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ORIGINAL ARTICLE

Key parameters governing the dynamic response of long-period structures

N. Fukuwa · J. Tobita

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Abstract The present study describes the important factors (period, duration, and intensity) involved in evaluating input ground motion and structural response for the design of long-period structures such as high-rise buildings and base-isolated buildings. First, the fundamental dynamic properties of high-rise buildings are explained based on the results of newly introduced vibration observations programs. Next, the distribution of the predominant period and duration of seismic ground motion within the Nobi Plain, one of the largest sedimentary plains in Japan, is discussed with respect to the possibility of resonance of long-period structures. Finally, we introduce a recently developed long-stroke shaking table that is intended to convince structural engineers and building owners to take adequate countermeasures against large floor response in high-rise buildings because of resonance.

Keywords Structural response · High-rise buildings · Resonance · Damping · Long-period input · Shaking table

1 Introduction

Many long-period structures, such as high-rise buildings and base-isolated buildings, are built in urban areas that are vulnerable to long-period seismic ground motion. Since the first high-rise buildings were built in Japan around 40 years ago, more than 1,000 such buildings and approximately 2,000 base-isolated buildings have been constructed in Japan (BCJ 2001; JSSI 2007). In the past, typical earthquake ground motions were used for response analyses in the structural design of high-rise buildings, and the long-period ground motion generated by the deep soil structure at the construction site was not specifically taken into account. However, the long-period ground motion within sedimentary basins has recently been clarified from deep-ground surveys and dense seismic observations (Koketsu and Higashi 1992; Kagawa et al. 2004; Fukuwa et al. 2002; Tobita et al. 2000), and its effects on tall buildings are of particular concern to structural engineers.

Most high-rise buildings, especially steel frame structures, originally have relatively low structural damping, such as 1% or less (AIJ 2000). Thus, in the present-day structural design of high-rise buildings in Japan, the priority is to avoid resonance by separating natural periods from the predominant period of seismic ground motion, which is approximately 3 to 8 s in most large sedimentary basins. In addition, most of the recently designed high-rise

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buildings in Japan are equipped with additional damping devices to reduce seismic response. In base-isolated buildings, the isolators can experience large displacements under large-amplitude long-period ground motions, and dampers with effective damping of 10 to 30% are used. Consequently, the most important factor in the evaluation of seismic ground motion is the difference of dynamic properties, especially damping, between high-rise buildings and base-isolated buildings.

The objective of the present paper is to clarify the fundamental dynamic properties of high-rise buildings with respect to input seismic motion on deep sedimentary soil. Newly introduced strategic observation programs make it possible to examine variations in the natural period and damping with different heights and structural systems. The observed natural period is approximately proportional to the building height, while the damping ratio is low for the higher buildings. For the ground, the predominant period in the long-period range is investigated in the Nagoya metropolitan area using the H/V spectrum (Nakamura 2000) of microtremors and the spectral characteristics of observed seismic motions.

In the case of long-period buildings with low damping, when the natural period is close to the predominant period of the soil, the seismic response of the building will be amplified in the case of long-duration ground motion (Miyake and Koketsu 2005). The random decrement method (Jeary 1986) is used for the evaluation of the period and damping of the building.

Finally, it is important to inform structural engineers and building owners of the possibility of an unexpectedly large floor response because of resonance and to provide them with adequate countermeasures. To demonstrate/observe experimentally the effects of resonance and added supplemental damping on structural response, we developed an innovative new shaking table, called the Triple-L shaker, which realizes linear movement with long period and long stroke. This shaking table moves with an amplitude of displacement of up to 3 m, a velocity of 5 m/s, and an acceleration of 20 m/s^2. It is possible to experience large-amplitude floor response on the higher floors of high-rise buildings.

2 Building response observation

2.1 Strategic seismic observation program

To investigate the dynamic behavior of buildings, the present authors have developed a strategic observation program that is able to distinguish the effects of different parameters that control building response, including building height, structural system, soil conditions, foundation type, building size, torsional eccentricity, and the properties of adjacent buildings. Figure 1 shows such a strategic program developed for various buildings on the campus of Nagoya University (Fukuwa et al. 2004). Fortunately, Nagoya University (the institution of the present authors) houses a large number of buildings, many of which are in their original state of construction and many of which have modifications such as seismic retrofitting.

For example, observations can be carried out in a single building during its construction to show the effect of building height on the dynamic characteristics of the building, particularly the effect of soil–structure interaction and damping. For this purpose, it is more suitable to consider buildings constructed with the same building system and different heights, rather than buildings constructed with different building systems and different heights. In addition, earthquakes are likely to occur during construction when different numbers of stories have been completed. Similarly, simultaneous observations of buildings of the same height that are located on the same site but that were constructed with different structural systems can provide data on the dynamic properties of these structure systems relative to each other. The instrumentation program is also being used to gather data on the effects of soil structure interaction (SSI) on the response of the both low-rise and high-rise construction (Fukuwa et al. 2004; Kojima et al. 2004; Kojima et al. 2005).

The observed results for high-rise buildings are presented in the following.

