KNOWLEDGE NOTE 1-1

CLUSTER 1: Structural Measures

Structural Measures against Tsunamis

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Structures such as dikes play a crucial role in preventing disasters by controlling tsunamis, floods, debris flows, landslides, and other natural phenomena. However, structural measures alone cannot prevent all disasters because they cannot mitigate damages when the hazard exceeds the level that the structures are designed to withstand. The Great East Japan Earthquake (GEJE) demonstrated the limitations of Japan's existing disaster management systems, which relied too heavily on dikes and other structures. Damage can be kept to a minimum by multilayered approaches to disaster mitigation that include structural and nonstructural measures and that ensure the safe evacuation of residents.

Dikes, dams, and other structures are regarded as core measures in disaster risk management in Japan. Japan has constructed dikes to mitigate flooding for nearly 2,000 years. The first dike system was constructed in the Yodogara River in Osaka in the fourth century. The Japanese used dike systems to protect crucial areas, such as castles and residential areas, in the middle and early modern periods. The government established after the Meiji Revolution in the late nineteenth century has promoted structural measures to control floods, high tides, landslides, and tsunamis by employing modern technology introduced from the Netherlands and other Western countries. Disaster damage had substantially decreased because of concentrated investment in structural measures (KN 6-1).

Surrounded by seas, Japan has an extremely long, geographically complex coastline of approximately 35,000 kilometers. People, productive assets, and social capital are concentrated on small coastal plains over a limited land area. Not only are Japan's coastal areas situated where earthquakes are exceptionally common, but they are also subject to harsh natural events, such as typhoons and winter ocean storms. Historically, the country has suffered severe damage from tsunamis, storm surges, ocean waves, and other natural phenomena. To protect life and property concentrated near its coastline, the country has been developing coastal and port facilities for the last half century.

FINDINGS

COASTAL STRUCTURES IN THE REGION AFFECTED BY THE GREAT EAST JAPAN EARTHQUAKE

When the tsunami hit eastern Japan in March 2011, 300 km of coastal dikes, some as high as 15 meters high, had been built (figure 1). Prefectural governments, which have the main responsibility for building the dikes (supported by national subsidies that cover two-thirds of the cost), built 270 kilometers of the total, with the national government building the remaining 30 km. The national government also had developed technical standards, guidelines, and manuals for use in the design and construction of coastal structures. In response to the economic damage caused by the GEJE – ¥300 billion ($3.75 billion) in destroyed dikes—the government has invested several hundred billion yen in dike construction in the Iwate, Miyagi, and Fukushima prefectures. It has also invested ¥400 billion ($5 billion) in constructing bay mouth breakwaters in major ports, such as Kamaishi, Kuji, and Ofunato, to protect them from tsunamis. A cost-benefit analysis of these investments appears in KN 6-1.

