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Key Parameters Governing the Dynamic Response of Long-Period Structures

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Abstract

This study details the important factors (period and duration as well as intensity) involved in evaluating input ground motion for the design of long-period structures such as super-high-rise buildings and base-isolated buildings. First, the fundamental dynamic properties of buildings are explained via the results of seismic observations undertaken by the authors. Next, we describe the distribution of the predominant period of ground motion within the Nobi Plain and note the possibility of resonance within long-period structures. The typical features of long-period structures are then explained analytically using a simple formulation. Finally, we introduce recently developed equipment that is intended to convince structural engineers and building owners to take adequate countermeasures against the large response of the building with the effects of resonance.

1. Introduction

Many long-period structures such as super-high-rise buildings and base-isolated buildings are built in urban areas that are vulnerable to long-period seismic ground motion. A feature of super-high-rise buildings is their small damping of about 1% due to the effect of minor soil–structure interaction. Since the first super-high-rise buildings were built in Japan about 40 years ago, more than 1000 such buildings and about 2000 base-isolated buildings have been constructed. In the past, long-period ground motion generated by deep structures was not specifically taken into account in structural design; however, the long-period component of ground motion within sedimentary basins has recently been clarified from ground surveys and seismic observations, and the large floor response to such ground motion has become an important problem for structural engineers.

In the present-day structural design of super-high-rise buildings, the priority is to avoid resonance by separating natural periods from the predominant period of seismic ground motion and to increase damping using vibration-control devices. For base-isolated buildings, large damping of about 20% is expected because of the additional damper. Consequently, the most important factor in the evaluation of seismic ground motion is the difference between super-high-rise buildings and base-isolated buildings.

In this paper, the fundamental dynamic properties of buildings are demonstrated from a large quantity of seismic observation data obtained by the authors. We examine variations in the natural period and damping with different heights and structures of buildings. We clarify that the natural period is approximately proportional to the building height, while the damping ratio is inversely proportional. In the case of long-period buildings with small damping, when the natural period is close to the predominant period of soil, the seismic response of the building is enormously amplified for long-duration seismic ground motion. This phenomenon is explained from both observations and a simple analysis of a system with one degree of freedom.

It is important to first identify those buildings that resonate with long-period ground motion. To do this, we require equipment that can easily determine the period of the soil and the period and damping of the building. We have developed such a device, named 'μ: micron,' which is able to automatically evaluate the soil period using the H/V spectrum and the building period and damping using the random decrement (RD) method.

Next, it is important to inform structural engineers and building owners of the possibility of an unexpectedly large response due to resonance and to provide them with adequate countermeasures. To make structural engineers and building owners aware of the resonance risk, it is necessary for them to know the amount of floor response and understand the effect of adding a damper. To this end, we developed an innovative new shaking table, named 'Triple-L shaker,' which realizes long period and long stroke movements. This table can move with an amplitude of displacement of up to 3 m, a velocity of 5 m/s, and an acceleration of 20 m/s^2. In this way, it is possible to experience the terrible response associated with the resonance.

2. Building response and soil–structure interaction

Strategic seismic observation system

To clarify the dynamic behavior of buildings, we developed a strategic observation program that is able to distinguish the effects of different parameters that control building response, including building height, building structure, soil conditions, foundation type, building size, eccentricity, and the nature of adjacent buildings. Figure 1 shows such a program developed at Nagoya University. Fortunately, Nagoya University (the institution of the present authors) houses a large number of buildings, with many in their original state of construction and many with additional constructions such as seismic retrofit measures.

