildings with shallow foundations, and various design methods were developed (Gajan and Kutter, 2009; Ha et al, 2014; Kim et al, 2020; Martakis et al., 2017; Somma et al, 2022).

NIST GCR 12-917-21 summarizes the results of various SSI studies and categorizes SSI effect into inertial interaction effects, kinematic interaction effects, and soil-foundation flexibility effects. Particularly, the inertial interaction effects are developed by the effect of flexible base causing period lengthening and damping changes. The effect of flexible base was considered using spring model for soil (Pais and Kausel, 1988; Gazetas, 1991; Mylonakis et al, 2006). The beam-on-nonlinear Winkler foundation (BNWF) model was also used to address the effect of flexible base, using vertical and horizontal springs (Matlock, 1970; Cox et al., 1974; Penzien, 1970; Nogami et al., 1992; Boulanger et al., 1999). In this study, vertical, horizontal, and rotational nonlinear spring was modeled to consider the effect of flexible base.

Gajan and Kutter (2009) developed a new contact interface model to analyze the movement of shallow foundation

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subjected to cyclic loading. Martakis et al. (2017) performed centrifuge tests on simplified lumped mass SDOF models with various dimensions, and estimate period lengthening ratio and system damping ratio.

As such, most of studies used a pier type structure with single mass and foundation. Thus, in the studies, the SSI effect of foundation subjected to overturning moment were studied. On the other hand, Mason et al. (2013) performed centrifuge tests on two 3D frame structures and analyzed soil-structure-soil interaction (SSSI) and soil-foundation-structure interaction (SFSI). The study focused on kinematic interaction, and motions such as settlement, uplift, rocking, and sliding of the structure according to the relative position of the two structures were analyzed. According to this study, neglecting the interaction between two adjacent structures can be unconservative, so the SSSI effect should be considered.

As mentioned, in the majority of previous studies focused on the SSI effect of foundation subjected to overturning moment on the behavior of structure under earthquake. However, in reality, many foundations of primary earthquake load resisting system are subjected to axial compression (or tension) as well as moment.

Thus, in the present study, centrifuge tests were performed to investigate the SSI effect on structures with multiple columns (foundations) subjected to axial forces. The behavior of the centrifuge test results was compared with that of structure models with fixed base. Further, finite element (FE) analysis using soil springs was performed to verify the SSI effect.

TEST PLAN

Centrifuge Test

In centrifuge test, gravitational pressure applied to soil is simulated by rotational centrifugal force. Prototype model (1g) can be simulated by 1/N scale model with N gc (gc: centrifugal acceleration). The soil was placed in an ESB model container that minimizes the effect of reflected waves to simulate horizontally infinite ground (Lee et al., 2013). The internal dimensions of the ESB model container are (0.49 m × 0.49 m × 0.6 m). At the prototype scale (40 gc), the dimensions of the prototype soil are (19.6 m × 19.6 m × 24.0 m) (length × width × depth).

Test Specimens

Table 1 presents the properties of four structure models used for centrifuge tests. Each structure model was designed with a different natural period by varying the number of columns and mass of frame. To investigate the dynamic properties (natural period (T_n) and damping ratio (ξ)) of each specimen, an impact hammer test was performed for the model with fixed base. The natural period (frequency) of the structure was estimated by Fourier transform of the impact hammer test results (Figure 1). The damping ratio (ξ) was estimated using the half-power bandwidth method as follows:

$$\xi = \frac{\beta_b - \beta_a}{2f_n} \tag{1}$$

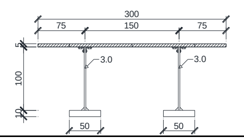
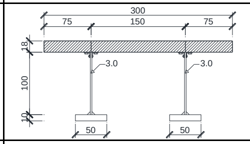
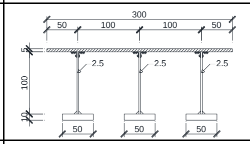
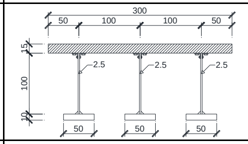
where ξ is the damping ratio, f_n is the frequency at maximum amplitude, and β_a and β_b are the lower and upper frequencies, respectively, at the maximum amplitude multiplied by $1/\sqrt{2}$.

Test results were measured from accelerometers which were located as shown in Figure 2. The accelerations of the structure model and each foundation were measured, and the free-field motion (soil surface, A1) was also measured.