2.2 Vibration observation of two high-rise buildings during construction

Figure 2 shows the observed high-rise buildings and locations of sensors. Building M is a 47-story steel

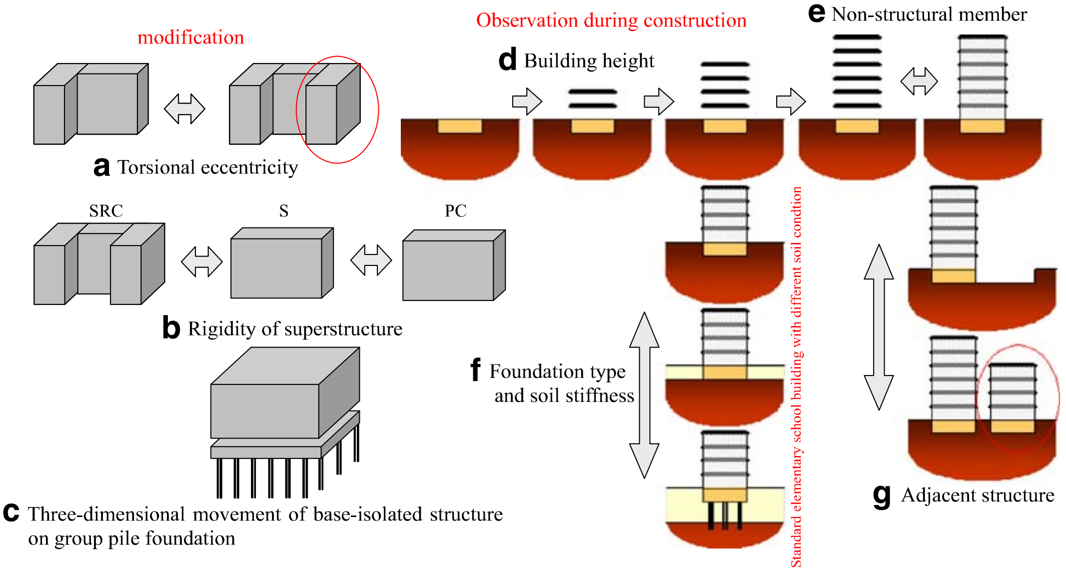
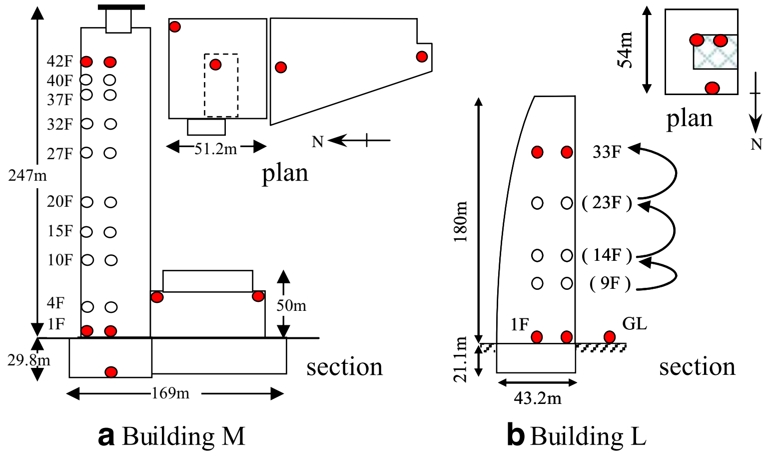


Fig. 1 Components of seismic-response observations required for the analysis of factors contributing to the dynamic behavior of buildings

frame structure with a seven-story low-rise part and a six-story reinforced concrete basement. The high-rise part, low-rise part, and the connection between the parts are equipped with oil dampers. Building L is a 42-story steel frame structure with a three-story basement and a mat foundation. Steel hysteretic bracings are attached to each story. These two buildings were located near each other and were constructed at approximately the same time.

The observation system used in the present study was developed for use at construction sites using all-in-one seismographs and a local area network connection (Kojima et al. 2005). Control and data correction from the remote site are possible through internet connection. The sensors are also effective for ambient noise, and a large amount of ambient vibration data and a few earthquake responses were recorded during the construction of the buildings.

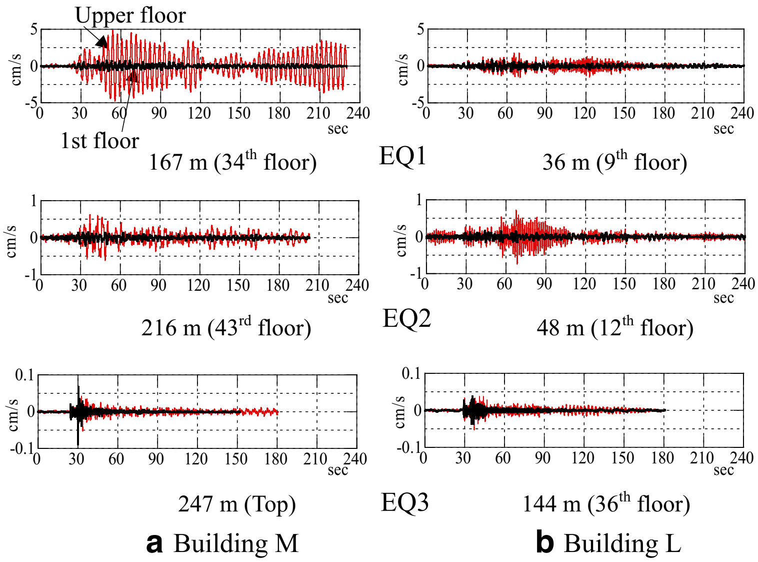
Figure 3 shows the seismic responses, and Fig. 4 shows the associated Fourier spectra of the two buildings that were recorded during three earthquakes. The heights of the buildings were different



