Measuring Quake-Resistance in Buildings

In last month's column introducing initiatives of Japan's Building Research Institute, we looked at the Institute's work to improve the fire-resistance performance of buildings. In this month's issue, we turn to the Institute's research into strong motion observation and measurement of the structural safety of buildings.

The problem of building structures capable of withstanding earthquakes is one that Japan confronts perennially, given that it is highly prone to suffering earthquakes. The first step to ensuring structural earthquake resistance is understanding earthquake ground motion and the effect this phenomenon has on buildings.

The Fukui Earthquake of 1948 caused more than 3,700 fatalities and destroyed more than 36,000 residences. There was no way of knowing what the earthquake ground motion at the site was like, however, nor how the buildings there were shaken so as to cause their destruction. While it is true there were, in fact, seismographs around at that time, such instruments as did exist were intended to measure only minute tremors; they were incapable of recording tremors of intensity sufficient to result in damage, as such violent shakes exceeded the design tolerances of these devices.

Lessons learned from the experience of the Fukui Earthquake gave rise to a renewed awareness of the need to reliably record large earthquake shakes, which led to the development of strong motion instruments for the purpose. Strong motion observation accordingly commenced in Japan in the 1950s, with the aim of reliably and accurately measuring structural vibrations that arise in the ground, as well as buildings and other structures, when major earthquakes occur. Particular emphasis was laid upon strong motion observation concerning buildings, owing to the direct threat that damage to these structures poses to their occupants. Aggressive efforts were accordingly made by the now former Japanese Ministry of Construction, among other organizations, to install strong motion seismographs in buildings.

Carrying out strong motion observations when the first skyscrapers were built in Japan in the 1960s led to verifications of analytical techniques and methods of design, and the fruits of these efforts have been put to good use in construction since that time. Technologies such as Seismic Isolation and Seismic Response Control, which first came into practical use in the 1980s, were also verified for performance by means of strong motion observation. They have rapidly proliferated since their initial adoption for their efficacy in improving structural quake resistance. In this fashion, strong motion observation of buildings has played a crucial part in the evolution of seismic technology.

A strong motion seismograph is a device that measures vibrations in the ground and buildings when an earthquake happens. Strong motion seismographs are typically made to measure vibrations traveling east to west, north to south, and vertically, as well as to function reliably regardless of how intense the shakes affecting them may be. Such shakes may be represented as changes in displacement, velocity, or acceleration over time. The strong motion seismograph commonly measures acceleration.

When an earthquake occurs in Japan, a detailed Distribution of Seismic Intensity Scale report is published within a matter of minutes. At present, the Japan Meteorological Agency (JMA) seismic intensity scale[1] is determined by computations derived from the strong motion record of a given quake. Another name for a strong motion seismograph that is specifically used in computations of seismic intensity is a seismic intensity meter. Together, the JMA, prefectural governments, and the Japanese National Research Institute for Earth Science and Disaster Prevention have distributed more than 4,000 seismic intensity meters and strong motion seismographs, which are used in this selfsame publication of seismic intensity following an earthquake. These seismic intensity meters and strong motion seismographs are planted on open ground.

Strong motion observation of buildings, by contrast, involves installing multiple sensors in a building and making a three-dimensional recording of the vibrations that the building experiences in an earthquake. What generally happens is as follows: a building's founda-

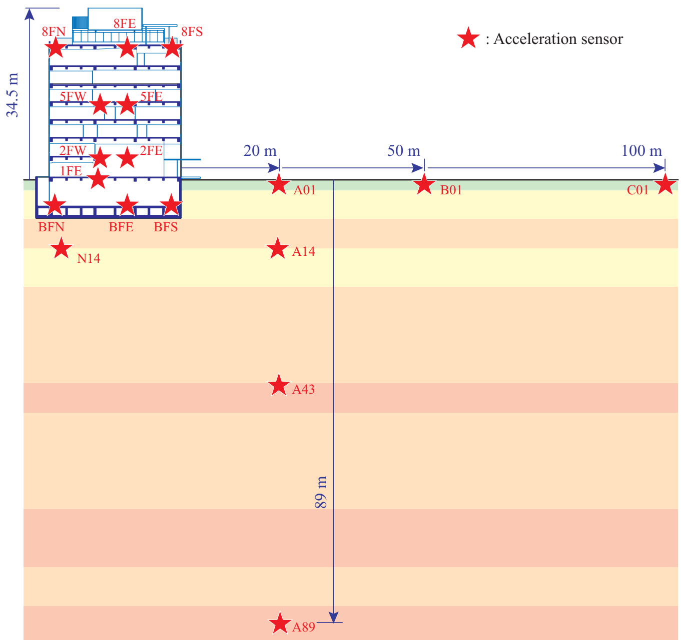

Figure 1: Observation taken by placing a plurality of seismic sensors both in a building and the surrounding ground. This observation used the portion of the Building Research Institute's Strong Motion Observation Network with the highest density of sensors in place.