For example, to understand the differences in structural response between structurally similar buildings with different numbers of floors, observations can be carried out in a single building during its construction, as earthquakes are likely to occur throughout the construction period when different numbers of floors have been completed. Similarly, simultaneous observations of buildings of the same height that are located on the same site, but that are of different structural types, can provide data on the effects of different structures on structural response. From our observation program, it became

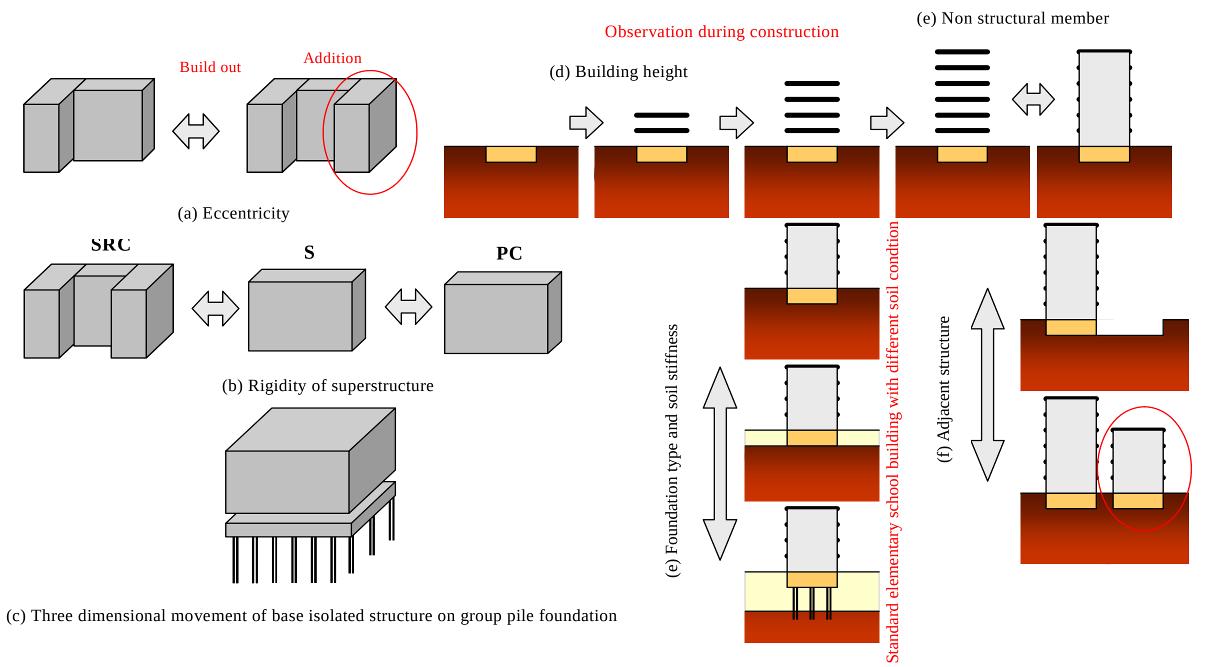


Figure 1 Components of seismic-response observations required for the analysis of factors contributing to the dynamic behavior of buildings

clear that the structural response of both low-rise and large buildings constructed on soft soils is strongly affected by soil–structure interaction (SSI). The SSI acts to increase the structural period and reduce the response because of additional radiation damping.

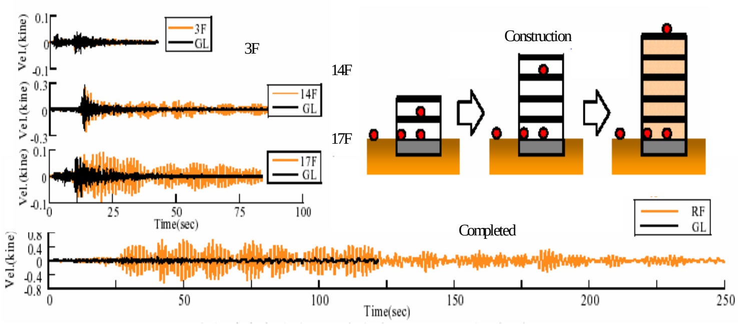
Variations in structural response with building height, structure type, and property of seismic ground motion

Figure 2 shows the seismic records for five typical buildings, including foundation and roof data for comparison. The left-hand figures show time histories during an earthquake with a distant epicenter, and the right-hand figures show corresponding results for an earthquake located directly beneath the campus. The differences in the response characteristics with different numbers of floors, structural types, and duration of seismic ground motion are apparent in the figure.