a Building M **b** Building L

Fig. 2 Outline of observed buildings and sensor locations

Fig. 3 Observed velocity response

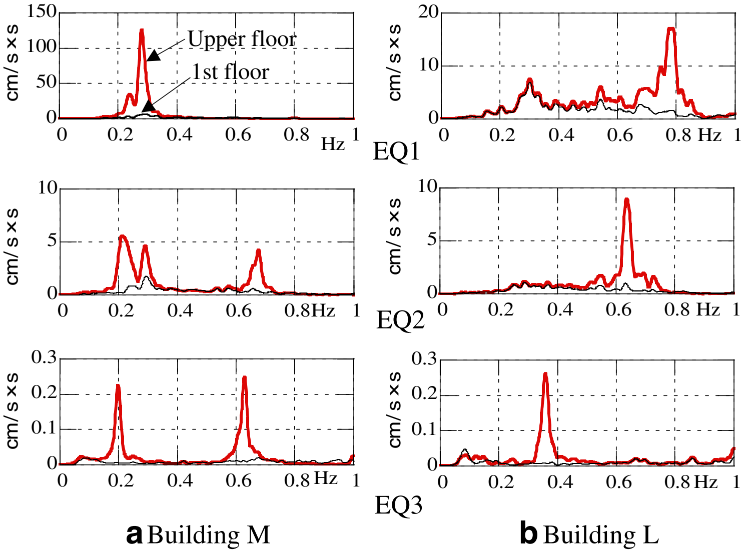


at the time of each earthquake, as shown in Fig. 3. In Fig. 3, the red and black lines show the responses of the top floor and the first floor, respectively.

During EQ1, the epicenter of which was very far from the site and which had a magnitude, Mj, of 7.2, the top floor response of building M was amplified to almost 20 times the first floor input motion, and the response did not readily decay. The height of the building was 34 floors or 166 m. On the other hand, the top floor response of building L, the height of which was nine floors or 36 m, was not amplified significantly, and duration of the response was rather short. This difference was caused by the properties of the input motion.

During EQ2 (far from the site, Mj=6.3) and EQ3 (near the site, Mj=4.0), the Fourier spectra indicate that both the second mode and the first mode were amplified for building M, whereas for building L, only the first mode was amplified. Comparing the building responses for the three earthquakes, differences in building response were described by the change in natural frequency with the height of the building, together with the frequency content and duration of the input ground motion.

Fig. 4 Fourier spectra of observed earthquake response



2.3 Changes in the dynamic characteristics of high-rise buildings during construction

Next, the effect of building height on the dynamic characteristics is examined, particularly with respect to the soil–structure interaction and damping.

Figure 5 shows the changes in natural periods and damping ratios obtained from ambient vibration records for the two high-rise buildings during construction. The natural period of building M increases almost linearly with building height, both for the first and second modes, while building L shows a curved relation between height and natural periods. The damping ratio is scattered at around 0.5%. This damping corresponds to the structural damping of the steel frame itself because additional damping devices were not active during construction.

Figure 6 shows the first mode natural period and damping ratio of the soil–structure system obtained from earthquake response at the top floor for the two buildings. Damping was evaluated by the half-power method. The natural periods are for the results from ambient vibration, while the damping is somewhat higher than the ambient case.

Figure 7 shows the sway and rocking ratios during earthquakes. In the east–west direction, the swaying ratio of building L decreased with building height.

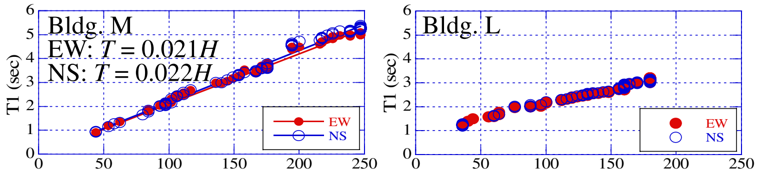
2.4 Amplitude dependency of dynamic characteristics

Figure 8 shows the amplitude dependency of the first mode natural period and damping obtained from the results of a forced vibration test on building M. The test was performed when the building was almost complete, but additional damping devices had not yet been installed. The active mass damper at the top floor was used for shaking. The amplitude in the horizontal axis of the figure is shown by the velocity response. The figure clearly shows amplitude-dependent characteristics. The elongation of the fundamental natural period is less than 10%. The damping increased up to approximately 1.5% for the larger amplitude of the forced vibration test. Such amplitude-dependent characteristics are expected based on the effects of nonstructural members.

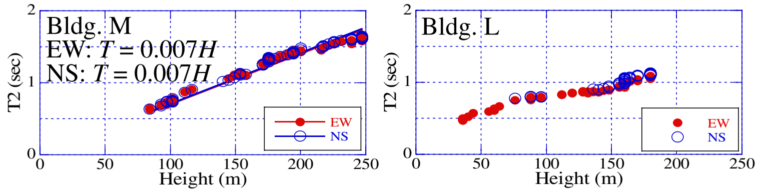
2.5 SSI effects on damping

The Damping Evaluation Subcommittee of the Architectural Institute of Japan (AIJ) has compiled a large volume of observation data on the natural period and damping ratio of buildings and has constructed graphs showing the relationships between both period and damping and building height (AIJ 2000). Figure 9 shows these relationships for

