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Monitoring the land and built-environment in Japan, its roles for earthquake disaster mitigation, and people's perception and expectation

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ABSTRACT

This article summarizes the current status of Japanese monitoring of land, infrastructural systems, buildings, and mechanical facilities. Over 4,000 sensors have been deployed to measure the shaking of land surface and underneath, and they are operated and maintained by the Government of Japan. The data obtained by land sensors have been incorporated successfully into the Earthquake Early Warning service started in 2007. Monitoring railways and elevators, whose objective is a safe operation, has been in practice for nearly three decades. Notably, the proprietors of such facilities take care of the expenditure necessary to implement such monitoring. Building monitoring has received much attention since the 2011 Tohoku earthquake in conjunction with the building owners' recognition of the tangible benefits of building monitoring as a service to their clients. The benefits of land and building monitoring are examined in the context of determining and modifying design seismic loads, characterizing the actual seismic performance of buildings designed using contemporary seismic design codes, and quantifying the damage of various nonstructural elements.

Keywords: Land monitoring, Facility monitoring, Building monitoring, Earthquake early warning, Market-driven monitoring

INTRODUCTION

Section Summary: This article reports a partial history and recent efforts regarding land and facility monitoring in Japan and applications of the data recorded by the monitoring to the actual disaster mitigation measures and the advancement of earthquake engineering research and practice.

Japan is earthquake-prone, and earthquake disaster mitigation has been one of the most serious national problems for centuries. The 1995 Kobe earthquake caused severe damage to the modern city of Kobe and its vicinities, and it revealed various issues that would impede a safer life and society. Assessment of seismic performance and capacity of buildings and infrastructural systems designed and constructed using the old-day practice, seismic retrofit of the buildings and infrastructural systems that were judged not sufficient in seismic capacity, evaluation of design seismic loads against the magnitude of shaking disclosed in the earthquake, and restoration of cities, towns, and villages that were severely damaged, were considered as the major topics to explore (for example [1]). In addition to those, the 1995 Kobe earthquake disclosed two notable challenges, that is, 1) the need for prompt responses immediately after a disastrous event to minimize the growth of damage and 2) the need for early warning before the arrival of severe shaking, both aiming to reduce human and properties losses after the intense shaking [1]. The public and private sectors responded to those needs and began monitoring our lands and built facilities. The efforts continue until now, installing monitoring systems and operating monitoring services throughout Japan.

This article introduces an overview of such monitoring systems and services available in Japan. It discusses how they have been utilized for actual practice (rather than for research) of earthquake disaster mitigation and how the Japanese public appreciates and responds to the services provided by such monitoring. First, monitoring land shaking is introduced, followed by monitoring utilities and transportation, and further by monitoring buildings. Then, how much monitoring interacts with the prompt response immediately after a severe event and the early warning for people, utilities, transportation, and other mechanical systems is summarized in light of the actual practice and experience. Also touched upon is the influence of the data obtained by such monitoring on the assessment and evolution of current seismic design.

MONITORING IN JAPAN

Monitoring of Land

Section Summary: Based on lessons learned from the 1995 Kobe earthquake, the Government of Japan deployed sensor networks that monitor the shaking of the land surface and underneath. By now over 4,000 sensors have been deployed throughout Japan, including about 200 seabed sensors. The government is in charge of all expenditures related to the sensor networks.

Japan is earthquake-prone, and its land has been shaken frequently in various parts of Japan. Even after the turn of the century, more than 150 earthquakes involved human injuries/deaths [2]. The Nankai Trough, located alongside Japan, is known to rupture periodically with an interval of about one to one-half century, and historical documents revealed the ruptures caused severe damage to both humans and properties. Following the pattern of rupture occurrences, the next large rupture along the Nankai Trough is expected to occur about 70 to 80% of the chance for the coming 30 years [3]. According to the examination by Cabinet Office of Japan, the magnitude of damage in the next Nankai Trough rupture could be more than ten times in the death toll and direct property loss than the 2011 Tohoku earthquake. Furthermore, Japan has many active faults throughout the country, adding threats of severe land shaking. As such, Japan cannot escape from devastating earthquakes, and how to cope with them has been fundamental to the safety and welfare of Japan and the Japanese in the past, present, and future.