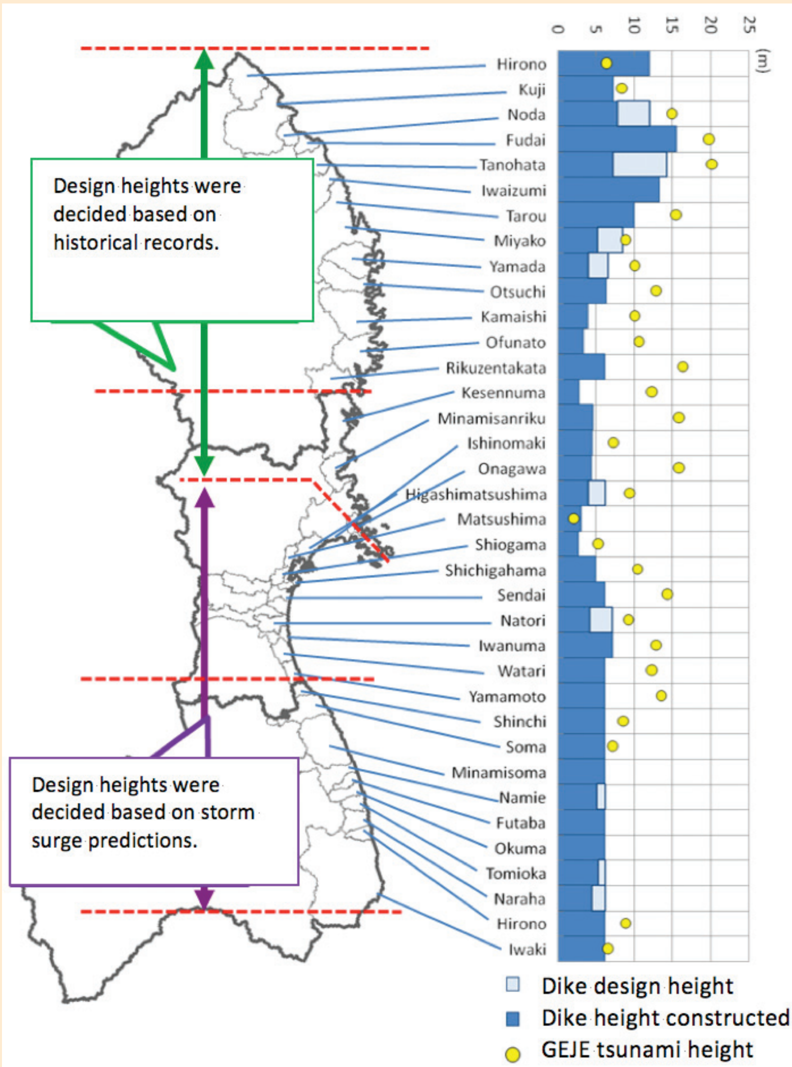
The disaster-affected region had frequently sustained devastating damage from tsunamis, including the Sanriku tsunamis of June 1896 and March 1933, and a tsunami caused by a massive earthquake off the coast of Chile in May 1960. The 1933 Showa Sanriku Tsunami was the first disaster to provoke modern tsunami countermeasures at the initiative of the central and prefectural governments. Those countermeasures included mainly relocation to higher ground and the building of dikes, albeit at just five sites (box 1).

The Chilean Earthquake Tsunami of 1960 prompted extensive construction of coastal dikes in the region. The dike height was initially based on the height of the 1960 tsunami but was revised several times thereafter to take into account other major tsunamis that had

BOX 1: **The enormous tsunami walls of Taro, Miyako City, Iwate Prefecture**

The people of the Tohoku region have built and maintained tsunami dikes for decades. Following the Meiji Sanriku Tsunami of 1896, the village of Taro was hit by a 15-meter tsunami that washed out 285 houses and killed 1,447 people. The 7.6-meter Showa Sanriku Tsunami of 1933 also hit Taro, washing out all 503 houses and killing 889 of the village's 2,950 residents. Because insufficient high ground could be found for 500 houses, the village chose to build dikes. Construction began in 1934 using borrowed money and took more than three decades to complete. The largest dike was 2,433 meters long and 7 meters high (10.65 meters above the sea level). It was 3 meters wide at the top and as much as 25 meters wide at the base. The March 11 tsunami swept over this dike before destroying it, leaving a path of death and destruction across the community.

FIGURE 1: **Determining dike height**



Source: MLIT.

occurred in the previous 120 years, as well as predictions of future storm surge levels. These dikes are designed to withstand the largest of the predicted tsunami heights and storm surge levels. In Iwate and northern Miyagi, the heights were based on historical records, whereas in southern Miyagi and Fukushima they were based on the predicted storm surges. Methods of risk assessment are explained in KN 5-1.

