# KNOWLEDGE NOTE 1-2

## CLUSTER 1: Structural Measures

# Building Performance

GFDRR
Global Facility for Disaster Reduction and Recovery
THE WORLD BANK

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# Building Performance

**The strong main shock of the Great East Japan Earthquake (GEJE) of March 11, 2011, caused little damage to buildings. Buildings designed under the current building code and those with base isolation fared well. However, seismic design guidelines for nonstructural members had not been considered adequately , which resulted in problems such as the collapse of ceiling panels. Soil liquefaction occurred in reclaimed coastal area along Tokyo Bay and riverside areas. The key lessons of the GEJE are that seismic-resistant building design prevent collapse of buildings and protects human lives, that retrofitting vulnerable buildings is essential to reduce damage, that seismic isolation functioned well, and that nonstructural building components can cause serious damage. When applying these lessons to developing countries, local technical and socioeconomic conditions should be taken into account.**

## FINDINGS

### HISTORY OF BUILDING CODES IN JAPAN

**The world's first national seismic design code.** Due to its location and tectonic settings, Japan is prone to large earthquakes. The Great Kanto Earthquake in 1923 caused some of the most serious damage in Japanese history, as fires consumed a large part of Tokyo, killing more than 100,000 people (table 1). Based on the lessons learned from the disaster, a seismic design code was introduced in the building code of 1924, the first national seismic design code applied anywhere in the world.

**Building code updates following major earthquakes.** After every major earthquake, Japan's national government and academic community carry out detailed surveys of building damage, and the building code is revised accordingly. Technical recommendations are based on the most recent lessons. The Tokachi-oki earthquake in 1968 caused serious damage to reinforced concrete (RC) buildings and inspired a major revision of the building code in 1981. Until 1981, the building code required buildings to withstand a lateral force of 20 percent of the total weight of the building without damage in structural members. The revised code, part of which is still in use, requires that buildings be strong enough to with-

TABLE 1: **Comparison of three major disasters in Japan**

| **Disaster** | Great Kanto Earthquake | Hanshin Awaji Earthquake | Great East Japan Earthquake and Tsunami |
|---|---|---|---|
| **Year** | 1923 | 1995 | 2011 |
| **Magnitude** | 7.9 | 7.3 | 9.0 |
| **Location** | Tokyo and surrounding area | Kobe and surrounding area | Extended area. Tsunami affected 1,000 km of coastline |
| **Casualties (dead and missing)** | 105,385 | 6,437 | 19,845 (as of September 26, 2011) |
| **Main cause of deaths** | Fire | Collapse of old houses | Tsunami (drowning) |
| **Conditions** | Noon. Residents were using stoves to cook lunch. Strong winds spread fire, which burned for three days. Fire created tornados and whirlwinds. | Before dawn. Sleeping residents were killed when their houses collapsed. Few were killed on trains or highways. | Mid-afternoon. People were at school or work, where evacuation protocols were put into effect. |

stand a lateral force equal to 100 percent of the building's weight. Damage to the building is permissible as long as human lives are not threatened.

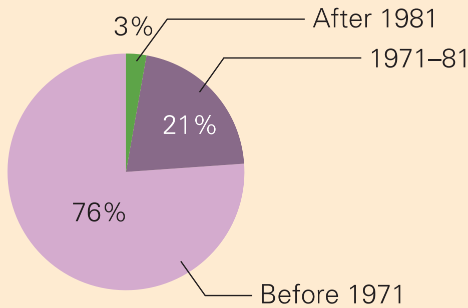
**Current building code (1981) in Japan.** The main aspects in the current building code of 1981 are as follows:

- Buildings should be able to withstand within their lifetime several large earthquakes without structural damage.
- Building should be able to endure, without collapse or other serious damage, an extremely large earthquake with a return period of 500 years.

Technical guidelines for assessing and retrofitting existing RC buildings constructed under building codes in effect prior to 1981 were produced.