THE NIIGATA NIPPO

Photo 1: The Niigata Earthquake of June 16, 1964, caused the four-story buildings of Kawagishi-cho Apartments to list significantly off center or topple altogether.

tion is shaken by an earthquake, the oscillations of the foundation are amplified throughout the building, and the uppermost portion of the building shakes widely. The ways that buildings shake vary depending on the building's structure and shape, and as a consequence, the placement of seismic sensors is planned in accordance with the characteristics of any given building. **Figure 1** depicts an example of an observation taken by placing a plurality of seismic sensors both in a building and the surrounding ground. The example shown involves the portion of the Japanese Building Research Institute's Strong Motion Observation Network with the highest density of sensors in place. With that caveat in mind, observing shaking on the part of a building in an earthquake requires that seismic sensors be installed in the foundation and at the top of that building at a minimum.

Strong Motion Observation by Japan's Building Research Institute

The Building Research Institute has been conducting strong motion observation continuously for more than fifty years. Many of the records of historical strong earthquakes in Japan, such as the records from the prefectural-run housing in the Niigata Earthquake of 1964 or the records from Tohoku University of the Off Miyagi Prefecture Earthquake in 1978, have been obtained by the Building Research Institute's Strong Motion Observation Network. The aforementioned Niigata Earthquake, which happened on June 16, 1964, caused tremendous amounts of damage centered on Niigata Prefecture, on the Sea of Japan coast of Honshu, Japan's main island. The Kawagishi-cho Apartments, which were operated by the Niigata Prefectural Government, sustained severe damage, when its four-story buildings listed significantly off center or toppled altogether (**photo 1**). The Building Research Institute's strong motion seismographs were installed in one of the buildings that listed to a degree off center, and the records obtained from those strong motion seismographs provided the first strong motion record of a damaging earthquake in Japan.

The resulting strong motion record clearly indicated that the ground liquefied during the quake, revealing that the listing and toppling of buildings during the quake was due to the Liquefaction[2] of the ground on which they stood. As for the Off Miyagi Prefecture Earthquake in 1978, records were obtained from the strong motion seismographs that were installed in the first and ninth floors of a nine-story building on the Tohoku University campus. The maximum acceleration readings obtained from the strong motion records from the strong motion seismographs that were installed on the ninth floor of the building in question exceeded one g[3], and the resulting records were useful in verifying the philosophy and techniques that were applied to quake resistance at the time. The strong motion records of the observations that were taken on the first floor of the building were used as the input seismic motion for building quake resistance designs.

As of this writing, the Building Research Institute's strong motion observation involves 214 seismic sensors located in 76 sites across Japan, making it the preeminent firm working in strong motion observation of buildings in the country. **Figure 2** depicts the locations of the Institute's observation sites. Of these, one-third are located in the metropolitan region centering on Tokyo, with the rest distributed so as to provide nationwide coverage, primarily focused on major regional cities. The Institute has made improvements to the organization of its systems and to its devices since it commenced observations, and is installing the very latest in digital strong motion seismographs at all of their observation sites as of this writing. Almost all of the Institute's strong motion seismographs are connected to the Building Research

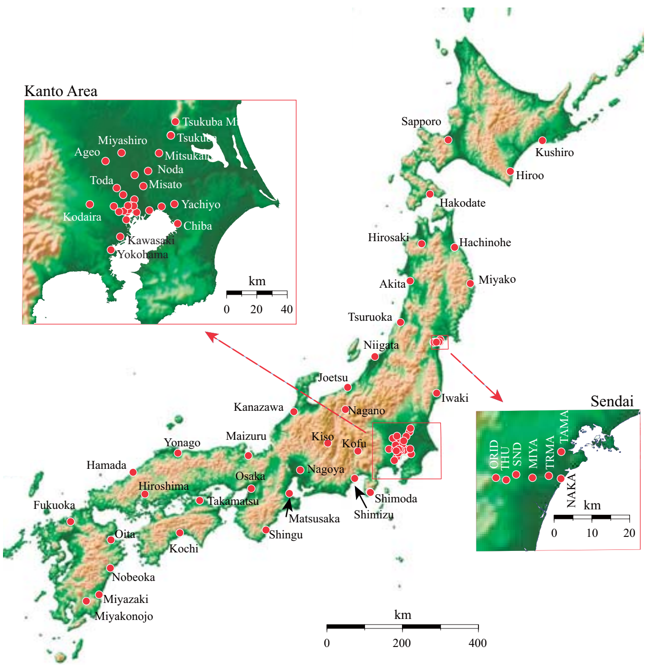

Figure 2: Locations of the Building Research Institute's observation sites

THE HOKKAIDO SHIMBUN PRESS

Photo 2: An earthquake off the Pacific Coast of Hokkaido in 2003 caused oil storage tanks to catch fire at a refinery in Tomakomai, over 200 km from the epicenter, when the naphtha and petroleum in the tanks shook in synchronization with the slow moving tremors.