HOW STRUCTURES PERFORMED AGAINST THE GEJE TSUNAMI

Some towns in the region were well protected by the structures in place, even though the tsunami caused by the earthquake far exceeded their design height. In Iwate's Fudai Village, the 15.5-meter floodgate, built in 1984, protected the village and its 3,000 inhabitants. The village was severely damaged by the Meiji Sanriku Tsunami of 1896 (height 15.2 meters), the Showa Sanriku Tsunami of 1933 (11.5 meters), and the Chilean Earthquake Tsunami of 1960 (11.5 meters). The mayor of the village in the early 1980s was convinced that a 15-meter tsunami would hit the village again at some point, and built the 200 meter-wide floodgate about 300 meters inland from the mouth of the Fudaigawa River, which runs through the village. Although the 20-meter-high GEJE tsunami did top the floodgate, the gate kept the water from reaching the town center (figure 2). The topography of Fudai Village, being surrounded by cliffs with a narrow opening to the sea, was a major factor in enabling the construction of such a high gate.

The dikes also served to protect communities in areas where the tsunami was lower than the dike (northern Iwate, Aomori, Ibaraki, and others), as shown in the example of Hirono Town (figure 3).

Certain breakwaters were also effective in mitigating damage from the tsunami. The breakwater at the mouth of Kamaishi Bay in Kamaishi City, Iwate, was completed in 2009, at a total cost of some ¥120 billion ($1.5 billion). It was the world's deepest breakwater. Although destroyed by the GEJE tsunami, it reduced its force, and therefore its height, by

FIGURE 2: **Inundation area in Fudai Village, Iwate**

Source: MLIT.

FIGURE 3: **No tsunami inundation in Hirono, Iwate**

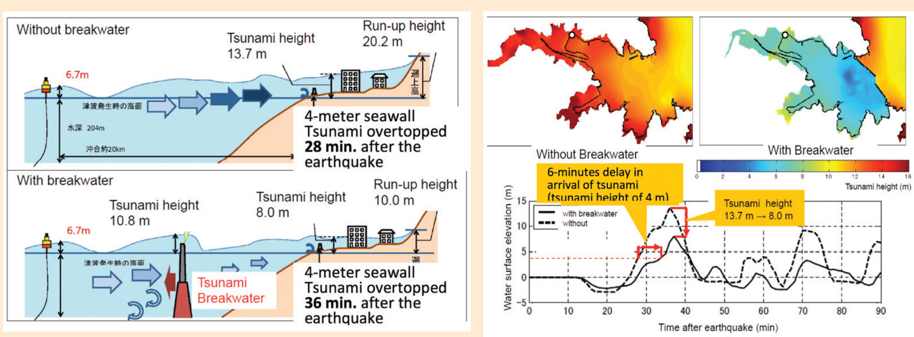
Source: MLIT.

about 40 percent and delayed its arrival by some six minutes, allowing more time for people to evacuate to higher ground (figure 4).

The GEJE tsunami destroyed many coastal structures. Of the 300 km of dikes along the 1,700 kilometer coast of the Iwate, Miyagi, and Fukushima prefectures, 190 kilometers were destroyed or badly damaged. In many cases the tsunami was twice the height of the dikes (figure 1). All 21 ports along the Pacific coast in the Tohoku region (from Aomori to Ibaraki) sustained extensive damage to their breakwaters, quays, and other coastal facilities, suspending all port functions.