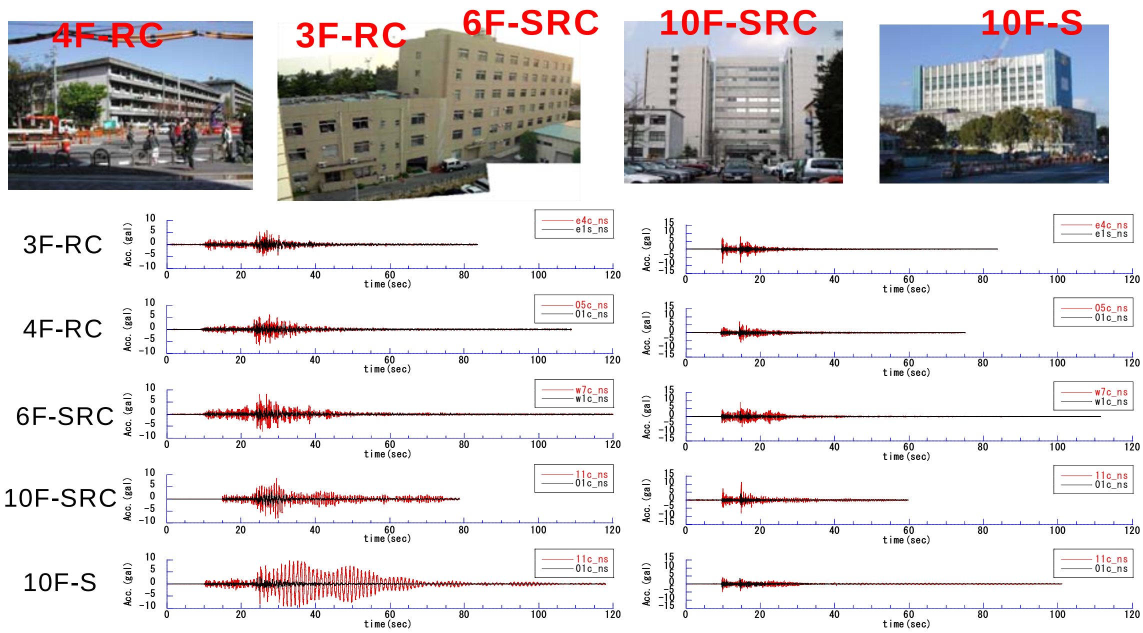
Changes in the seismic response of tall buildings during the construction period

Figure 3 presents the earthquake response records of an 18-story steel-frame building while construction. The data reveal a tendency for increased resonance and a reduction in radiation damping in taller buildings.

Figure 4 shows the changes in natural periods and damping ratios obtained from microtremor records for a 47-story building while under construction. The natural period increases almost linearly with building height, both for the first and second modes, while the damping ratio is scattered around 0.5%. This damping value corresponds to the material damping of the steel itself. In the figure, the earthquake response for the 2005 Miyagiken-oki earthquake (M7.2) is shown for the time when the floor slab was built up to 33 stories in height. As the damping ratio is less than 1%, the building response is amplified to almost 20-times the ground motion, and it does not readily decay.



Figur 3 Record of an 18-story building (under construction) during earthquake



(a) Distant Earthquake:2001 Shizuokaken-chubu(M4.8) (b) Subjacent Earthquake:2001 Aichiken-seibu(M4.1)

Figure 2 Records of the observations of five buildings during an earthquake (left-hand figures, distant epicenter; right-hand figures, nearby epicenter)

Changes in structural amplification during construction

To confirm the magnitude of the SSI effect on the dynamic response of a building, we compiled the observation results of microtremors for a 10-story steel-frame building and a 10-story steel-reinforced concrete (SRC) building (Figure 5).

The results for the semi-completed buildings, at 6 and 8 stories in height, are shown in addition to the results for the completed heights of 10 stories. Figure 5 provides a comparison of the Fourier spectral ratios of microtremor records for the soil and the building roof and for the foundation and the building roof. A greater SSI effect is recorded in the stiffer SRC building, particularly at lower heights. In contrast, there is almost no SSI effect recorded in the plain steel-frame building, especially at greater heights. When the superstructure is rigid relative to the soil, the soil deformation is large; consequently, SSI effects such as period-lengthening, additional radiation damping, and input loss are also large.