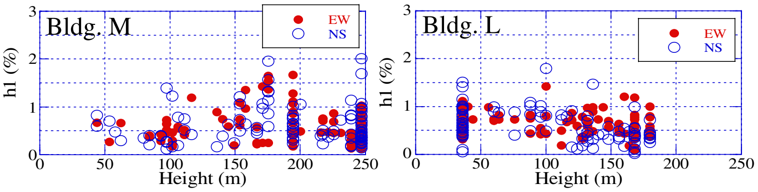
Fig. 5 Natural period and damping obtained from ambient vibration observation during construction



a 1st natural period

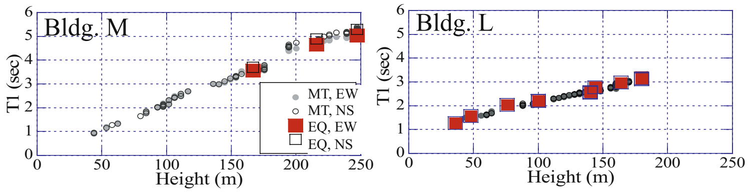


b 2nd natural period

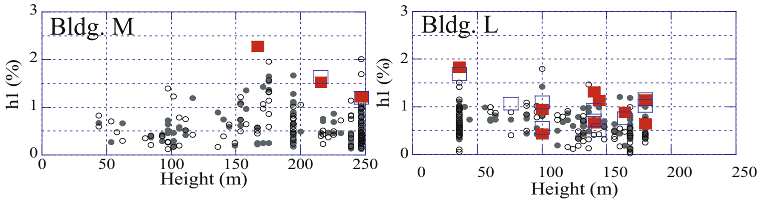


c 1st damping ratio

Fig. 6 Natural period and damping obtained from earthquake response during construction (with ambient test)



a 1st natural period



b 1st damping ratio

steel buildings based on relatively low-level response under ambient vibration and vibration tests. As with the results shown in Figs. 5 and 6 for two buildings under construction, the natural period is approximately proportional to the building height. In contrast, the damping ratio is low for the higher buildings. As the structural damping of steel structure is relatively low (less than 1% for the observed data), the radiation damping because of SSI dominates the modal damping.

The damping property because of radiation damping is expected to be inversely proportional to building height. For simplicity, we consider a building supported by a disk foundation of radius r on a homogeneous half-space with a shear wave velocity of V_s and a mass density of ρ. The impedance function K of this foundation is expressed approximately by (Fukuwa and Nakai 1989)

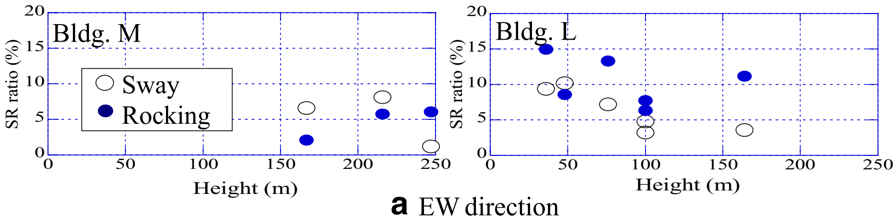
$$K \approx K_0 + i\omega C = \frac{8Gr}{2-\nu} + i\omega\rho V_S \pi r^2 \tag{1}$$

where K_0 is the static stiffness, C is the damping coefficient, G is the shear stiffness of the soil, and ν is Poisson's ratio. The corresponding damping ratio becomes

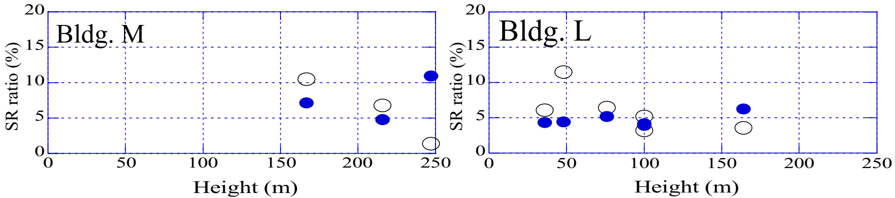
$$h \approx \frac{C\omega}{2K} = \frac{\pi(2-\nu)}{16} \times \frac{r\omega}{V_S} \approx \frac{2r}{V_S}\frac{1}{T} \propto \frac{1}{H} \tag{2}$$

where T is the natural period and H is the height of the building. The damping ratio increases for large low-rise buildings constructed on soft soil. This feature explains the damping properties shown in Fig. 9.

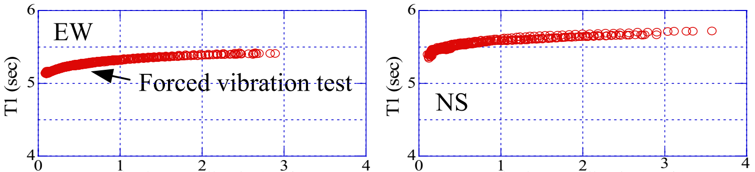
Fig. 7 Sway and rocking ratios of the first mode obtained from earthquake response during construction



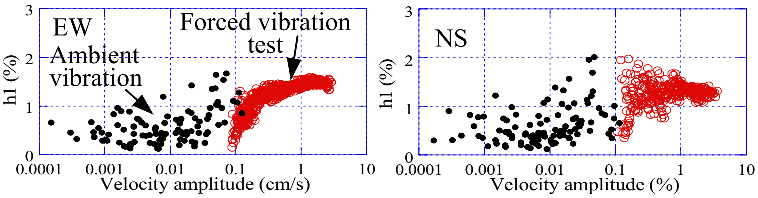
a EW direction



b NS direction



a 1st natural period



b 1st damping ratio

Fig. 8 Velocity amplitude dependency of the first natural period and damping of building M obtained from forced vibration and ambient test

3 Soil, building period, and ground motion in the Nagoya metropolitan area

3.1 Soil period in the Nagoya area

In this study, we consider the possibility of resonance in the Nagoya City area based on the predominant period of ground and the natural period of high-rise buildings. In Fig. 10, the locations of high-rise buildings are shown on the map along with the predominant period obtained from the H/V spectra of microtremors. Most high-rise buildings are located in the center of the city, where the soil period is around 3 to 4.5 s.