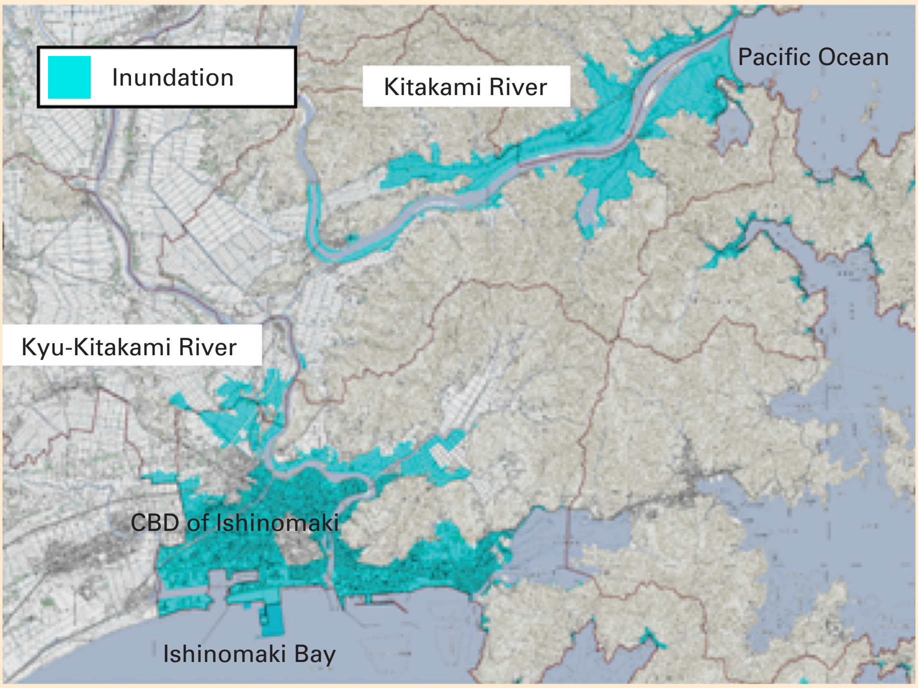
Run-up from the tsunami caused significant damage along major rivers in the region. Traces of the run-up were found as far as 49 kilometers upstream from the mouth of the Kitakami River. Ishinomaki City in the Miyagi Prefecture, where the Kitakami flows out to the sea, experienced severe tsunami run-up in addition to the direct attack along the coast. Approximately 73 square

FIGURE 4: **Effectiveness of the Kamaishi tsunami breakwater**



Source: MLIT.

FIGURE 5: **Tsunami inundation area along the Kitakami and Kyu-Kitakami rivers**



Source: MLIT.

kilometers along the river, or about 13 percent of the entire city, were inundated (figure 5). The city suffered badly, with 3,280 dead and 539 missing (as of March 11, 2012). 20,901 houses were completely destroyed, and 10,923 houses badly damaged (as of October 21, 2011).

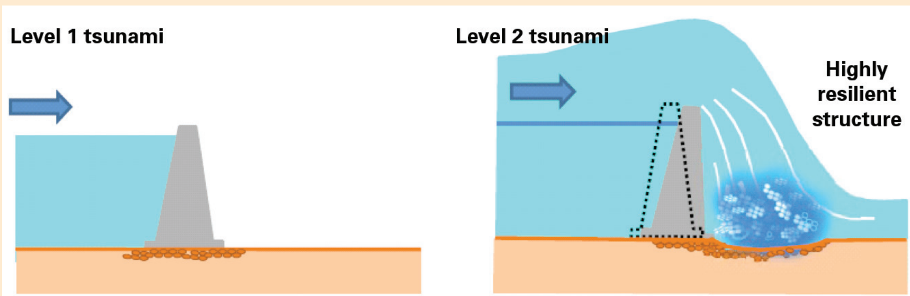
NEW THINKING ABOUT STRUCTURAL MEASURES IN LIGHT OF THE GEJE

The GEJE exposed the limitations of disaster risk management (DRM) strategies focused disproportionately on structural measures. Dikes and breakwaters built before the GEJE were designed to protect against relatively frequent tsunamis, and were effective in preventing damage from those of limited height. In the GEJE, however, the height of the tsunami far exceeded predictions. Although the structures helped to reduce water levels, to delay the arrival of the tsunami, and to maintain the coastline, many of them were breached, resulting in enormous inland damage.

