Study of the relationship between recent large earthquakes and damage to concrete structures*[1]

Hiroshi SAKURAI*[2], Koichi AYUTA*[2],
Noboru SAEKI*[3], Kaneyoshi OKADA*[2]

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Abstract

Five large earthquakes have recently caused death, injuries, and damage to industrial and civil property—the Kushiro-oki, Hokkaido Nansei-oki, Hokkaido Toho-oki, Sanriku Haruka-oki, and Hyogoken Nanbu earthquakes. The characteristics of each of these earthquakes influenced the resulting damage to concrete structures. If such an earthquakes occurred in a density populated metropolitan area like Tokyo, it is feared that damage would be on a huge scale, and several organizations have been looking into the damage done by these earthquakes and studying the effectiveness of earthquake proofing methods. This work is an analysis of site research and some of the reports published already, and it compares the concrete damage these earthquakes caused.

1. Introduction

Between 1993 and 1995, five large earthquakes causing death, injuries, and damage to structures occurred in Japan. They were the Kushiro-oki, Hokkaido Nansei-oki, Hokkaido Toho-oki, Sanriku Haruka-oki, and Hyogoken Nanbu earthquakes. Many concrete structure of the infrastructure were also heavily damaged. It is very important to investigate the characterristics of the damage caused by these large-scale earthquakes, and to check for similarities, on the assumption that a similar event might occur in a high-density metropolitan area such as Tokyo. Though the authors were previously investigating the Kushiro-oki and Hokkaido Nansei-oki earthquakes, they have stepped up their investigations since this rash of large earthquakes become clear.

2. Outline of the recent earthquakes and the resulting damage

2.1 Earthquake outlines

These earthquakes had magnitudes ranging 7.2 to 8.2, as shown in Table 1. All occurred between 8 : 06 in the evening and 5 : 06 in the morning, so they missed the critical

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*[1] A part of this report was presented at Hokkaido branch of JSCE conference in 1994.
*[2] Department of civil Engineering, Kitami Institute of Teachnology.
*[3] Department of civil Engneering, Faculty of Engineering, Hokkaido University

periods in which many people travel to work, business hours, study, our cook meals. Aside from Kobe city, all areas which recorded more than 5 on the Japanese scale of seismic intensity had low population densities. Kobe, a city of high population density, suffered a seismic intensity of 7 in the Hyogoken Nanbu earthquake. As shown in Fig.1, the Hyogoken Nanbu earthquake was a destructive inland earthquake, while in the case of the Kushiro-oki and Hokkaido Nansei-oki earthquakes the seismic center was near land. It was relatively far offshore in the case of the Hokkaido Toho-oki and Sanriku Haruka-oki earthquakes. As to focal depth, it was 107 km in the Kushiro-oki earthquakes, and there was no tsunami.

Where the focal depth was deep and under the sea, tsunami did not occur. Particularly large tsunami were caused by the Hokkaido Nansei-oki and Hokkaido Toho-oki earthquakes.