**Initiative to retrofit buildings following the Great Hanshin-Awaji Earthquake (Kobe earthquake) in 1995.** The 1995 Kobe earthquake caused heavy damage, 6,437 casualties,

FIGURE 1: **Percentage of houses that collapsed in 1995 Kobe earthquake, by year of construction**




and economic losses estimated at more than $120 billion. Of the buildings that collapsed in the Kobe quake, 97 percent were built before 1981 (figure 1). Based on this finding, the government implemented a new law in 1995 to promote retrofitting of old buildings.

Under the *Act for Promoting Seismic Retrofitting of Existing Buildings (1995)*, the national and local governments offer incentives to private homeowners, such as:

- Subsidies for assessments of structural soundness
- Subsidies for the cost of retrofitting
- Reductions in income tax and property tax
- Low-interest loans to cover the cost of retrofitting.

Some 80 percent of local governments have established subsidy programs to encourage owners to assess the structural integrity of their homes, and, as of April 2011, some 64 percent of the local governments had programs that subsidized retrofitting work. The government's target is to increase the ratio of earthquake-resistant houses to 95 percent before 2020. In 2008, the ratio was 79 percent, with some 10.5 million houses still requiring retrofitting. In spite of efforts to promote retrofitting, only 300,000 houses were retrofitted between 2003 and 2008. These numbers show that it is difficult to motivate homeowners to retrofit.

## DAMAGE TO BUILDINGS BY THE GEJE

**Minimal damage by large shaking.** Table 2 shows the summary of the damage caused to the buildings following GEJE. Most of the collapsed residential buildings were washed

TABLE 2: **Damage to buildings following the GEJE**

| *Category* | *Number* |
|---|---|
| Residential buildings | |
| Total collapse | 107,779 |
| Partial collapse | 117,019 |
| Burned | 263 |
| Partial damage | 434,327 |
| Nonresidential buildings | 32,445 |

*Sources:* NILIM and BRI (2012).

FIGURE 2: **Houses and cars were washed away by the tsunami**

*Source:* Yamada-machi.

FIGURE 3 (top): **The tsunami destroyed the outer walls of steel structures**

FIGURE 4 (bottom): **Reinforced concrete buildings withstood the tsunami even though it was submerged. Note the car on the roof.**

*Sources:* BRI and NILIM.

away or destroyed by the tsunami rather than the earthquake. The death toll from earthquake ground shaking is estimated to be less than 200.

The earthquake produced violent shaking over a very wide area. The strongest peak acceleration of 2,933 gal was recorded in Tsukidate, Miyagi Prefecture, but 18 observation stations in six prefectures observed acceleration greater than 1,000 gal. In spite of the strong acceleration, damage from shaking was minimal, owing partly to the characteristics of the ground motion (the dominant frequency was relatively high). Damage to buildings constructed under the 1981 and later building codes was limited and within the range anticipated by the design code.

**Serious damage by the tsunami.** The cause of most of the damage to houses was the tsunami that followed the main shaking. Most wooden houses in deeply inundated

FIGURE 5 (top): **Reinforced concrete building damaged by scouring**

FIGURE 6 (middle): **Reinforced concrete building damaged by liquefacton**

FIGURE 7 (bottom): **Overturned building of reinforced concrete with pile foundation**

*Sources:* BRI and NILIM.

areas were washed away or totally destroyed (figure 2). Many steel structures were also severely damaged (figure 3). By contrast, buildings of reinforced concrete performed well against the tsunami. Although many were completely submerged, they did not suffer structural damage (figure 4). Those reinforced concrete buildings that were damaged tended to be small and without a pile foundation (figures 5 and 6). Figure 7 shows a damaged building where the probable causes of the damage were a combination of weak connections between piles and footings, strong water pressure from the tsunami current, and liquefaction.*

## EFFECTIVENESS OF SEISMIC COUNTERMEASURES ON BUILDINGS

**Good performance of seismic base isolation system.** Japan's Building Research Institute (BRI) reported that the seismic base isolation systems† in all 16 buildings in Miyagi Prefecture performed well, reducing lateral motion by 40–60 percent. No damage was observed to the structures or to mechanical and electrical facilities inside the buildings. No fittings or furnishings fell. The dampers and the cover over the slits between the isolated and nonisolated parts were damaged as expected.