Planning for the largest possible event is a significant policy shift in Japan's thinking about DRM. Building 20- or 30-meter tsunami dikes is neither realistic nor financially, socially, or environmentally practical. But lives can and must be protected by other means, notably multi-layered approaches that combine structural and nonstructural measures to ensure the safe

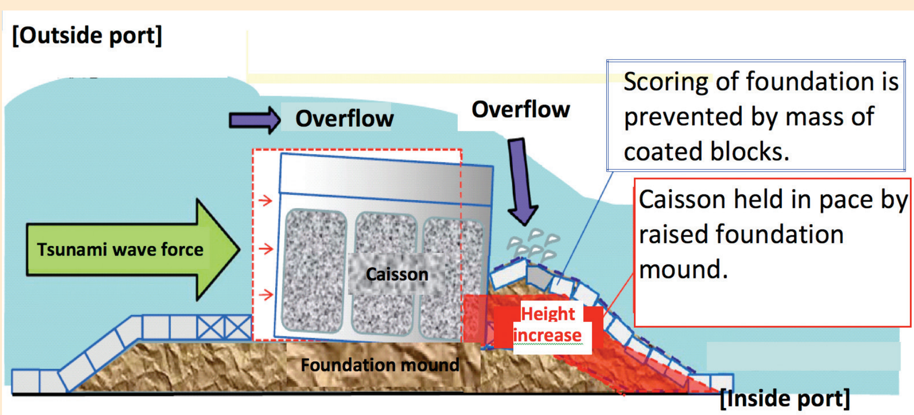
FIGURE 6: **Countermeasures against level 1 and level 2 tsunamis**

	Tsunami to be considered	*Required performance*
Level 1 tsunami	Largest in recent history (return period of approx. 100 yrs.)	Disaster prevention • Protect human lives • Protect properties/economic activities
Level 2 tsunami	Maximum level (return period of approx. 1000 yrs)	Disaster reduction • Protect human lives • Mitigate economic loss • Prevent major secondary disasters • Enable early recovery



Source: MLIT.

FIGURE 7: **Structure of a highly resilient breakwater**



Source: MLIT.

evacuation of residents (KN 6-5). Nonstructural measures are discussed in the knowledge notes of cluster 2. Planning for the new generation of multilayered DRM approaches is based on a comprehensive assessment of historical records, documents, and physical traces of past tsunamis, and by drawing on the latest seismological research and simulations.

Since the GEJE, the Japanese government has taken a two-level approach. Level 1 includes tsunamis that occur as frequently as every 100 years and that cause significant damage, whereas level 2 covers the largest possible tsunami, which has an extremely low probability of occurrence (once every 1,000 years) but that has the power to cause devastating destruction (figure 6).1 Conventional structural measures such as dikes and breakwaters protect human lives and property, and stabilize local economic activities, in the face of level 1 tsunamis. To withstand level 2 tsunamis, however, coastal structures must be improved to be more resistant to collapse and to reduce the likelihood of their complete destruction through scouring (figure 7). Some 87 percent of dikes that had been reinforced against scouring were not damaged in the GEJE, although the tsunami spilled over them.

The government has issued new guidelines for rebuilding river and coastal structures, taking into consideration their appearance as well as local characteristics, ecosystems, sustainability issues, and financial feasibility.

OPERATION OF FLOODGATES AND INLAND LOCK GATES

Although floodgates and inland lock gates can protect against tsunamis, their operation posed problems during the GEJE. Such gates should be closed before the tsunami arrives, but in the case of the GEJE tsunami this operation could not be completed in time, and a number of volunteer fire fighters and other workers were killed in the process. In addition, many gates were left open because equipment failed or because operators were caught in traffic jams and could not reach the site. Other gates became nonfunctional owing to power losses.

In December 2011, the Flood Prevention Act was amended to require local governments to ensure the safety of volunteer firefighters and other workers who operate floodgates, inland lock gates, and similar facilities. In March 2012, MLIT and the Fire and Disaster Management Agency issued the following recommendations to local governments and other concerned organizations:

- Remove unnecessary floodgates and ensure that the remaining floodgates can be operated automatically, semi-automatically, or by remote control.
- Keep inland lock gates closed at all times. Introduce automatic floating gate systems or install ramps or steps.
- Install emergency power supplies and make facilities earthquake-resistant.