SSI effects on damping

The Damping Evaluation Sub-committee 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 constructed graphs that show the relationships of period and damping to building height (AIJ, 2000). Figure 6 shows these relationships for steel buildings. As with the results shown in Figure 4 for a building under construction, the natural period is approximately proportional to the building height. In contrast, the damping ratio is inversely proportional to building height. As the material damping of steel is less than 1%, the radiation damping due to SSI dominates the modal damping.

The damping property due to radiation damping is examined below. For simplicity, consider a building supported by a disc foundation of radius r on a homogeneous half-space with a shear wave velocity of Vs and a mass density of ρ. The impedance function of this foundation is expressed approximately by

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

The corresponding damping ratio becomes

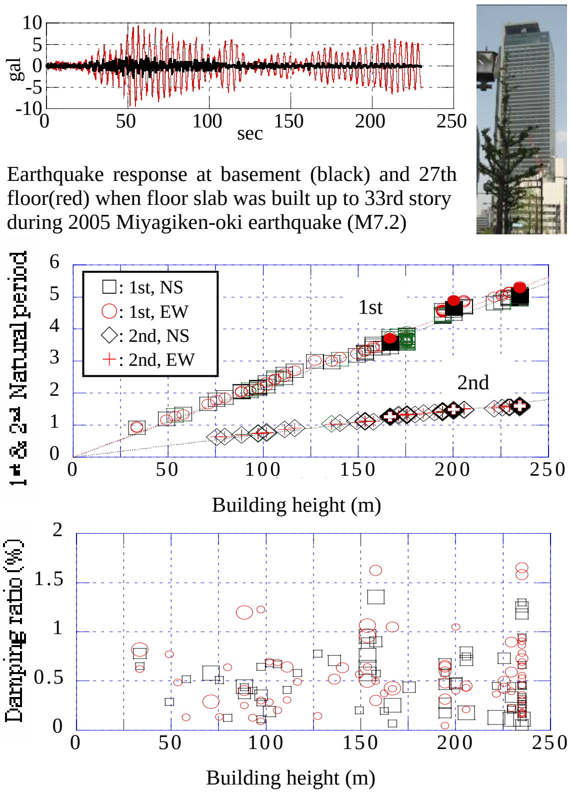


Figure 4 Changes in the natural period of a 47-story steel building during construction and an example of an earthquake response record

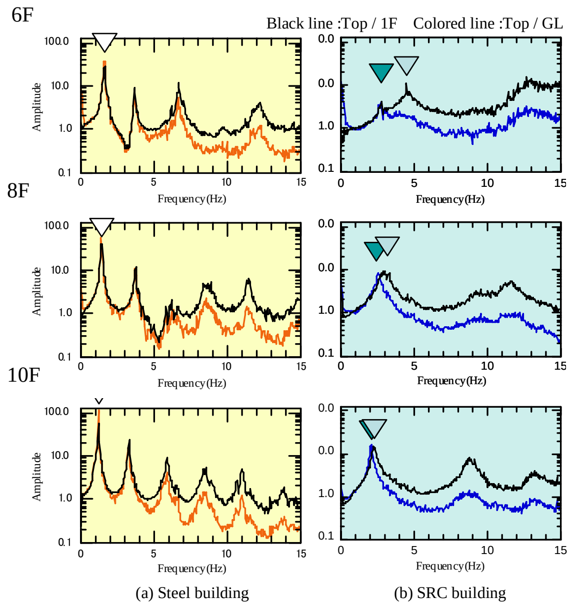
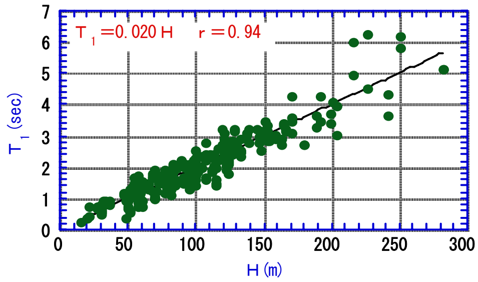
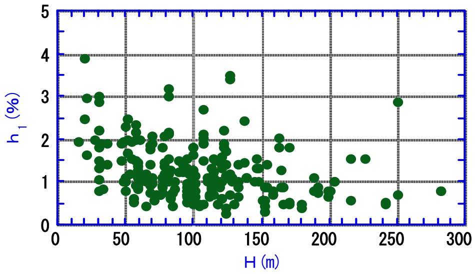