Input Seismic Accelerations

For input seismic accelerations, four actual accelerations that recorded at rock sites were used (1984 Morgan Hill earthquake, 1994 Northridge earthquake, 1995 Kobe earthquake, and 1957 San Francisco earthquake). Tests were repeated while increasing the input peak ground acceleration.

Table 1. Properties of structure models

Structure models	**SDOF1**	**SDOF2**	**SDOF3**	**SDOF4**
Dimensions (mm)				
Total mass (kg)	1.22	2.76	1.48	2.66
Effective mass, m_s[1)] (kg)	0.827	2.362	0.886	2.067
Natural frequency (Hz) in 1gc	116	74	121	80
Natural period, T_n (s) in 1gc	0.009	0.014	0.008	0.0125
Natural period, T_n (s) in 40gc	0.345	0.541	0.331	0.500
Damping ratio, ξ (%)	0.91	1.39	0.60	0.75

[1)] Note: mass without foundation

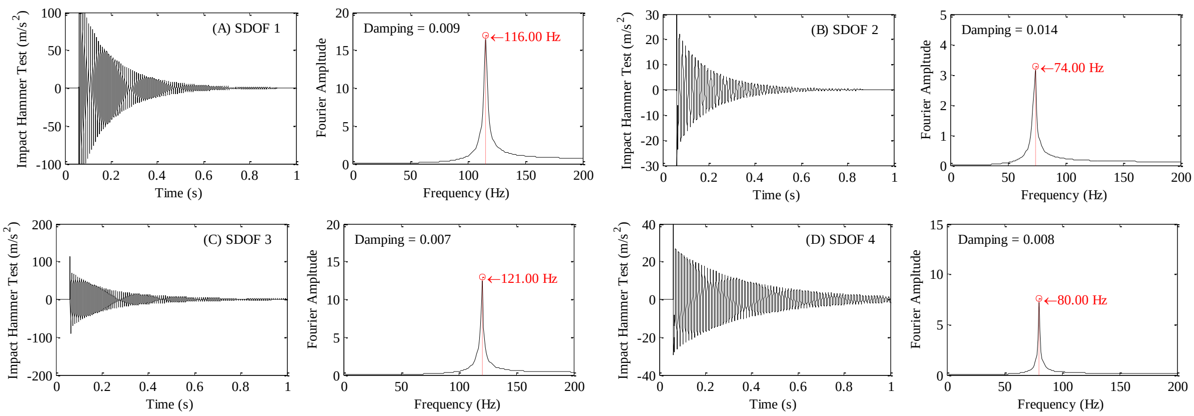


Fig. 1. Impact hammer test results of test specimens with fixed base

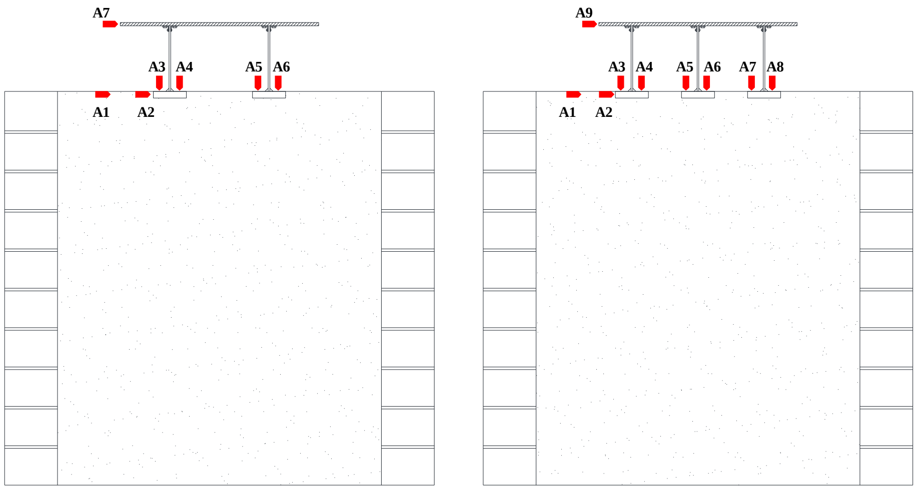


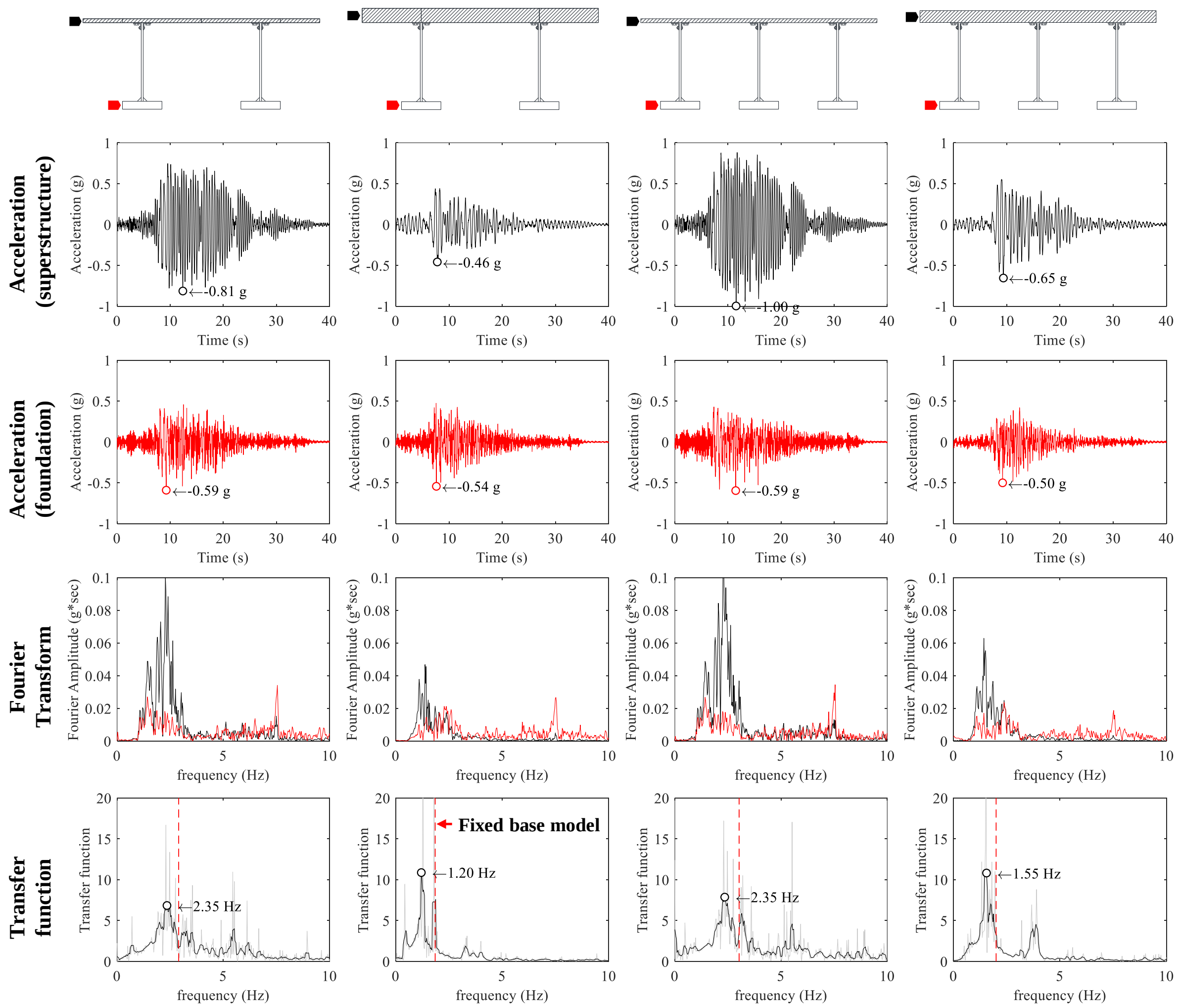
Fig. 2. Test specimens and locations of accelerometers

TEST RESULTS

Response of SDOF structures

Figure 3 shows the time history accelerations, Fourier transform, and transfer function at the structure model and foundation of SDOF1, SDOF2, SDOF3, and SDOF4 in the case of Kobe EQ with free-field motion of 0.444 ~ 0.542 g. Accelerations of the structure models were amplified to 0.81 g and 1.0 g for SDOF1 and SDOF3 which has the higher frequency (shorter period), respectively. On the other hand, in SDOF2 and SDOF4, there was no significant amplification in the structures compared to the response of the foundations.

In order to estimate the dynamic properties of structures during seismic loading, the Fourier transform at the structure (black solid line in Figure3) and foundation (red solid line in Figure 3) were calculated. Then, the transfer function was calculated to obtain the dynamic frequency of each specimen. The transfer function was calibrated by moving average of seven data to remove outlier. The dynamic frequencies of all specimens were lower than those of the fixed base models (red dotted line in Figure 3) calculated by the impact hammer test (chapter 2.2). As revealed in existing codes and studies, period lengthening occurred in the shallow foundation structures due to the SSI effect (NIST GCR 12-917-21). In Figure 4, the natural period (reciprocal of frequency) calculated from the transfer function and the natural period of the fixed base model calculated from impact hammer test were compared. The period of the structures with shallow foundation was longer than that of the fixed base model regardless of the magnitude of the acceleration.