The history of deployment of strong motion accelerographs was long in Japan, but before the 1995 Kobe earthquake, systematic and organizational efforts to deploy such accelerographs, and record and store the data in a unified manner remained limited. At the time of the 1995 Kobe earthquake, only about a dozen such accelerographs recorded the strong motion near the areas that sustained the strongest motions and severe damage [4]. To recognize the importance of monitoring land shaking, the Government of Japan launched national programs to deploy various types of sensors to monitor the shaking of land surfaces and underneath. The sensor networks developed by the national programs have continued to be maintained and upgraded until now. Notable is that nearly 200 sensors have been installed on the seabed of the Pacific Ocean to capture the fault and rupture mechanisms of the Nankai Trough and other major trenches in the Pacific Ocean. By this writing, over 4,000 such sensors have been deployed throughout Japan, combining those operated by the public and private sectors. The networks are the pillars to provide the basic information on the research of land shaking and on various measures to be taken for immediate earthquake disaster responses.

Earthquake Early Warning (EEW)

Section Summary: Using the networks of land sensors, the Government of Japan developed a nationwide Earthquake Early Warning (EEW) system and began its service in 2007. After 15 years of experience and appreciation, the EEW has been regarded as essential for Japanese life.

Most notable practical application of data obtained by land sensors is the Earthquake Early Warning (EEW) System [5]. The 1995 Kobe earthquake revealed how strongly the EEWS would have contributed to reducing human and material losses. Alongside installing various land sensors after the 1995 Kobe earthquake, the development of EEW continued. In 2004, a trial of EEW began, and in 2007, the official nationwide service of EEW started. The developed system has been robust, providing reliable information, i.e., the arrival time of primary shaking and its magnitude (using the Japanese “Shindo” scale) to all people residing in seemingly affected areas. With nearly two decades of successful experience, Japan’s EEW, maintained and operated by the Japan Metrological Agency (JMA), has become a part of the daily life of Japanese people and businesses. The EEWS continues to be upgraded; for instance, a new option of EEWS that targets long-period ground motion was integrated into the service in 2023.

Monitoring of Utilities and Mechanical Systems

Section Summary: Unlike land monitoring, facility monitoring is private-driven and market-driven, and the facility owners invest in monitoring at their discretion. Notable examples are railway monitoring, started in 1992 and led by the Japan Railways for the operation of fast trains, and elevator monitoring, enforced mandatory in 2009 and led by the coordinated efforts between the building owners and elevator suppliers.

Monitoring of land shaking, including new installation, maintenance, and replacement, has been led exclusively by the Central Government of Japan, with the belief that the Government shall provide its people with the basics to maintain their safety, security, and welfare. For this reason, the Government takes responsibility for all expenditures necessary to maintain nationwide monitoring. However, when it comes to monitoring built facilities such as utilities, public transport, manufacturing factories, and private buildings, the Government does not offer any financial support. Such monitoring is being implemented on the basis of "market," and proprietors of respective facilities and buildings are in charge of necessary expenditures. This difference brings about a new picture regarding the development facility monitoring.

The Tokai Japan Railway (JR), a railway firm operating the Japanese fast train system dubbed "Shinkansen," developed a system in the 1980s in which fast trains would reduce the speed and stop safely before primary shaking. Its concept was very similar to EEW, but notable is that JR's development started earlier than what the Japanese EEW did. In 1992, the system, dubbed UrEDAS (Urgent Earthquake Detection and Alarm System), began its operation and has been used successfully for the past three decades. For instance, twenty-seven Shinkansen trains were on service in the Tohoku region at the inception of ruptures in the 2011 Tohoku earthquake. Those trains reduced the speed and stopped before the primary shaking arrived, and all trains and passengers remained safe [6]. Since the start of operation, the system has been expanded to all fast train systems and upgraded by combining it with the JMA's EEW. The JR took care of the entire expenditure associated with the system.