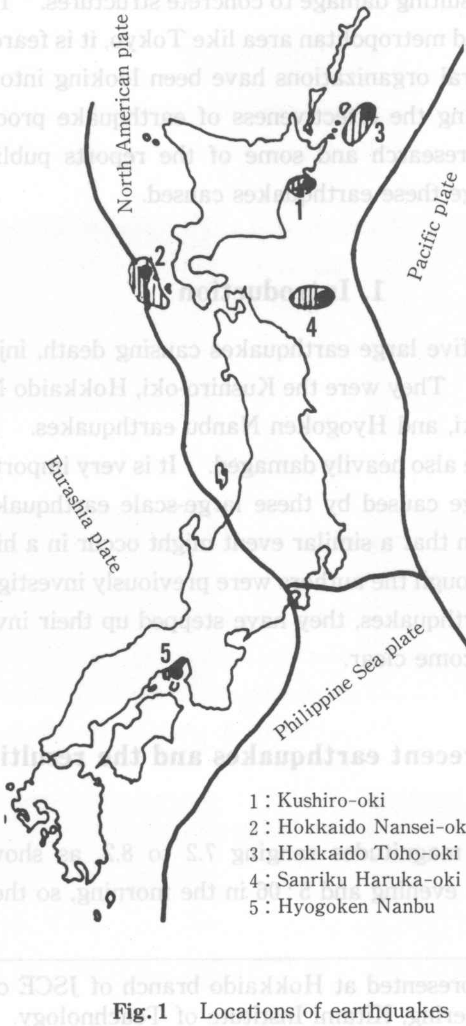

Fig.1 Locations of earthquakes

Table 1 Outline of earthquake

Earthquake	In 1993 Kushiro-oki Earthquake	In 1993 Hokkaido Nansei-oki Earthquake	In 1994 Hokkaido Toho-oki Earthquake	In 1994 Sanriku Haruka-oki Earthquake	In 1995 Hyogoken Nanbu Earthquake
Time occurred	20 : 06, 15 January 1993	22 : 07, 12 July 1993	22 : 23, 4 October 1994	21 : 19, 28 December 1994	05 : 16, 17 January 1995
Location of seismic center	42.9° N 144.4° E	42.5° N 139.1° E	43.5° N 147.9° E	40.4° N 143.7° E	34.6° N 135.0° E
Forcal depth	107 km	10 km	50 km	20 km	10 km
Seismic intensity 7	—	—	—	—	Kobe
Seismic intensity 6	Kushiro	Okushiri	Kushiro Akkeshi	Hachinohe	Sumoto
Seismic intensity 5	Urakawa Obihiro Hiroo Hachinohe	Otaru Esashi Suttsu Fukaura	Nemuro Hiroo Urakawa Nakashibetsu Rausu Ashyoro	Mutsu Aomori Morioka	Kyoto Tomioka Hikone

2.2 Outline of damage

Table 2 outlines the damage caused by these earthquakes. The Hyogoken Nanbu earthquake resulted in damage on a huge scale, with many fatalities, structurs destroyed, and extensive damage to roads and bridges. This is typical of a destructive inland earthquake that strikes a city. The Hokkaido Nansei-oki earthquake caused a large number of fatalities, and it damaged or destroyed many houses. Damage was particularly severe on Okushiri island, at a distance of 80 km from the seismic center, where a tsunami, tsunami-induced fires, and the collapse of hillsides were the main cause of destruction. Aside from these two cases, the damage was contained because, although almost matching the 1923 Kanto earthquake in magnitude, the earthquakes did not hit density populated areas. The total damage caused by the Hyogoken Nanbu earthquakes was about ¥10 trillion, 80 times the severe tsunami damage resulting from the Hokkaido Nansei-oki earthquake.

Table 2 Outline of damage

Earthquake		In 1993 Kushiro-oki Earthquake	In 1993 Hokkaido Nansei-oki Earthquake	In 1994 Hokkaido Toho-oki Earthquake	In 1994 Sanriku haruka-oki Earthquake	In 1995 Hyogoken nanbu Earthquake
Fatality	Dead	1	202	—	2	5462
	Missing	—	29	—	—	2
	Seriously injured	64	81		—	
	Slightly injured	657	240	227	285	35080
Damage to const -ruction	Totally demolished houses	18	558	—	—	107388
	Partially demolished houses	182	247	17	128	
	Damage to roads	994	711	44	28	665
	Collapsed cliffs	—	14		3	182
Amount of damage		About ¥70 billion	About ¥132.3 billion	About ¥9 billion	About ¥84.2 billion	About ¥10 trillion

3. Study of several results

3.1 Typical damage to concrete structure

3.1.1 The Kushiro-oki earthquake

There was a great deal of significant damage to the supports of structures and abutments of bridges where the ground had peaty shallow layers and the piers penetrated deeply.

Particularly striking was the damage to relatively heavy T-shaped concrete girders. Damage due to displacement in the direction of the earthquake motion was clear. Cracks and other signs of damage were observed at the points where longitudinal reinforcing steel ended. It is clearly necessary to further study the shear strength of columnar piers. Since the maximum acceleration measured by strong motion recorders at the Kushiro Weather Observatory exceeded 900 gal, a re-evaluation of the relationship between structural damage and input acceleration appears to be in order [2].