**Enhanced seismic design and retrofitting of transportation infrastructure facilities.** A major campaign to reinforce key infrastructure such as bridges following the Kobe earthquake in 1995 was undertaken by highway and railway companies and governmental agencies. As a result, serious structural collapses of infrastructure were avoided following the GEJE. The East Japan Railway Company had reinforced more than 17,000 bridge piers under the Shinkansen (bullet train) lines, and the central government had retrofitted 490 bridges in the Tohoku Region. Because of these works, some 1,500 bridges on national routes in the region were spared serious damage. Five bridges collapsed under the force of the tsunami. Because damage was generally limited, it was possible to repair the main highways and roads to the affected areas within one week of the event. However, serious damage in the coastal areas affected by the tsunami took longer to repair. Shinkansen service to the Tohoku region resumed after 49 days (KN 4-1), a huge improvement over the situation after the Kobe earthquake, when reconstruction of the roads required more than 18 months and repair of the Shinkansen line took 82 days.

## AREAS FOR IMPROVEMENT

**Damage to nonstructural building components.** Much of the damage observed in buildings following the GEJE involved nonstructural components attached to structures, such as ceiling panels, nonstructural walls and finishing materials (figure 8). To date, no guidelines or codes cover the wide variety of materials and designs used on nonstructural components. In Japan, few engineers have devoted attention to the matter.

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* In an earthquake, soil behaves like a liquid, losing its strength and bearing capacity.

† Isolated structures damp the effects of earthquake ground motion through decoupling of horizontal components. Isolation systems may be laminated steel with high-quality rubber pads, or other energy-absorbing materials

FIGURE 8 (top): **Fallen ceiling panels in school gymnasium**

FIGURE 9 (bottom): **Subsidence of houses from liquefaction.**

*Sources:* BRI and NILIM.

**Liquefaction.** Liquefaction occurred on reclaimed lands and river banks over a wide area. Small buildings without pile foundations built on plots that had not been treated for liquefaction were affected (figure 9). Existing building codes cover countermeasures against liquefaction for reinforced concrete and other buildings, but not for the detached wooden houses owned by most ordinary people. The Ministry of Land, Infrastructure, Transport and Tourism has now produced technical guidelines to fill these gaps. Some local governments have provided liquefaction risk maps to encourage building owners to take countermeasures.

**Damage from failure of retaining walls.** In Sendai City, more than 4,000 houses were damaged by landslides caused by the strong ground shaking (figure 10). Since 1961, to prevent landslide disasters the city government has regulated housing in hilly areas under the Act on the Regulation of Housing Land Development. Most locations that experienced

FIGURE 10: **Houses damaged by landslides**

landslides following the GEJE were developed before the act came into effect. In 2009, in response to landslides caused by earthquakes since 2000, the central government established a subsidy mechanism whereby local governments were tasked to carry out geotechnical work to stabilize the ground for large-scale housing projects in high-risk areas. However, stabilization work had not started by the time the March 2011 disaster struck.

**Effect of ground motion of long periods on skyscrapers.** The potentially devastating effect of ground motion of long periods on skyscrapers and seismically isolated buildings has been recognized in the recent years. Recently skyscraper designs take into account the effects of ground motion of long periods. Some skyscrapers had been retrofitted by installing devices to control deformation or absorb energy. On March 11 strong and sustained ground motion of long periods reached Tokyo (approximately 400 km from the epicenter) and even Osaka (800 km), affecting the skyscrapers in both of these metropolitan areas. Recognizing the importance of countermeasures against the risks from sustained ground motion, the