Elevators are another type of mechanical facility in which monitoring was considered from earlier in Japan. Stimulated by the elevator damage in the 1971 San Fernando earthquake, development was carried out for "elevator control" before and during the primary shaking [7]. The system's concept was to install one sensor on the base floor to detect the P-wave and the other sensor on the roof floor to detect the S-wave. The bottom sensor recognizes the arrival of an earthquake, and when the acceleration exceeds a threshold value, the elevator stops at the immediate floor. Then the top sensor checks the magnitude of primary shaking. When its value does not exceed a preset threshold value, the elevator's emergency stop is released, and the operation resumes. When the value of top shaking exceeds the threshold value, it continues to pause until the completion of safety checked by elevator engineers. By 2009, elevator monitoring became mandatory, as stipulated by the Building Standard Law of Japan except for the existing ones. By now, over three-quarters of elevators operated in Japan have been equipped with elevator monitoring [8]. The system has been maintained and supervised continuously by respective elector manufacturers and their subsidiaries. As noted before, all expenditure regarding the emergency measures is handled through the transaction between the building owners and elevator manufacturers.

Monitoring of Buildings

Section Summary: Unlike land monitoring, building monitoring is also market driven. Until the 2011 Tohoku earthquake, monitored buildings were limited to a range of about 150. The Tohoku earthquake changed the attitude of building owners, many of whom recognized the importance of knowing the safety and continued operation of their buildings and occupants immediately after significant events. As a service to their clients, they began installing monitoring systems, attached with immediate assessment of building status, out of their expenditures. The number of monitored buildings has reached a range of 1,000. Details are presented in Kanda et al. [10].

Building monitoring began in Japan in the 1950s using a type of strong motion accelerograph called SMAC, developed after the 1948 Fukui earthquake. The Japan Building Research Institute (BRI) of the Ministry of Construction installed SMAC in about ten buildings in various parts of the country. In the early days of the design and construction of Japanese high-rise buildings (1980s), some seismic monitoring systems were also installed, primarily for design verification, but such efforts remained ad hoc. There was no more movement to promote building monitoring until 1995.

After the 1995 Kobe earthquake and succeeding earthquakes that hit various parts of Japan, both the public and private sectors began feeling the benefits of seismic observation to identify the level and location of actual damage and eventually to calibrate the effectiveness of seismic design codes and regulations. As a result, the installation of sensors in buildings gradually increased, but again primarily led by the Government. BRI installed accelerographs in nearly 80 public facilities throughout the country. Since that time, many records have been collected during large earthquakes, including the 2011 Tohoku earthquake, and analyses of the obtained records have been used to advance our understanding of input ground motions and building response.

Finally, the attitude changed after experiencing the 2011 Tohoku earthquake. About 5.15 million people in the Tokyo metropolitan region had trouble returning to their homes after the quake, and pedestrians overflowed roads, which created a severe problem throughout the Tokyo metropolitan region. The Tokyo Metropolitan Government [9] enforced in 2013 an ordinance in 2013 that, for the sake of safety, people should remain in their buildings when possible rather than leaving them. The ordinance states that facility managers should confirm the safety of buildings and neighborhoods when a large shaking occurs. If security is ensured, people in the building are instructed to wait in it. It was easy to say it, but the building managers encountered the problem of how to judge safety. Note that managers stationed in buildings are commonly not very familiar with structural engineering concepts.

These difficulties suggested the potential of building monitoring to prompt the assessment of building safety, particularly in large metropolitan areas. Building owners, particularly those who manage many buildings and are keen on business continuity planning (BCP), have come to understand this advantage. This new trend also differs from the movement we saw before for land monitoring in that the installation of building monitoring is driven primarily by business and market forces rather than by public expenditure. Before the 2011 Tohoku earthquake, the number of instrumented buildings in Japan was in the range of 150. Since the market-based instruments began, the number of monitored buildings increased dramatically, now (as of 2023) in a range of 1,000, among which over 80% are regarded as private-owned and private-operated.