(a) SDOF1 **(b) SDOF2** **(c) SDOF3** **(d) SDOF4**

Fig. 3. Test results of SDOF1, 2, 3 and 4 (PGA_{ff} = 0.444 ~ 0.542 g, 40 gc, Kobe EQ.)

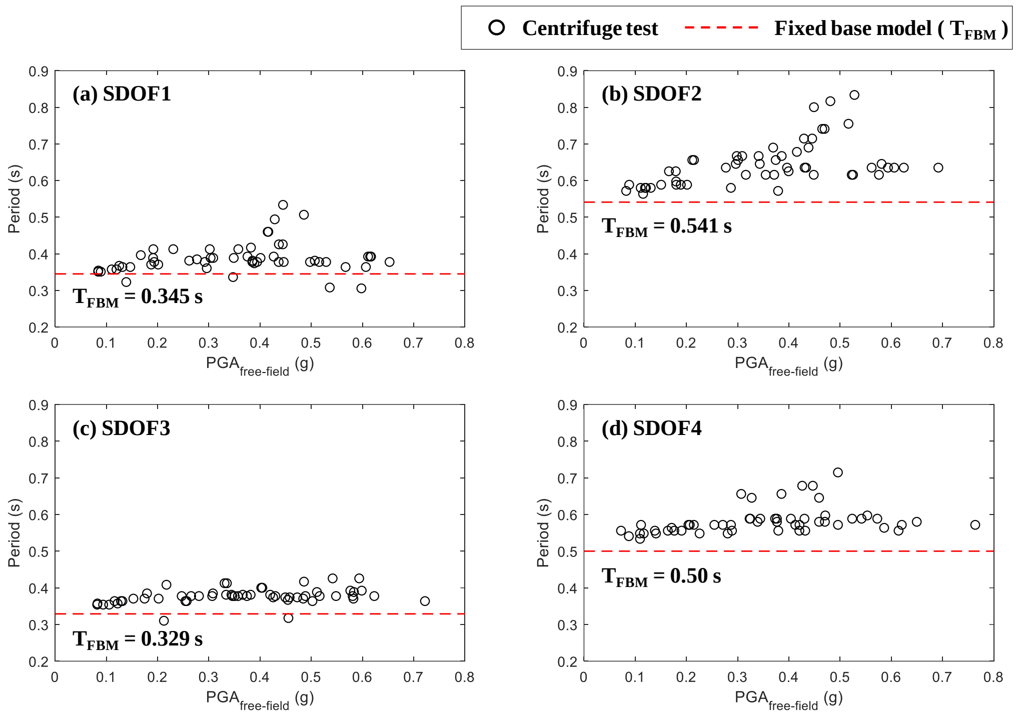


Fig. 4. Natural period according to PGA_{ff}

Fixed Base Model (OpenSEES)

To understand the SSI effect, dynamic analysis was performed on the fixed base model using OpenSEES (Open System for Earthquake Engineering Simulation). For the fixed base model, the damping ratio estimated from the impact hammer test was used. The input motion for analysis was free-field motion measured on the soil surface.

Figure 5 and Figure 6 show the time history acceleration of the structure (SDOF1 and SDOF3) of the fixed base model and the tested model under low ground motion (peak ground motion of free-field, PGA_{ff} = 0.084 ~ 0.106 g) and strong ground motion (PGA_{ff} = 0.444 ~ 0.542 g), respectively. Under low ground motion, the maximum acceleration of the fixed base models and the centrifuge tested models was similar, but under strong ground motion, the maximum acceleration of the fixed base model was much greater. In addition, in weak ground motion, damping occurred faster in the test model than in the fixed base model. This is due to additional damping of the soil by the shallow foundation. This behavior also appeared in SDOF2 and SDOF4.

Figure 7 compares the maximum acceleration of the tested model and the fixed base model. When the acceleration of the fixed base model is low, the two accelerations are similar (near 1:1 line). On the other hand, when the acceleration increases, the acceleration of the tested model converges to a limit value.