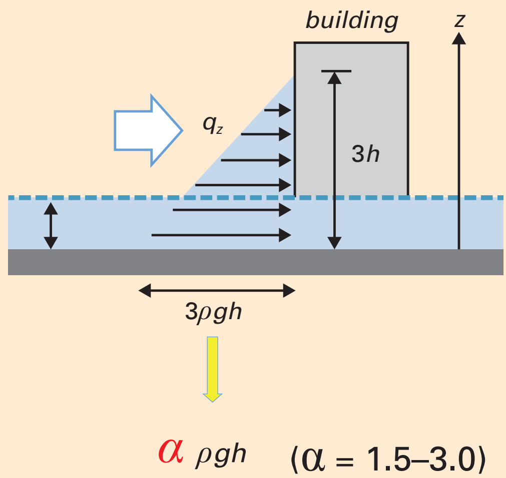
FIGURE 11: **Revised design load requirements against tsunamis**

## 2005 guideline

*Design wave pressure*

$$q_z = \rho\, g(3h - z)$$

*Design water depth: h*




## 2011 guideline

$$q_z = \rho\, g(\alpha h - z)$$

Japanese government has now released a draft of a new technical guideline that revises structural design procedures, safety measures for furnishings and fittings, and a screening method to identify skyscrapers that need to be examined in detail.

**Technical guideline for tsunami evacuation shelters.** Japan's first technical guideline for tsunami shelters was published in 2004. A revised guideline was released in November 2011, based on detailed surveys of the areas affected by the GEJE. Where the risks from tsunamis pressure are less serious, the tsunami load can be smaller under the revised guideline than under the previous guideline (figure 11).

## LESSONS

**The importance of retrofitting older buildings.** The importance of retrofitting buildings is demonstrated by the fact that buildings designed under the 1981 building code and retrofitted buildings performed well in the GEJE, whereas most of the damaged buildings were constructed before 1981 and had not undergone any retrofitting. Further efforts to retrofitting are required, including more attractive incentives for those who cannot afford to invest in safety or are reluctant to do so (as are many elderly people). More affordable retrofitting methods should be developed. Partial retrofitting, safety shelters inside the home, and beds covered by safety frames are examples of affordable options.

**Safety of nonstructural building components.** The GEJE demonstrated the importance of considering nonstructural elements when thinking about earthquake safety. The materials, design, and construction of nonstructural components vary greatly. Technical guidelines are needed to ensure that such components are earthquake-resistant.

**Structural safety and functional continuity of buildings.** Even when structures withstood ground shaking and saved the lives of their inhabitants, inhabitants could not reoccupy their dwellings because of deformation of walls and doors. Substantial sheer cracks in nonstructural walls made the inhabitants feel that it was dangerous for them to stay. Besides structural safety is achieved, it is recommended that efforts to achieve functional continuity of the buildings—with minimum disruption to everyday lives—are made.

**Liquefaction and landslides.** Countermeasures against liquefaction and landslides need to be enhanced in Japan. Following the GEJE, the Japanese government has reviewed the method of assessing the risk of liquefaction. Developing more effective and affordable antiliquefaction treatments is needed. The government is considering a requirement that home buyers be notified of the risk from liquefaction. The government is also providing subsidies for projects to stabilize slopes with landslide potential near houses.

**Long-period ground motion.** The GEJE demonstrated the possibility of a gigantic earthquake occurring as a result of three large earthquakes (Tokai, Tonankai, and Nankai) occurring in short succession. Such a series of earthquakes would be likely to produce strong ground motions of long periods. Structural and retrofitting measures should be performed according to the new guideline, lowering the risk from long period ground motion by preventing amplification of shaking motion through increasing buildings' capacity to absorb energy, and reducing structural deformation.

**Seismic isolation.** Buildings with isolated bases performed well during the GEJE, enabling them to be used without interruption even immediately after the main shock of the earthquake.

## RECOMMENDATIONS FOR DEVELOPING COUNTRIES

**Seismic resilience of buildings is the most effective risk mitigation measure.** One of the most basic and effective measure to mitigate risks from earthquakes is to build structures that are resilient to ground shaking. Many buildings in developing countries are extremely vulnerable to collapse (figure 12).