Figure 5 Fourier spectral ratio of microtremor for a 10-story SRC structure and a 10-story steel structure under construction (building vs. soil; building vs. foundation)



(a) Natural period



(b) Damping ratio

Figure 6 Relation between the first natural period and damping ratio vs. building height (after AIJ (2000))

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

where T is the natural period and H is 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 Figure 6.

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

Soil period in the Nagoya area

Here we consider the possibility of resonance in the Nagoya City area. In Figure 7, the locations of super-high-rise buildings are shown on the map along with the predominant period obtained from the H/V spectra of microtremor records. Super-high-rise buildings are clustered in the central city where the soil period is around 3 to 4.5 s.

In the Nagoya City area, the depth to 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 Figure 8, which shows the predominant period of seismic ground motion during the 2004 Tokai-oki earthquake (M7.4). A three-dimensional schematic view of the subsurface structure is also presented in the figure.

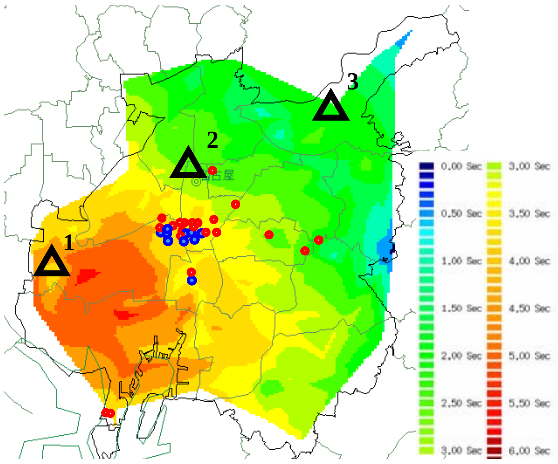


Figure 7 Distribution of the predominant period in the Nagoya City area based on the H/V spectrum of microtremors, and the sites of super-high-rise buildings (blue dots show the locations of buildings selected for microtremor observations in Figure 9)

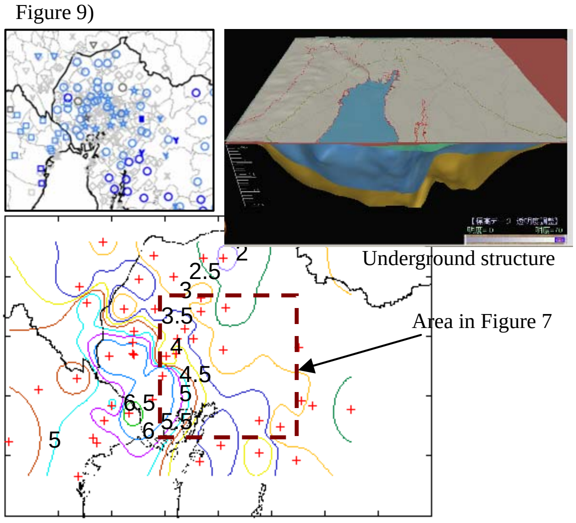


Figure 8 Distribution of the predominant period across the Nobi Plain during the 2004 Tokai-oki earthquake (M7.4), and locations of seismic observation stations and subsurface structure

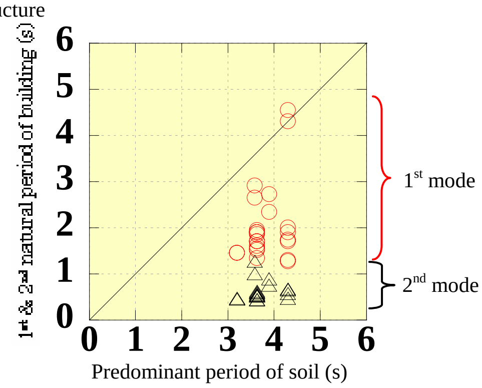


Figure9 Natural periods of buildings and predominant periods of soils for the 12 super-high-rise buildings indicated by blue dots in Figure 7