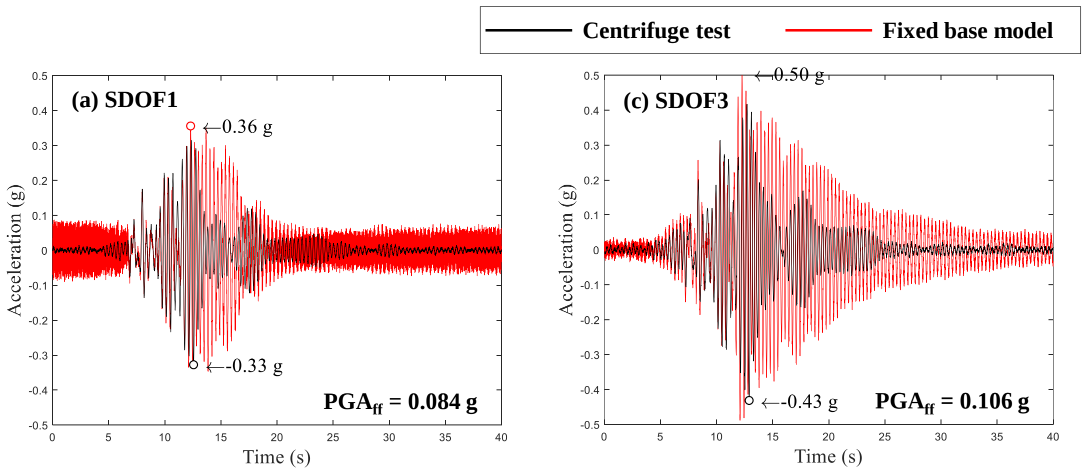


Fig. 5. Comparison of centrifuge test model with fixed base model of SDOF1 and SDOF3 at low ground motion (PGA_{ff} = 0.084 ~ 0.106 *g*, Kobe EQ.)

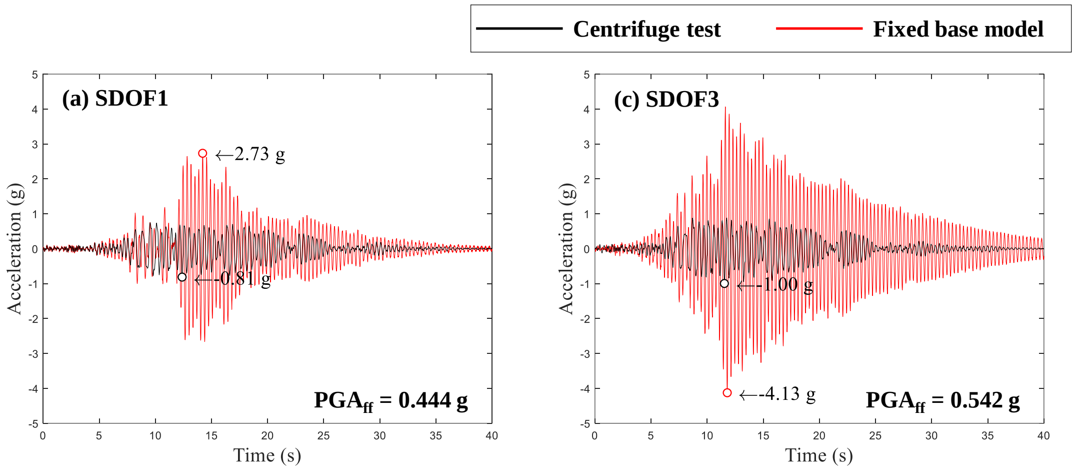


Fig. 6. Comparison of centrifuge test model with fixed base model of SDOF1 and SDOF3 at strong ground motion (PGA_{ff} = 0.444 ~ 0.542 g, Kobe EQ.)