**Use of technologies appropriate for developing countries.** Various seismic design guidelines have been developed around the world. Direct application of such guidelines may not be appropriate in developing countries because of their costs, the limited knowledge and skills of builders, and limited tools and facilities on construction sites. What is needed are seismic design guidelines that are suited to local conditions and capable of enhancing the resilience of buildings.

**Knowledge and lessons should be adapted and customized to local conditions.** In Indonesia a simple technical guideline that is consistent with local technical capacities and other conditions was developed and is being disseminated with help from the Japan International Cooperation Agency (box 1). Knowledge based on detailed surveys of construction sites and motivation on the part of engineers, workers, government officials, and owners of buildings can improve safety. may be effective approach,

FIGURE 12: **Revised design load requirements against tsunamis (Yogyakarta province, following Central Java Earthquake, 2006)**

**Implementation of building codes.** Another important issue is how best to implement building codes and how to monitor their implementation. Legislation should include provisions related to the issuance of building permits, inspection of construction, and enforcement of building codes. Enforcement requires sufficient numbers of trained and equipped officials and inspectors with access to technical information.

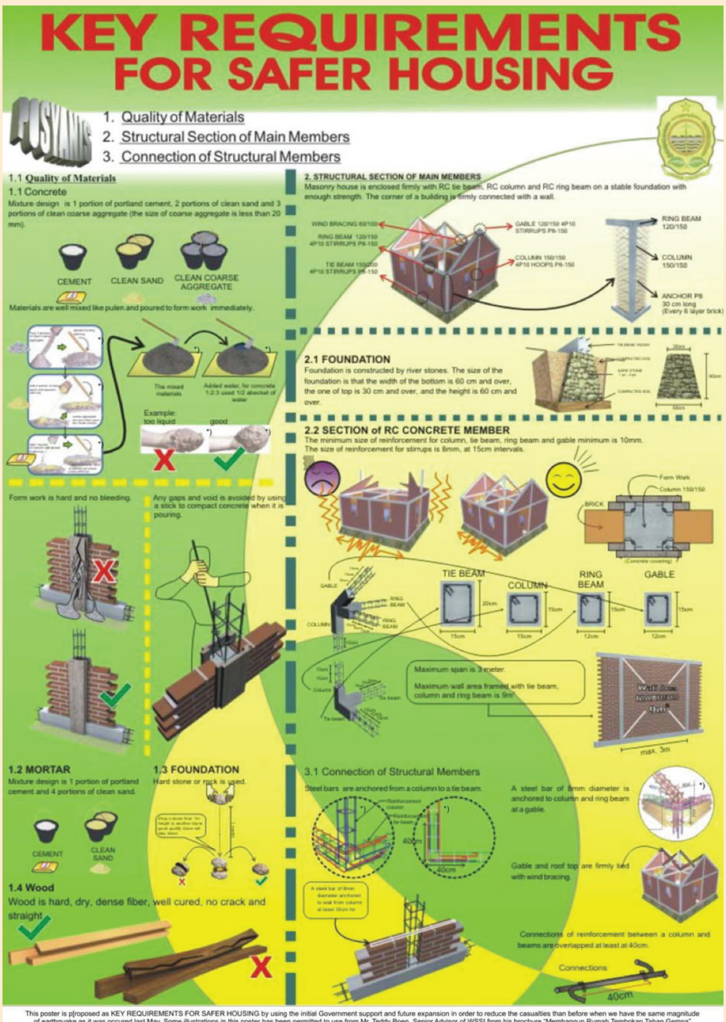
Japan's Building Standard Law mandates the implementation systems shown in figure 13. Local government officials (or "designated confirmation bodies") conduct examinatiion/inspections before, during, and after construction. If conformity with building standards is confirmed, the building official (or "designated confirmation body") issues a "confirmation certificate." An interim inspection is performed on buildings that have certain structural characteristics or purposes. Multifamily dwellings, multistoried buildings, and public buildings are generally subject to this type of inspection.