In the Nobi Plain, which includes the Nagoya City area, the depth to the seismic bedrock increases toward the west, and the period increases accordingly from 1 to 5 s. This trend is confirmed in the earthquake data shown in Fig. 11, which shows the predominant period and peak acceleration of seismic ground motions during the 2004 off Kii peninsula earthquake (Mj=7.4). A three-dimensional schematic diagram of the subsurface structure is also presented in the figure.

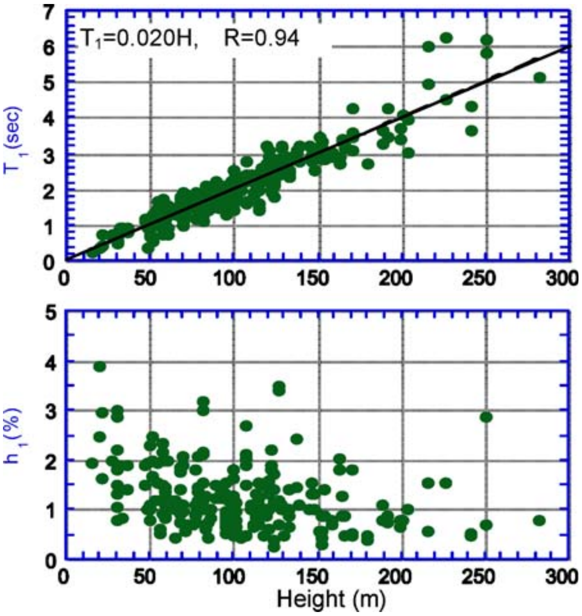


Fig. 9 Relationships between the first natural period and damping ratio and building height (AIJ 2000)

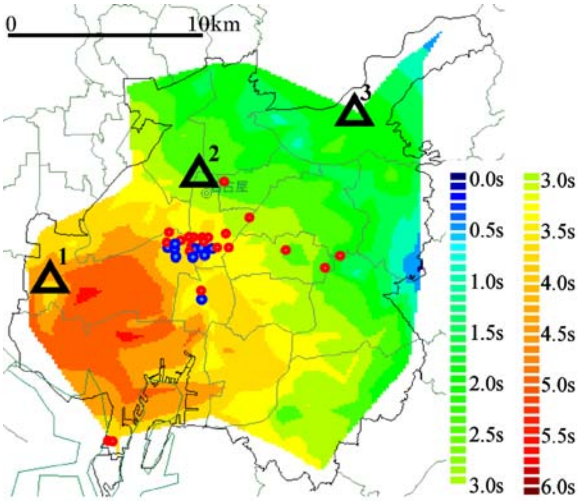
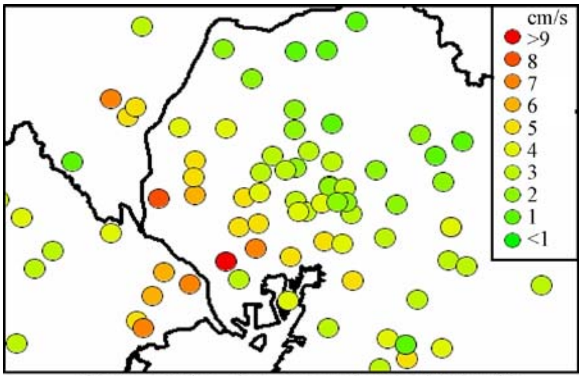
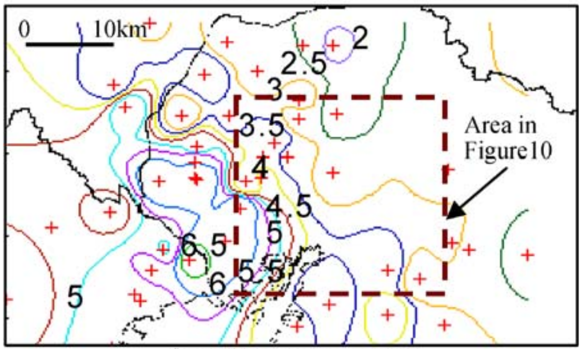


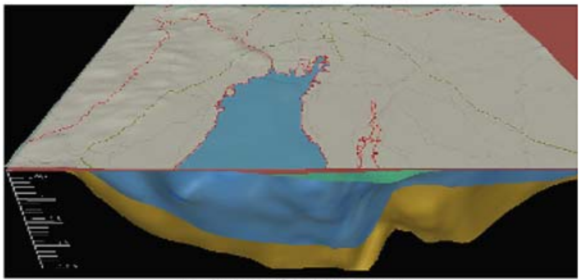
Fig. 10 Distribution of the predominant period of ground in the Nagoya City area based on the H/V spectrum of microtremor. *Blue* and *red dots* show the location of high-rise buildings (*blue dots* show the buildings selected for Fig. 12)



a Observation sites and peak velocity (cm/s)



b Predominant period (s)



c Subsurface structure

Fig. 11 Distribution of the observed peak acceleration and predominant period across the Nobi Plain during the 2004 off Kii peninsula earthquake (Mj=7.4)

3.2 Natural periods of high-rise buildings in Nagoya

Figure 12 shows the natural periods and corresponding soil periods of the 12 buildings indicated by the blue dots in Fig. 10. Because the heights of most of the high-rise buildings in Nagoya are between 80 and 150 m, the building periods are generally around 1.5 to 3 s, as shown in Fig. 9. Because the building periods are less than the soil periods, most of the buildings are not significantly affected by resonance.