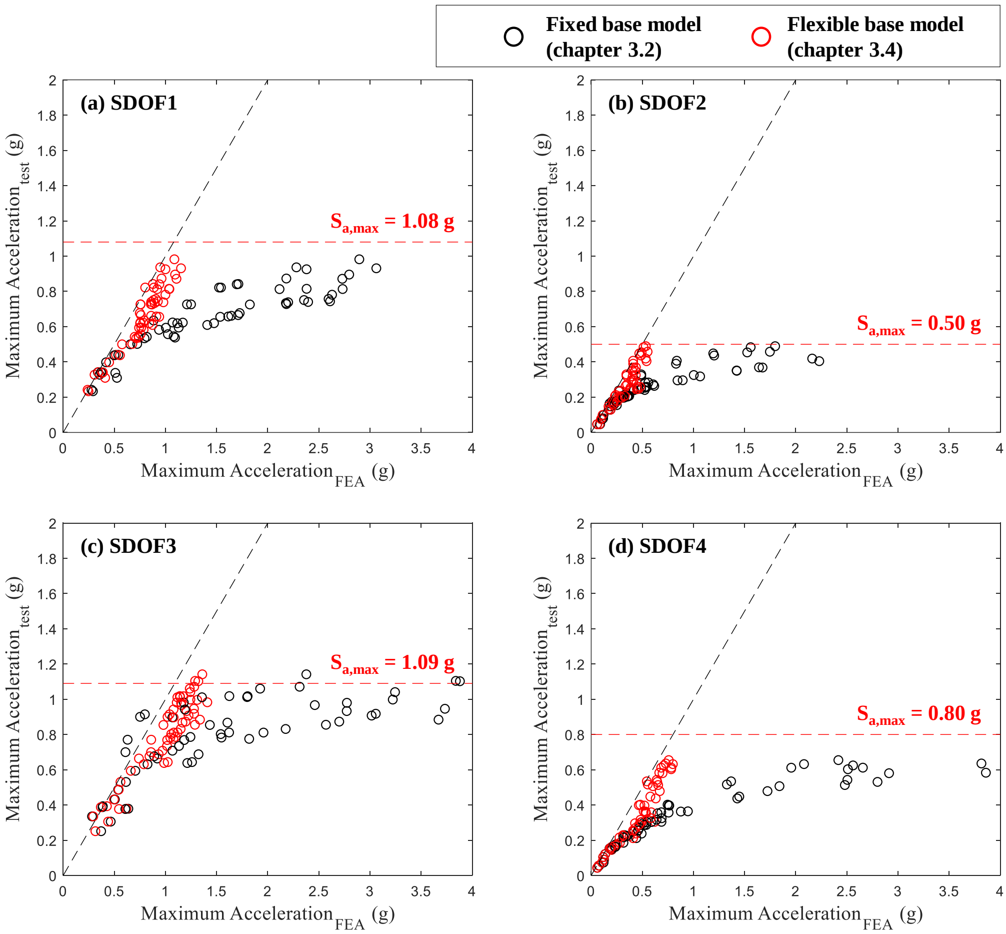


Fig. 7. Comparison of maximum accelerations estimated from centrifuge test model, fixed base model, and flexible base model

Ultimate Acceleration of Structure Model

In structural analysis for fixed based structure models, when a large lateral load develops the column axial force developed by a large lateral load exceeds the axial force caused by gravity load, tension forces can be developed in the columns and foundations. However, shallow foundations cannot resist tension forces. Further, the compressive force of a column cannot exceed the bearing capacity of the soil. Considering the two criteria in tension and compression, the maximum capacity of the foundation is limited by the two criteria: tension and compression criteria. The maximum foundation capacity and the corresponding structure accelerations can be calculated in Figure 8 and Figure 9. The dynamic bearing capacity of soil used in this experiment was 350 kN/m^2

at 0.55 g of seismic motion (varies according to the size of the ground motion) (Richards Jr et al., 1993)

In the case of SDOF1 (light weight structure), the foundation capacity was limited by tension criteria (Figure 8 (b)), while in the case of SDOF2 (heavy weight structure), the foundation capacity was limited by compression criteria (Figure 8 (c)). In the case of SDOF3 and SDOF4 with three columns, the foundation capacity was limited by the tension criteria Figure 9 (b).

The estimated maximum acceleration, $S_{a,max}$ (1.08 g, 0.50 g, 1.09 g, and 0.8 g for SDOF1, SODF2, SDOF3, and SDOF4) are plotted in Figure 7. The results agree well with the maximum test results.