**Retrofit historical buildings.** In countries with many vulnerable historical buildings, retrofitting is a big issue. Retrofitting should be considered in the context of striking a balance between affordable and effective retrofitting methods, a balance that motivates both private owners and government officials and politicians.

**Secure safety of nonstructural components.** The issue of nonstructural building components is common in developing countries, although the critical elements may be different. Nonstructural walls, roofing materials, and ornamental attachments such as pediments and signs are examples observed in field surveys in affected areas. Complicating this issue are the large variety of materials and designs and the scarcity of engineers. Materials that provide shelter and the curtain walls of outside buildings must be regulated first, given the

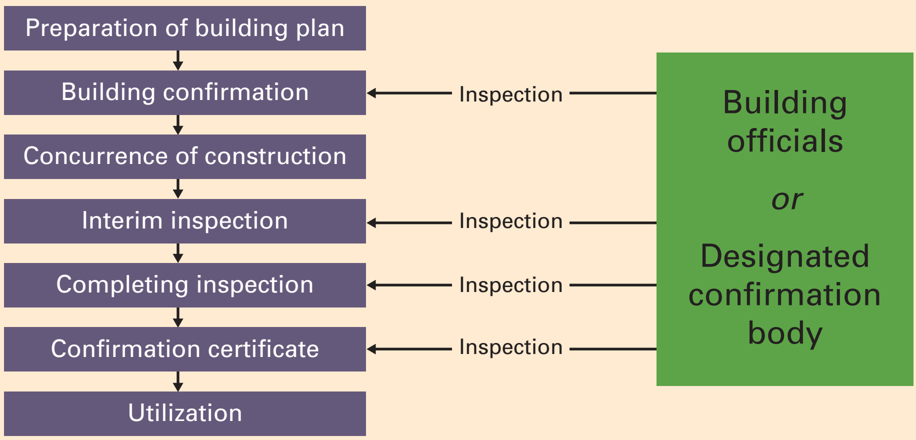
BOX 1: **Simple technical guideline and its dissemination through the building permit process throughout Indonesia**

The Central Java Earthquake in 2006 caused heavy damage and killed some 6,000 people, mostly through collapse of their houses. During reconstruction, the provincial government developed a technical guideline for small, one-story houses. The guideline, simple enough to be illustrated in a poster, has been well accepted by the population. The central government decided to apply it across the country through the building permit system.




*Source:* Japan International Cooperation Agency (JICA).

FIGURE 13: **Flowchart of Japanese building permit process**




BOX 2: **Tsunami evacuation shelters applying the Japanese technical guideline**

Banda Aceh was severely damaged by the Indian Ocean Tsunami of 2004. Despite the devastation wrought by the tsunami, local people are returning to the coastal areas because their livelihoods are tied to the sea. Because no suitable evacuation areas are found along the coast, evacuation shelters are being constructed. The Japan International Cooperation Agency is supporting the construction of vertical evacuation shelters that embody Japanese technical guidelines. The shelter shown below was used for emergency evacuation in 2012.

*Source:* JICA.

risks they pose to pedestrians. To resolve the issue of roofing materials, manufacturers and engineers should be involved in improving construction methods and materials. Also, construction workers should be trained to install such materials in safer ways.

**Prevent large deformation of structures.** Japanese experts are examining ways to minimize structural deformation. This could be useful to countries whose seismic design codes allow larger deformation than Japan's.

**Prepare for tsunamis.** Japan's experience and knowledge with tsunami evacuation shelters is useful to other countries exposed to tsunamis, such as Indonesia. The tsunami evacuation shelter in Banda Aceh is an example of Japanese technical cooperation (box 2).

**Promote seismic base isolation.** Buildings with seismic base isolation features suffered very little damage from the GEJE. More key public buildings, particularly those that will be used for emergency relief activities and emergency response—that is, evacuation shelters and fire stations—should be built using base isolation. Simple and affordable techniques for base isolatation should be developed for use in developing countries.

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