Institute by telephone lines, allowing reduced complexity in maintenance and rapid collection of data records.

Ascertaining of Input Seismic Motion as Applied to Buildings

Following the Kobe Earthquake of 1995, the JMA and other organizations assembled a large-scale Seismic Intensity Network, which has accumulated many data records concerning tremors, or seismic vibrations, happening in the ground when major earthquakes occur, and consequently allowed the obtainment of a variety of kinds of knowledge about the subject. At the same time, analyses of the resulting tremendous volume of data have led to the discovery that the seismic vibrations that are observed in the ground do not act directly on buildings standing on that ground. The input seismic motion that acts on buildings is altered by the very presence of the buildings themselves, rather than simply the conditions of the ground on which the buildings stand. The alterations in question are complicated and very difficult to assess, as they are influenced by the scale and embedding of the building, as well as the form of the foundation. The strong motion observation of the building is an efficacious means of accurately assessing such phenomena and elucidating what sort of effect they have on the seismic response of the building. An example is depicted in **figure 3**. The graph shown on the right hand side of this figure compares the intensity of the strong motion records obtained to-date from the basement (B1 floor) of a ten-story government building in the city of Hachinohe and the ground level (GL) nearby at respective maximum acceleration values. The maximum acceleration in the basement (B1) is as much as half or less that of the surface of the ground away from the building, owing to the basement being affected by the building itself. Collection and analysis of case histories of observations of a variety of ground surfaces and buildings facilitates accurate assessment of input seismic motion, leading to improvements in quake resistance technologies.

Long-period Earthquake Motion and Responding with Long-period Buildings

Long-period earthquake motion[4], in which long, slow shakes occur, has drawn people's attention in recent years. The motivation for such interest lies in the Off Tokachi Earthquake on the Pacific Coast of Hokkaido, in 2003. As a result of this earthquake, oil storage tanks caught fire at a refinery located in the city of Tomakomai, over 200 km (125 miles) from the epicenter (**photo 2**). The fire was caused by a sloshing effect, wherein the naphtha and petroleum in the tanks experienced great shaking in synchronization with the slow moving waves that were emitted by the earthquake. The quake intensity registered at Tomakomai was 5-, which would normally not have been a strong enough level to cause damage. At times, long-period earthquake motion may cause unimaginable catastrophe, and have a significant effect on the vibrations that buildings suffer as well.

Skyscrapers first appeared on the Japanese landscape in the 1960s, and

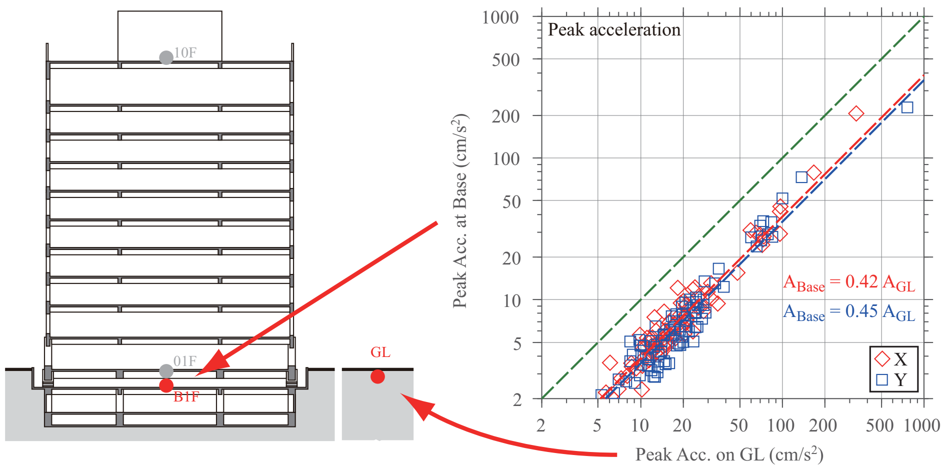

Figure 3: The graph on the right compares the intensity of the strong motion records obtained to-date from the basement (B1 floor) of a ten-story government building in the city of Hachinohe and the ground level (GL) nearby at respective maximum acceleration values.