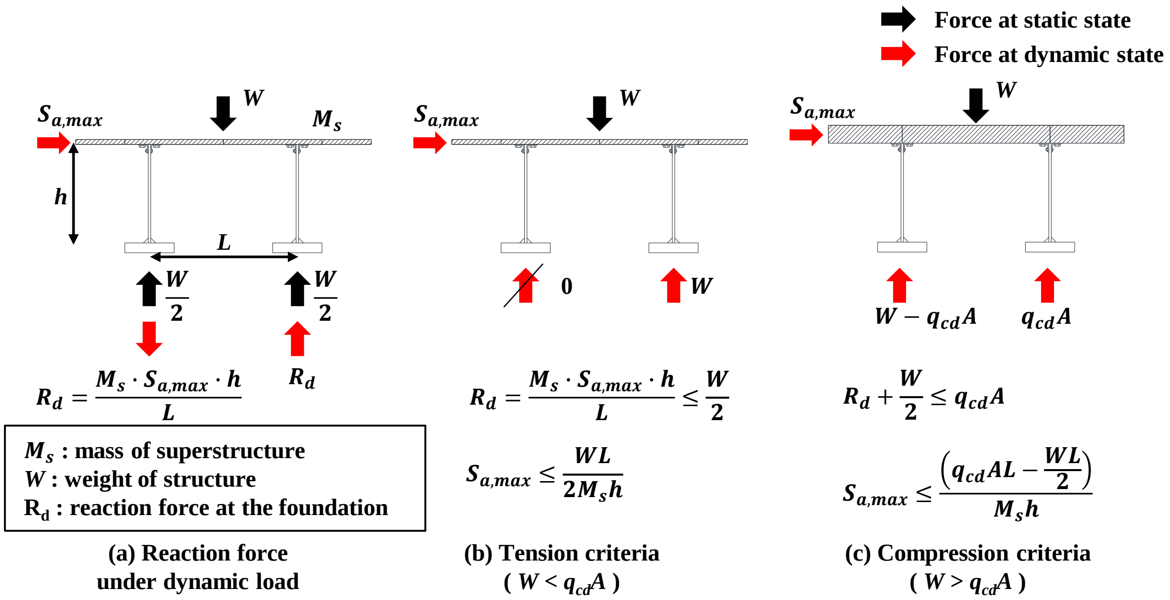


Fig. 8. Reaction force distribution and limit state during dynamic load for structure model with 2-columns

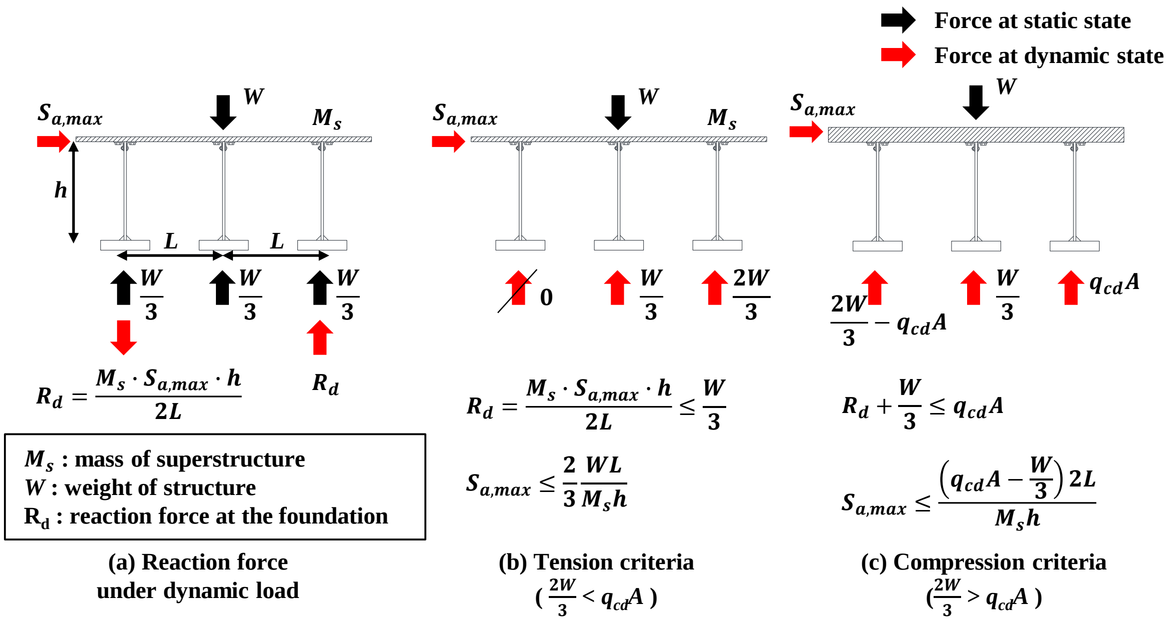


Fig. 9. Reaction force distribution and limit state during dynamic load for structure model with 3-columns

Flexible Base Model (OpenSEES)

To verify the test results, FE analysis using soil springs (considering SSI effect) was performed. FEMA 356 proposes to model the flexible foundation using translational and rotational soil springs. The vertical spring was modeled using the ElasticPPGap material (OpenSEES) to limit the maximum force to the dynamic bearing capacity without receiving the tension force. The rotational spring was modeled using ElasticPP material to limit the maximum force to the dynamic bearing capacity.