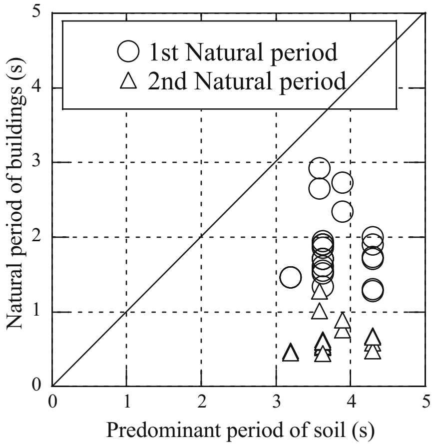


Fig. 12 Natural periods of buildings and predominant periods of soils for the 12 high-rise buildings indicated by the *blue dots* in Fig. 10

3.3 Seismic ground motion in the Nagoya area

Figure 13 shows the observed velocity time histories at sites north of the epicenter of the 2004 off Kii peninsula earthquake (Mj=7.4). Because the Nobi Plain is on a large sedimentary basin, the duration of Seismic ground motions are much longer in this area than elsewhere.

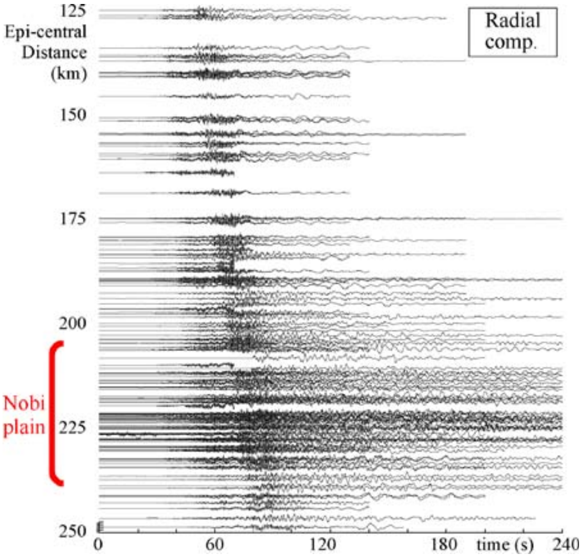


Fig. 13 Velocity time histories of ground motion observed during the 2004 off Kii peninsula earthquake (Mj=7.4)

Figure 14 shows the velocity time histories at the three sites indicated by triangles in Fig. 10 and their response spectra. Site no. 1 is located on an alluvial plain, site no. 2 is located on a diluvial upland, and site no. 3 is located on a diluvial hill. The duration, amplitude, and predominant period of the observed waves differ markedly between the three sites. At site no. 2, which is located next to the city hall in central Nagoya City, a sharp peak, which is caused by the surface layers above the seismic bedrock, occurs at around 3 s.

4 Some fundamental aspects of the response of long-period structures

4.1 Maximum floor response

The angle of story drift is one of the most general response criteria for assessing structural safety in the earthquake-resistant design of buildings. In this study, we adopt the angle of story drift, Δ, as a criterion and assume a triangular-shaped structural mode. If the height of the building is denoted as H, then the displacement at the top of the building is ΔH. As shown in Fig. 9, the natural period of a building is proportional to the building height: $T=\alpha H$. Then, the amplitudes of displacement, velocity, and acceleration at the top floor are expressed as follows:

$$\begin{aligned} y &= \Delta H \\ \dot{y} &= \frac{2\pi}{T}\Delta H = 2\pi\frac{\Delta}{\alpha} \\ \ddot{y} &= \left(\frac{2\pi}{T}\right)^2 \Delta H = 4\pi^2\frac{\Delta}{\alpha^2}\frac{1}{H} \end{aligned} \qquad (3)$$

Thus, the velocity response is constant regardless of the building height. In this study, we assume Δ to be 1/100 and α to be 0.02, and the maximum velocity response is approximately 3 m/s. The acceleration and displacement responses depend on the building height. For buildings of 200 and 20 m in height, the accelerations are 4.5 and 45 m/s^2, respectively, and the displacements are 2 and 0.2 m, respectively. Structures will show nonlinear behavior under such large deformation, and the natural period elongation will reduce the response to some extent. However, it is important to consider that the angle of story drift of 1/100 in structural design means a large response.