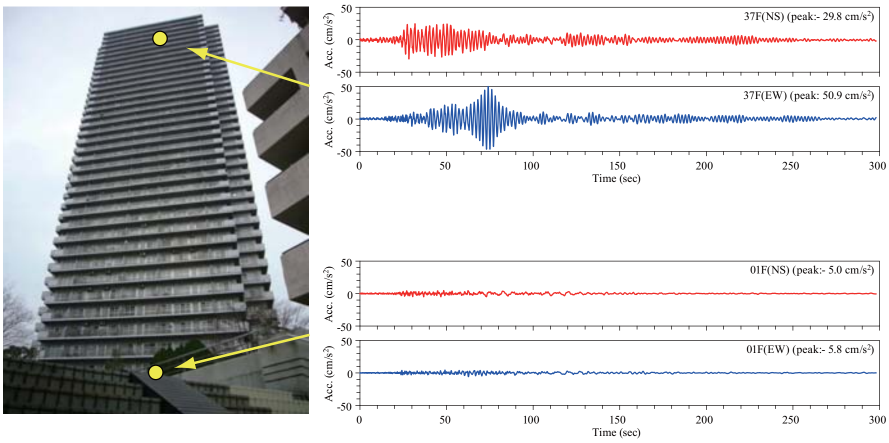

Figure 4: Strong motion record of the first and thirty-seventh floors of a thirty-seven-story apartment building built of reinforced concrete in the Tokyo Bay area following the Chuetsu Offshore Earthquake of July 16, 2007.

base-isolated buildings came into general use in the 1980s. Many skyscrapers and base-isolated buildings are being built in metropolitan areas across Japan as of this writing. At the same time, there are also many examples of Japanese cities making expansions into large plains areas. The soft, flexible, thick sedimentary layers and geographical features of the ground on which these cities stand cause a significant risk of amplification of long-period earthquake motion. Skyscrapers and base-isolated buildings are both characterized by having a long natural period[5], which leads to a risk that they will resonate with long-period earthquake motion that would be amplified by large plains, resulting in the buildings being assaulted by vibrations beyond imagination. It is thus crucial to employ the latest knowledge and technology to accurately envision what would happen should a major earthquake strike at some future time.

Figure 4 shows a strong motion record of the first and thirty-seventh floors of a thirty-seven-story apartment building built of reinforced concrete in the Tokyo Bay area that was obtained on the occasion of an earthquake that occurred in the Sea of Japan off the coast of the Chuetsu region of Niigata in 2007. Whereas the first floor of the building experienced quake vibrations on the order of five gals[6], a small degree of acceleration, this selfsame acceleration was amplified between six and nine times at the top of the building, and the vibrations went on at that part of the structure for five minutes or more. Given that the typical earthquake duration is on the order of one to two minutes, these results mean that the top of this building shook for as much as three times as long. The facts are that major Japanese cities such as Tokyo have not experienced major quake vibrations since the commencement of strong motion observation, and old models of strong motion seismographs lacked the capability to capture strong motion records that vibrate long and slowly, and with a small amplitude. High performance strong motion seismographs have been assembled in recent years, however, and have been shedding light on phenomena such as these. The Chuetsu Earthquake of 2007 registered a magnitude 6.8 on the Richter Scale, and the future great earthquake that people fear is envisioned to be magnitude 8.0 or greater. Measures are thus necessary that take into account the likelihood of having to respond to quakes of much longer duration and greater amplitude.

It has been more than half a century since Japan commenced strong motion observation. In that time, the fruits of such strong motion observation have played a significant role in improving technologies for designing quake resistance into buildings. The number of observation sites on the ground increased dramatically following the Kobe Earthquake of 1995, due to the assembly of a seismic intensity observation network. The number of observation sites and records on buildings is still far from adequate for the task, however.

Many issues yet remain for which further research and development efforts are needed, including more precise assessments of input seismic motion and more accurate determinations of the structural soundness of buildings. At the Building Research Institute, we intend to contribute to building both stronger buildings and a stronger community by undertaking sustained research and development efforts related to the strong motion observation of buildings, while we promote the further proliferation of just such observation.

Notes:

1. Japan uses its own unique seismic intensity scale, which is divided into 10 levels as follows: 0, 1, 2, 3, 4, 5-, 5+, 6-, 6+, and 7.

2. A phenomenon in which the ground loses its rigidity, and takes on the properties of a liquid, as a result of intense earthquake shaking.

3. The acceleration of an object in Earth gravity in free fall: 980 cm/s^2, or 32 $ft./s^2$. Quake resistance designs for buildings at the time were predicated on withstanding earthquakes on the order of one-g acceleration.

4. A "period" refers to the time required for a tremor to complete one cycle. "Long-period earthquake motion" refers to a seismic vibration wherein a single period lasts between several seconds and up to 20 seconds.

5. Buildings have natural periods, which refer to the periods at which they are most likely to shake. A building's natural period is affected by such factors as its shape, size and structural form.

6. gal, short for Galileo Unit, is a unit of acceleration, defined as one gal being equal to one cm/s^2, such that Earth gravity, one g, is equal to 980 gal.