Natural periods of super-high-rise buildings in Nagoya

Figure 9 shows the natural periods and corresponding soil periods of the 12 buildings indicated by blue dots in Figure 7. As the heights of most of the super-high-rise buildings in Nagoya are between 80 and 150 m, building periods are generally 1.5 to 3 s, as shown in Figure 6. As the building periods are less than the soil periods, most of the buildings are unaffected by resonance.

Seismic ground motion in the Nagoya area

Figure 10 shows the time histories of the velocity response at sites north of the epicenter of the 2004 Tokai-oki earthquake (M7.4). As the Nobi Plain is located above a large sedimentary basin, the duration is much longer in this area than elsewhere.

Figure 11 shows the velocity time histories and response spectra at the three points indicated by triangles in Figure 7. Point 1 is located upon an alluvial plain, Point 2 on a diluvial upland, and Point 3 on a diluvial hill. The duration, amplitude, and periods differ markedly between the three sites. At Point 2, which is located next to the city hall in central Nagoya City, a sharp peak occurs at around 3s.

Generated ground motion to test structural design

As five of the buildings at Point 2 used for offices of the local and national government are to be retrofitted with base-isolation, the authors generated the ground motion expected for the predicted Tokai-Tonankai earthquake (M8.4) using the empirical Green's function method. Figure 12 shows the generated acceleration time history and its response spectra. The response spectrum of observed data for the 2004 Tokai-oki earthquake is also plotted.

The maximum amplitude of the generated time history is not exceedingly large, but it shows 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. Even if the building does not suffer serious structural damage, the interior areas within higher floors will be severely affected. Most structural designers and building owners would never have imagined this terrible response. As existing shaking tables are unable to reproduce this movement, nobody has experienced this response. As described later in the text, we developed a new and novel shaking table that

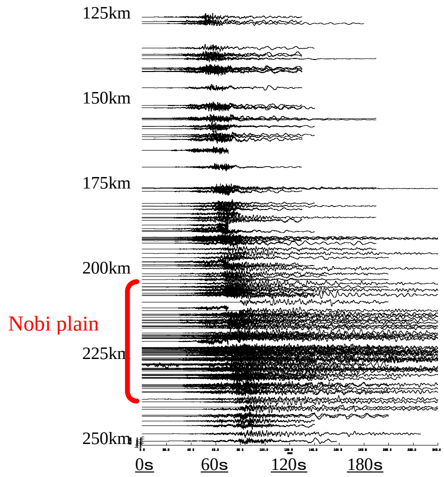


Figure 10 Velocity time histories of ground motion observed during the 2004 Tokai-oki earthquake (M7.4)

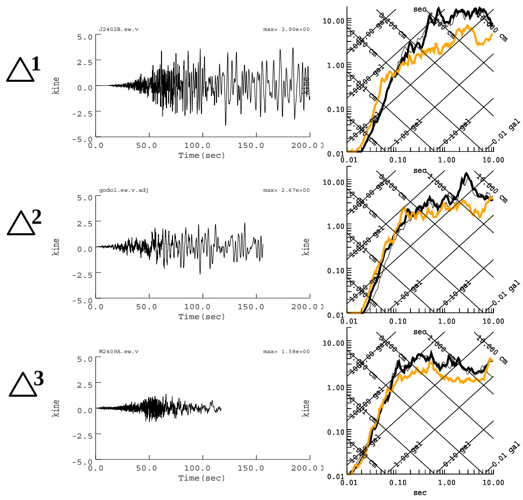


Figure 11 Velocity time histories and response spectra for the 2004 Tokai-oki earthquake (M7.4), as recorded at the three sites indicated by triangles in Figure 7