LESSONS

The enormous tsunamis experienced in the GEJE have revealed the limitations of DRM measures that rely too heavily on structures. Structural measures cannot completely prevent tsunami disasters.

Many dikes and breakwaters were destroyed by tsunamis. They were nevertheless effective to some extent in reducing inundation areas and mitigating damage.

It is important to learn from past disasters and to revise countermeasures accordingly. In the GEJE-affected areas, various structural measures had been implemented in light of historical disasters, and they were successful in mitigating damage until the GEJE.

Scenarios that envision the greatest possible hazard should be taken into consideration when designing DRM measures. An appropriate combination of structural and nonstructural measures is required in order to achieve maximum mitigation of damage.

Structural measures should be designed to prevent damage to human lives and properties caused by level 1 events and to mitigate damage from level 2 events.

Though it is unrealistic to build structures large enough to protect against the largest conceivable events, the resilience of conventional structures must be enhanced. These should be built to mitigate damage even when the hazard level exceeds their design specifications. It is possible for structures to "fail gracefully" (meaning that they do not fail completely failure or collapse), thereby delaying the onslaught and reducing the energy of tsunamis. The concept of failure should be incorporated into the design to take into account unforeseen events.

Coastal facilities such as floodgates should be designed so that they can be properly managed even in the event of power failure and in the absence of operators. Standardized guidelines should be established for their safe operation in emergencies.

RECOMMENDATIONS FOR DEVELOPING COUNTRIES

Prepare for disasters by integrating structural and nonstructural measures. DRM measures should account for two levels of hazard. Level 1 events are *relatively frequent and produce major damage*; level 2 events, *the largest possible disasters, have an extremely low probability but produce devastating impact.* Every possible structural and nonstructural measure should be employed to protect against level 2. Structural measures should be designed to protect people, property, and socioeconomic activities against level 1 and to mitigate damages at level 2.*

* The two-level approach has already been adopted in the design of other key infrastructure, such as dams and flood-prevention dikes. Dams typically consider the maximum probable flood or a flood with a 10,000-year return period when designing structural safety, and a 100–200 year flood for flood-control operations. For flood-prevention dikes to protect some critical areas of Tokyo and other locations, the government has increased design standards beyond the norm of 100–200 year floods.

Provide technical and financial support for local governments. The central government plays a crucial role in reducing disaster risks across the country. The central government should encourage local governments to promote structural measures by providing financial support and guide them in meeting minimum requirements for structures by producing technical guidelines and manuals. Also, the central government should provide the local governments with technical support, such as conducting training for technical staff in planning, design, operations, and maintenance.

Consider designs and improvements to enhance the resilience of structures and to prevent sudden and complete failure. Extraordinary external loads caused by earthquakes, floods, and other events should be considered in designing structures such as dams and dikes, which should be designed in a way so that they will mitigate damage even when the hazard level exceeds their design levels. Their effectiveness in mitigating damage should be ensured even in the event of their technical failure.

Raise dike levels in a phased manner, considering the country's financial and social conditions. Safety standards and structural design upgrades against level 2 events should reflect the concentration of population and economic assets in the protected areas. Although it may not be possible to build dikes capable of withstanding level 2 disasters, appropriate and feasible targets for dike design safety should be identified.

Assure reliable operation of key facilities during emergencies. The safe and reliable operation of infrastructure must be ensured in emergency situations. Structural measures such as floodgates cannot provide reliable protection if they cannot be operated under extreme conditions, such as power failures and the absence of operators. Multiple layers of operation should be assured. A sufficient number of qualified operators should be available during disasters, but not necessarily onsite. Developing manuals and conducting regular drills are required during normal times. The danger to which operators are exposed should be minimized.

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