For base-isolated buildings, deformation of the base-isolation device, which is made of materials such

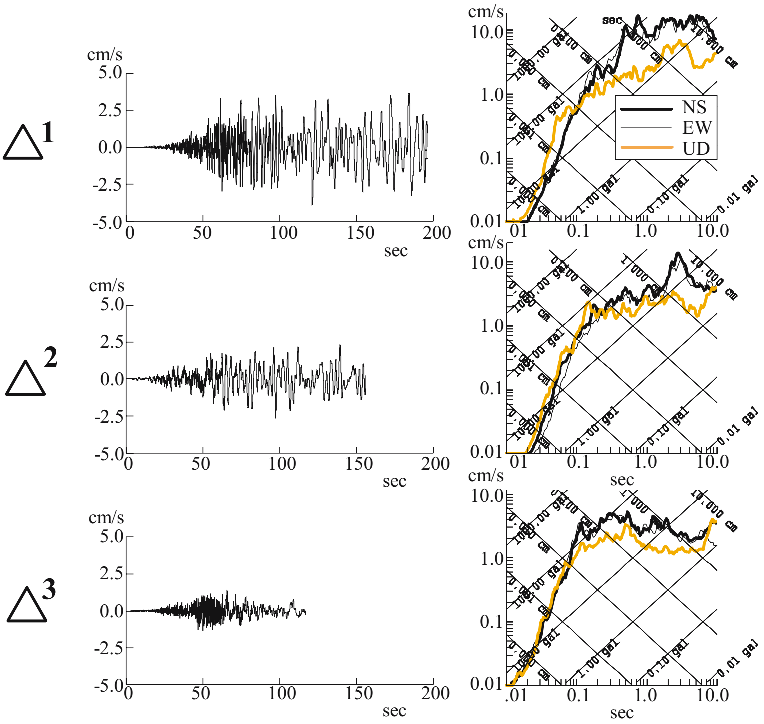


Fig. 14 Velocity time histories and response spectra for the 2004 off Kii peninsula earthquake (Mj=7.4), as recorded at the three sites indicated by the *triangles* in Fig. 10

as laminated rubber, is a principal criterion in the design. The displacement is constant, and the velocity and acceleration decrease with longer base-isolation periods. In this study, we consider a rigid superstructure placed on base-isolation devices that can deform by up to 0.5 m. If the base-isolation period is 4 s, then the subsequent response has a displacement of 0.5 m, a velocity of 0.78 m/s, and an acceleration of 1.23 m/s^2. Compared to the response of high-rise buildings, the floor response is drastically reduced.

4.2 Duration required for resonance

Considering the transient response of a single degree of freedom system with a long natural period and low damping, the amplitude of the stationary response becomes very large, although it takes a long time to reach a stationary state. The number of waves required for a β-fold increase in the stationary response is

$$n = -\frac{\ln(1-\beta)}{2\pi h} \tag{4}$$

In the case of β=0.8, we have nh=0.256. If the damping ratios are 5 and 1%, then 5 and 25 wave cycles are required, respectively, to increase the response. Because the natural period is approximately T=0.02H, for a typical building of 20 m in height and damping of 5%, 2 s is required to develop resonance. For a high-rise building with a height of 200 m and damping of 1%, the required duration of input motion is 100 s. With respect to high-rise buildings, it is important to consider the resonance effect of long-duration input motions caused by the plate-boundary-type large earthquakes, such as the predicted Tokai–Tonankai earthquake, as shown in Fig. 15.

Base-isolated buildings with a large damping ability of approximately 20% reach resonance after only one wave cycle. As a result, in designing a long-period structure with low damping, such as a super-high-rise building, it is important to select an input ground motion of sufficient duration.

4.3 Response for a rectangular pulse

The maximum acceleration response of an undamped single degree-of-freedom system subjected to a unit rectangular pulse input acceleration with a length of $T_0/2$ is

$$\ddot{y}_{\max} = \begin{cases} 2 & T = \frac{2\pi}{\omega} \leq T_0 \\ 2\sin\frac{\omega T_0}{4} & T = \frac{2\pi}{\omega} > T_0 \end{cases} \tag{5}$$

The above equation shows that a pulse with a period that is shorter than the natural period of a building is not destructive to the structure. For example, if the period of the pulse is T_0=1.0 s, then the response of low- and medium-rise buildings having periods shorter than 1.0 s is amplified to twice that of the ground motion. In contrast, the response of a high-rise building with a period of 5 s is only 60% of that of the ground motion. Such a short and pulse-like input ground motion is commonly observed during strong local earthquakes, such as the 1995 Kobe earthquake. This is one of the reasons why damage to low- and medium-rise buildings was greater than the damage to high-rise buildings in Kobe.

5 Shaking table for tracing and experiencing the floor response of high-rise buildings

5.1 Generated ground motion for structural design

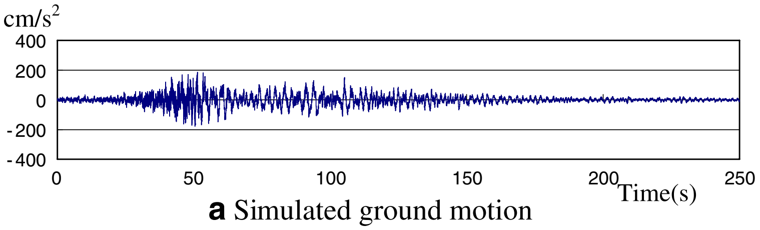
Because five of the buildings at site no. 2 in Fig. 15 that are used for offices of the local and national governments are to be retrofitted with base isolation, the authors generated the expected ground motion for the predicted Tokai–Tonankai earthquake (Mj=8.4) using the empirical Green's function method (Dan and Sato 1998). Figure 15 shows the generated acceleration time history and its response spectra. The response spectrum of an observed record is also plotted.