Monitoring System: q-NAVIGATOR (q-NAVI)

Session Summary: Experiences of about ten years with a building monitoring system named q-NAVIGATOR, installed in about 530 private owned buildings, are summarized. (1) Charging annual maintenance fees is vital to secure the building owners' sense of participation; 2) Accuracy in monitoring is essential but is not as crucial as its robustness (no disconnection, no wrong signals, no power failure); 3) Building monitoring only is insufficient to respond to actions necessary after a significant event and should be combined with quick surveys by the onsite building managers and detailed surveys and following repair work by the building contractors; and 4) Regular communication between the owners and monitoring supplies is indispensable to ensure mutual understanding. Details are presented in Kanda et al. [10].

Among the market-based building monitoring systems deployed in Japan, a monitoring system named q-NAVIGATOR (or q-NAVI in short), started for installation in 2015, has the largest share, with 530 buildings equipped with q-NAVI. The system consists of a few 3D sensors installed in some stories along the height and wired to the PC installed in the building's maintenance room; the PC for collecting the sensor data and assessing the maximum story drifts and floor accelerations, and the screen to show the results, with "safe", caution," and "danger." The PC is further connected via the Internet to a cloud system, from which the building owners and managers can receive the necessary data within a short period, say 2 to 5 minutes.

Out of the interaction with the building owners and managers, those engaged in q-NAVI learned many informative lessons. 1) Sense of participation in monitoring their buildings has to be nurtured among the owners and managers, which can be secured simply by their paying (no matter how small) for the maintenance fee; 2) Accuracy of monitoring, for instance, the accuracy in estimating the maximum inter-story drift, is essential but not as critical as the robustness of the monitoring system, i.e., continuous recording without disconnections, wrong signals, or power failures; 3) The monitoring system only is not sufficient to take proper actions immediately after a significant event, i.e., the system needs to be combined with the emergency operations and preliminary surveys done by the onsite managers and engineers, and with the detailed surveys and succeeding repair work carried out by the constructors who have regular contacts with the owners and managers; and 4) Regular communications between the monitoring supplier and the owners and their representatives to enhance mutual understanding and sympathy. All those factors are rooted in the unique nature of earthquake monitoring, remaining invisible until a significant earthquake event arrives and, therefore, rather forgettable. The full details of q-NAVI and its experience regarding the interaction with the building owners and managers are presented in Kanda et al. [10].

INTERACTION OF MONITORING WITH SEISMIC DESIGN

Section Summary: The systems that monitor the land and facilities of Japan have collected numerous records for the past years. The data have been used in many ways to promote the research and practice of earthquake engineering. Here, the following three issues, i.e., how the data contribute to the determination and modification of seismic loads used for design of buildings, how the data obtained by building monitoring have been utilized when calibrating the current performance criteria adopted in the contemporary seismic design, and how the data obtained by building monitoring can be utilized for the characterization of functionality, including the damage to nonstructural elements.

Design Seismic Loads

Earthquake hazard maps are essential to determining and modifying design seismic loads. Although numerous data have been obtained from the land sensors and reflected in the latest maps, motivation remains little to change (increase) design seismic load. Japan's centralized operation system at disastrous events and the general public's sentiment toward "equality" may be responsible for the reluctance. Details are presented in Suzuki et al. [11].

In response to the severe damage disclosed in the 1995 Kobe earthquake, the Government of Japan established the Headquarters for Earthquake Research Promotion (HERP) of Japan. One of the institution's primary missions is to develop and regularly update Japan's earthquake hazard maps. The hazard maps can serve as a benchmark to evaluate and modify the design seismic loads stipulated in the seismic design code. However, in the past two decades, the design seismic loads remained unchanged despite a few large earthquakes in some parts of Japan, such as the 2011 Tohoku and 2016 Kumamoto earthquakes. In fact, the Japanese design seismic loads have stayed more or less the same for nearly forty years since the last overhaul of the Japanese seismic design in 1981.