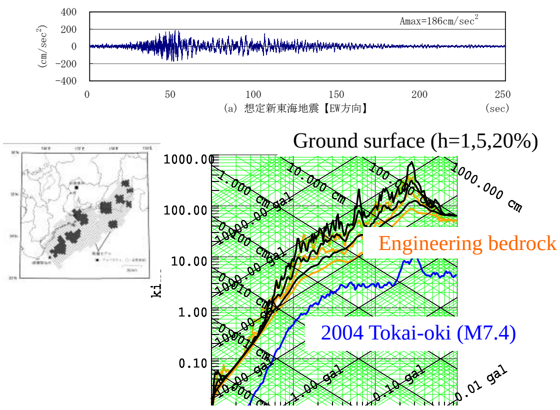


Figure 12 Simulated ground motion for the Tokai-Tonankai earthquake (M8.4) at Point 2 and response spectra compared to those for the 2004 Tokai-oki earthquake (M7.4)

is able to simulate the response of the top floor of a resonating super-high-rise building.

4. Basic dynamic properties of buildings based on a simple formulation

Here, simple formulations are presented to describe the fundamental dynamic properties of buildings.

Maximum floor response

Structural designers generally adopt the angle of story drift as a criterion for assessing safety of the structure in the earthquake-resistant design of super-high-rise buildings. Here, 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 by H, the displacement at the top of the building is ΔH. As shown in Figure 6, 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:

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

The velocity response is constant regardless of the building height.

Here, we assume 1/100 for Δ and 0.02 for α. In this case, the anticipated velocity response is about 3m/s. The acceleration and displacement responses depend on the building height. For buildings of 200 and 20m in height, the acceleration is 4.5 and 45 m/s^2, respectively, and the displacement is 2 and 0.2 m.

For base-isolated buildings, deformation of the base-isolation device, which is made of material such 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. Here, 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, the subsequent response has a displacement of 0.5 m, velocity of 0.78 m/s, and acceleration of 1.23 m/s^2. Compared to the response of super-high-rise buildings, the floor response is drastically reduced.

Duration required for resonance

Next, we consider the transient response of a system with one degree of freedom in terms of sinusoidal ground motion. If we denote the exciting circular frequency by p, the natural circular frequency by ω, and the damping ratio by h, the transient response becomes

$$y = A\left[\cos(pt-\theta) - e^{-h\omega t}\left\{\cos\theta\cos\omega' t + \frac{h\cos\theta + (p/\omega)\sin\theta}{\sqrt{1-h^2}}\sin\omega' t\right\}\right]$$
$$A = \frac{(p/\omega)^2}{\sqrt{\left\{1-(p/\omega)^2\right\}^2 + 4h^2(p/\omega)^2}} \quad \theta = \tan^{-1}\frac{2h(p/\omega)}{1-(p/\omega)^2} \quad \omega' = \omega\sqrt{1-h^2} \qquad (4)$$

where A is the dynamic amplification factor and θ is the phase delay. The first term is the stationary vibration and the second is the free vibration. In the case of resonance ($p = \omega$), Eq. (4) becomes

$$y = \frac{1}{2h}\left\{\sin\omega t - \frac{e^{-h\omega t}}{\sqrt{1-h^2}}\sin\omega' t\right\} \approx \frac{1}{2h}\left(1-e^{-h\omega t}\right)\sin\omega t \qquad (5)$$

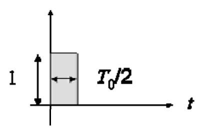
This equation shows that in the case of a long-period building with slight damping, such as a super-high-rise building, the amplitude of the stationary response becomes very large, although it takes a long time to reach a stationary state. Let us examine the number of waves required for an increase up to β-times the stationary response. This is easily derived from Eq. (5):

$$n = -\frac{\ln(1-\beta)}{2\pi h} \qquad (6)$$

In the case of $\beta = 0.8$, we have $nh = 0.2561$. If the damping ratio is about 1%, as with a steel-frame structure, 25 wave cycles are required to grow up the response. As the natural period is approximately $T = 0.02\,H$, for a typical building of 20 m in height a duration of 10 sec is required to develop resonance. For a super-high-rise building with a height of 200 m, the required duration of input motion is 100 sec.