The maximum amplitude of the generated time history is not exceedingly large but does have a long duration with a specific period of 3 s. The response spectrum for a 1% damping ratio reaches a displacement of 3 m and a velocity of 5 m/s. Under such large floor responses, humans and objects in the buildings would be severely affected, even if the structure itself is not seriously damaged. This situation is not properly recognized by structural engineers or building users.

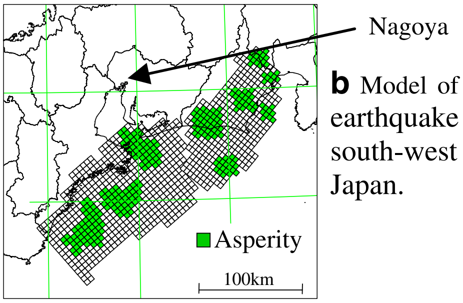
5.2 Development of long-stroke shaking table

To promote countermeasures against long-period ground motions arising from predicted massive earthquakes for

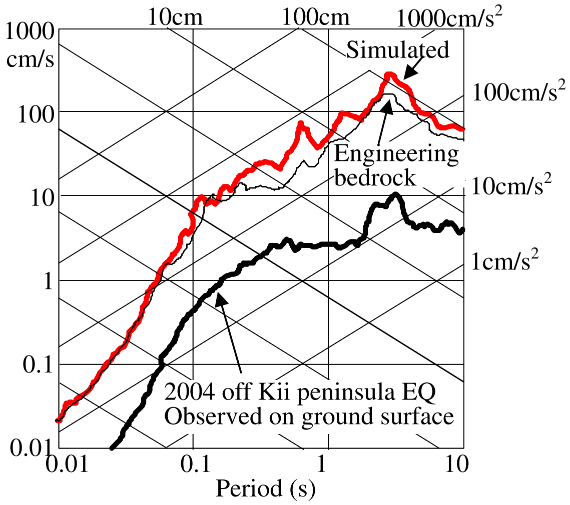
Fig. 15 Simulated ground motion for the expected Tokai–Tonankai earthquake (Mj=8.4) at site no. 2 and response spectra compared to those of the observed seismic record



a Simulated ground motion



b Model of expected Tokai-Tonankai earthquake (Mj = 8.4) in the south-west pacific coastal area of Japan.



c Response spectra for simulated ground (*h*=0.05)

high-rise buildings, it is necessary to inform structural designers and building owners that buildings might suffer from an unexpectedly large response because of resonance. To ensure that structural designers and building owners are aware of this risk, it is necessary for them to experience the amount of floor response. This will facilitate an understanding of the necessity of safety measures for indoor areas

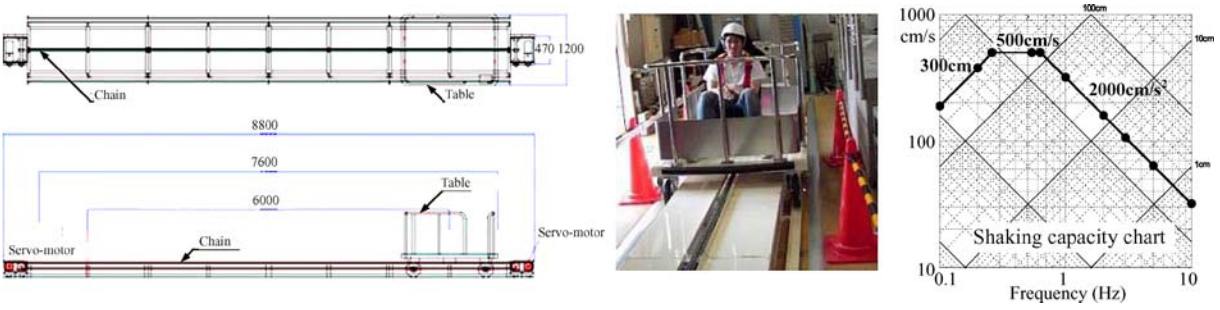


Fig. 16 The "Triple-L shaker"

and the importance of the addition of dampers to reduce the response.

Conventional shaking tables are unable to reproduce this movement because of the displacement limit of the dynamic actuator used to drive the table. We developed a new shaking table called the Triple-L shaker, which stands for Long-stroke Long-period Linear shaker, to reproduce the response of high-rise buildings. The innovation behind this concept is the use of two servo-motors that pull a chain connected to the shaking table by a rail, as shown in Fig. 16. Compared with ordinary shaking tables, this system does not require a large laboratory space or special power supplies. The table reproduces amplitudes of displacement of up to 3 m, velocities of 5 m/s, and accelerations of 20 m/s^2. The shaking capacity spectrum is also shown in Fig. 16. Using this table, people can easily experience the arbitrary response of various buildings for different soil conditions.

6 Conclusions

Evaluation of large response of long-period structures subjected to long-period seismic input is one of the most important aspects in structural design of high-rise buildings. In this study, the fundamental dynamic properties of high-rise buildings were explained by the observed results, which were obtained by newly introduced vibration observations programs. Damping of steel high-rise buildings was approximately 0.5–1.5%, considering the amplitude-dependent properties. This means that the effect of radiation damping by SSI is relatively small, and the resonance will be more serious for such buildings under long-period input motion of long duration. The predominant period and observed earthquake properties of the ground were investigated based on observed records for the Nobi Plain. The possibility of resonance of long-period structures was also pointed out considering the duration of seismic motion. Finally, a newly developed long-stroke shaking table, which is effective for encouraging structural engineers and building owners to take adequate countermeasures against large floor response of high-rise buildings, was introduced.

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