Differences in the estimated magnitude of strong shaking are significant among the regions in Japan. When looking into the hazard maps, the difference is by several times between the largest and smallest strong motions. However, the corresponding difference in the design seismic loads is only 20%. Furthermore, discrepancies were disclosed in many cases between the level of recorded shaking, say, PGA and PGV, and the degree of actual structural damage observed in the recorded region. Such observations naturally discouraged the motivation to change (increase) the design seismic loads. Public sentiment also plays an important role in determining the design seismic loads. Japan exercises a centralized operation system at the time of disastrous events, and the public sector covers most post-disaster recovery supports. The general public also values "equality" for such post-disaster recovery supports. Those bring cautiousness in the revision of relevant codes and specifications. The full detail of this argument is presented in Suzuki et al. [11].

Performance Criteria

Section Summary: Building monitoring has provided information on the actual behavior and performance of the monitored buildings. In many cases, such data have disclosed superior performance of the buildings, particularly those designed using the latest codes, over the performance expected in design. Even in Level 2, where structural damage is permitted, modern buildings designed using performance-based design procedures tend to remain nearly elastic. It is thanks primarily to design considerations for better control against maximum interstory drifts to enhance life and business continuity. Details are presented in Hori et al. [12] and Kolozvari et al. [13].

For the past quarter century, the land sensors deployed around Japan recorded ground motions more significant than what has been stipulated in the Japanese seismic design code. Japanese seismic design enforces two levels of design seismic load, i.e., Level 1 for serviceability and Level 2 for safety. Level 2 corresponds to about 1 g in terms of the pseudo acceleration spectrum. For Level 2, the designed building shall stay safe, but damage to the structural and nonstructural members and elements is permitted in design. In not a few cases, recorded ground motions were significantly greater than what is expected in the design. Still, the actual damage to major structural elements and even the damage to nonstructural elements remained minimal, ensuring life and business continuities. Many reasons have been speculated, for instance, the soil-foundation-structure interaction by which the effective input to the superstructure could decrease notably and the contribution of nonstructural elements to the actual strength of the building. With the increase in building monitoring, we have learned that the structural performance itself has been enhanced significantly. The structure remains nearly elastic even in the Level 2 design seismic load, particularly for large and tall buildings in which performance-based design (involving response history analysis) is employed. Details about the performance-based design and analysis of tall buildings designed by the Japanese seismic codes are presented in Hori et al. [12] and Kolozvari et al. [13].

Damage to Nonstructural Systems and Components

Section Summary: Building monitoring is very effective in characterizing damage to nonstructural elements. Detailed surveys of the nonstructural damage combined with the maximum responses of individual nonstructural elements obtained by building monitoring can create realistic fragility curves of respective nonstructural elements. Details are presented in Kanda et al. [10].

Another notable benefit of building monitoring is characterizing the damage to nonstructural elements. After damaging earthquakes, we found various types of damage to nonstructural elements, and such surveillance has given us valuable information for assessing the nonstructural damage. However, what we saw from the surveillance was only the final state of damage and cannot give us any clue for the magnitude of responses, i.e., the maximum interstory drifts and/or the maximum floor accelerations that the damaged elements had sustained. Once the building is equipped with sensors, however, we can assess such response magnitudes. We can develop “fragility curves” for nonstructural elements with the magnitude and damage level combined.

There is a good example presented in [10], in which various nonstructural elements (exterior walls, window glasses, interior walls, doors, ceilings, furniture, and expansion joints) were surveyed in detail for 27 buildings shaken during the 2018 Osaka earthquake. Observed were only for 27 buildings, but the numbers of nonstructural elements, for instance, the number of ceilings, were very many when counted for each room as a ceiling unit. Considering the inherent nonuniformity and variability of nonstructural elements, particularly in their connection details, "approximate" but "many" sample data are exceptionally suited for the purposes of "fragility curves." This benefit of building monitoring can never be underestimated.

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