Time history analysis was performed for the flexible base models. Figure 9 show the time history accelerations of the structure and the tested model under strong ground motion (PGA_{ff} = 0.444 ~ 0.542 g). The acceleration of the fixed base model (chapter 3.2, Figure 4) increased significantly, while the flexible base model showed similar trend with the test results. The maximum acceleration of the flexible base model agrees well with the test results. The fixed base model greatly overestimated the test results.

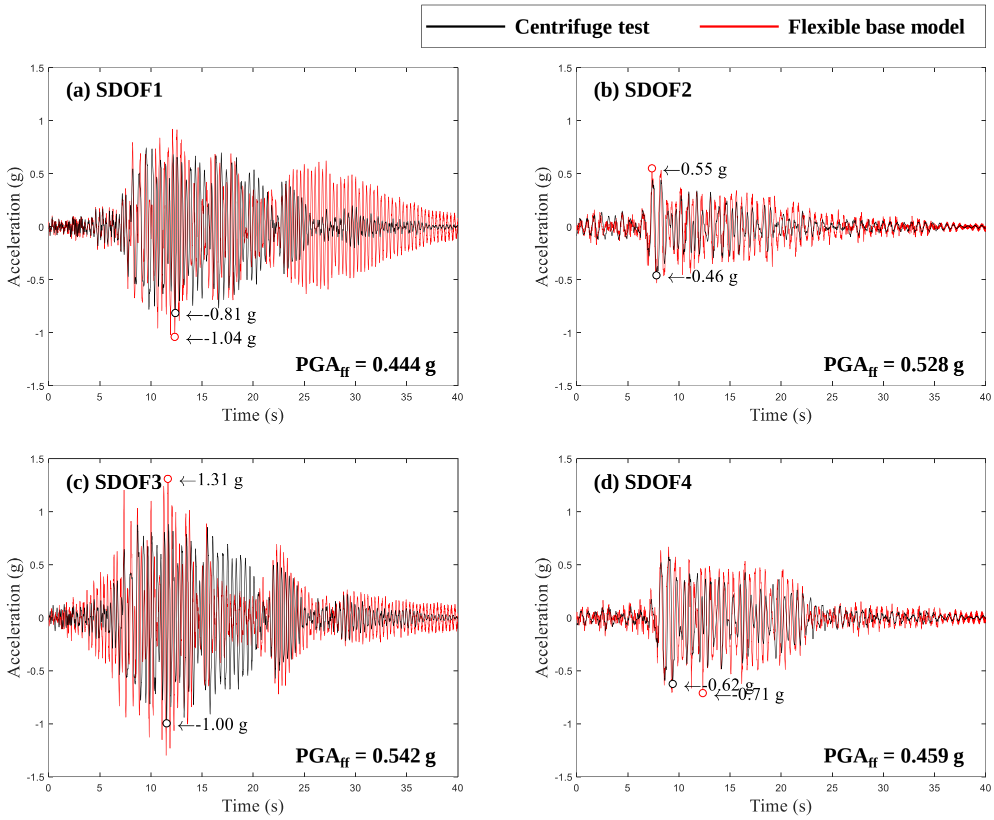


Fig. 9. Comparison of centrifuge test model with flexible base model at strong ground motion (PGA_{ff} = 0.444 ~ 0.542 g, Kobe EQ.)

TEST RESULTS

Centrifuge tests were performed to study the SSI effect of structures with multiple columns and foundations. The test parameter was the number of columns and mass of the frame. Acceleration was measured in the structure, foundation, and free-field to estimate the movement of the structure. To investigate the SSI effect, FE analysis was performed for specimen models with fixed base or flexible base. The results of the present study are summarized as follows:

1) In the results of centrifuge test, for all test models, the natural periods were longer than the natural periods of fixed base models estimated from the impact hammer test. Due to the rotation and slinding of the shallow foundation, the natural period was lengthened by approximately 10%.
2) The acceleration of the centrifuge test specimens was significantly less than that of the fixed base model as the soil did not resist the tension force in the foundation. Thus, in the centrifuge test models, the acceleration converged to a limit value as the free-field motion increased. The maximum acceleration of the specimens was predicted at the onset of pullout force at the foundation. The prediction agreed with the tested maximum accelerations.
3) In FE analysis, the specimens were modeled as flexible base models with soil springs (only compression spring). The results of numerical analysis agreed with the test results. This result indicates that to address the SSI effect, such soil spring model should be used.

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