Base-isolated buildings with a large damping ability of about 20% reach the 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 with sufficient duration.

Response for a rectangular pulse



The response of an undamped system with one degree of freedom to a unit rectangular pulse acceleration with a length of $T_0/2$ is expressed in simple terms by

$$y=\begin{cases}-\dfrac{1}{\omega^2}\left(1-\cos\omega t\right) & t\le\dfrac{T_0}{2}\\[2ex] -\dfrac{2}{\omega^2}\sin\dfrac{\omega T_0}{4}\sin\left(\omega t-\dfrac{\omega T_0}{4}\right) & t>\dfrac{T_0}{2}\end{cases}\qquad(7)$$

From this equation, the maximum acceleration response is

$$\ddot{y}_{\max}=\begin{cases}2 & T=\dfrac{2\pi}{\omega}\le T_0\\[2ex] 2\sin\dfrac{\omega T_0}{4} & T=\dfrac{2\pi}{\omega}>T_0\end{cases}\qquad(8)$$

The above equation shows that a pulse whose period 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 sec, the response of low- and medium-rise buildings whose periods are shorter than 1.0 sec is amplified to twice that of the ground motion. In contrast, the response of a super-high-rise building with a period of 5 sec is only 60% of that of the ground motion. This is one of the reasons why damage to low- and medium-rise buildings during the Kobe earthquake was greater than the damage to high-rise buildings.

5. Newly developed equipment designed to identify resonant buildings and reproduce floor response

MicrOn 'μ': equipment designed to identify resonant buildings

To identify buildings that resonate with long-period ground motions, it is necessary to develop equipment that is easily able to determine the period of the soil and the period and damping of the building.

We have developed such a piece of equipment. The name of the device is MicrOn 'μ', which stand for the 'Microtremor Observation and Analysis Unit'. Three component moving coil sensors and a touch-panel PC are assembled in a carry case, as shown in Photo 1. The PC monitors the time histories and their Fourier spectra and can also automatically evaluate the soil period from the H/V spectrum and the building period and damping using the RD method.

Photo 1 'μ' which is able to identify resonant building by evaluating the period and damping using H/V and the RD method, respectively

The 'Triple-L shaker:' a shaking table designed to trace the floor response of super-high-rise buildings

To promote countermeasures for super-high-rise buildings against long-period ground motions arising from predicted massive earthquakes, it is necessary to inform structural designers and building owners that buildings might suffer from an unexpectedly large response due to 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. They will then understand the necessity of safety measures for indoor areas 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 named the 'Triple-L shaker,' which stands for he 'Long-stroke Long-period Linear shaker,' to reproduce the response of super-high-rise buildings. The innovation in this idea is the use of two servo-motors that pull the rope connected to the shaking table on the rail from both sides, as shown in Figure 13 and Photo 2. Compared with ordinary shaking tables, this system doesn't require a large space or special power supplies. The table reproduces amplitudes of displacement of up to 3 m, velocities of 5m/s, and acceleration of 20m/s^2. Using this table, people can easily experience the arbitrary response of various buildings upon different soil conditions.

Photo 2

References

AIJ, 2000, Damping in Buildings, Architectural Institute of Japan

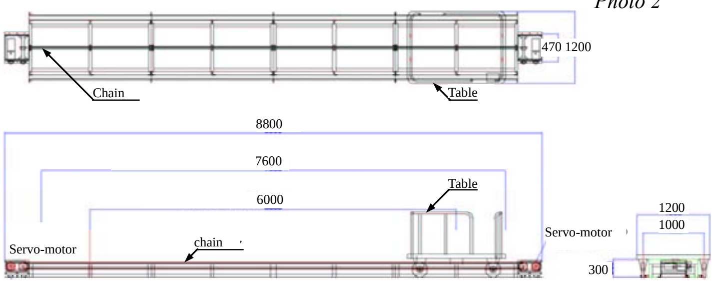


figure13 The 'Triple-L shaker,' which is able to trace the floor response of resonant super-high-rise buildings