3.1.2 The Hokkaido Nansei-oki earthquake

Road retaining walls and similar structures collapsed, and the force of the tsunami moved the abutment protection from a road bridge on Okushiri island near the seismic center, causing its collapse [2]. The base walls of a PC-arch snow shelters and the superstructure of PC-arches collapsed near the seismic center. The damage structures were on the soft peaty and sandy ground of the low-lying Kuromatsunai area of southern Hokkaido prefecture. Gaps appeared in road surface as the filling behind abutments and bridge pier bases slipped away. Three bridges suffered damage at points where longitudinal main reinforcing steel ended in the RC piers [3].

3.1.3 The Hokkaido Toho-oki earthquake

Among roads under the jurisdiction of Kushiro and Nemuro, where most damage occurred and close to seismic center, 11 out of 12 national highways suffered slight damage or worse (with 4 routes damaged seriously) with 198 damage locations (with 13 sites seriously damaged). A great deal of damage was caused to Hokkaido prefectural highways and municipal roads. The principal damage caused to concrete was as follows [4]. Gaps arose between the road surface and subbase course at bridge approaches and on bridge floor slabs. As a result of the collapse of the subbase course, cracking, slipping, and bulging of sections of bridge abutments was noted in many place. Bridge girders, on the other hand, were themselves hardly seen to be damaged, although damage to supports did occur in a few cases.

Photo 1 shows the extent of damage to a road bridge (composite girder), where failure of the anchor support, cracking, and scaling of the concrete abutment occurred. Photo 2 shows another case of a road bridge (composite girder) where failure and scaling of concrete, exposure of stirrup steel, and other damage were caused when the girder was crushed against the abutment. Photo 3 shows a 3-span continuous box section road bridge with 2 main girders; in the case, failure of anchor support, cracking, and scaling of the concrete abutment

(275 cm in width at top and 460 cm at the bottom) occurred. This came about since the inertia of such a 3-span design would cause a large force to act on shoe supports.

Concrete port and harbor structures commonly suffered from damage including tilting of quaywalls and cracking aprons. Subsidence and failure of concrete aprons resulted from overall inclination of wharves. Photo 5 shows how an anti-tidal wave sea wall suffered cracking at the concrete base for the gates and shear cracks on the wall itself. This leads to questions of the wall's ability to withstand tsunami.

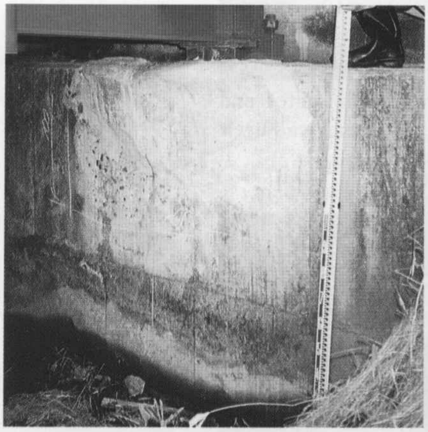

Photo 1 Failure of the anchor support, cracking, and scaling of the concrete abutment (Road bridge, composite girder, Manmen in Bekkai town)

Photo 2 Failure and scaling of concrete, exposure of stirrup steel, and other damage were caused when the girder was crushed against the abutment (Road bridge, composite girder, Furen in Bekkai town)

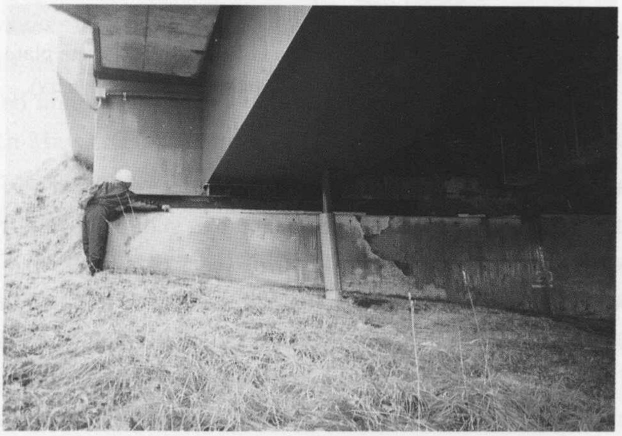

Photo 3 Failure of the anchor support, cracking, and scaling of the concrete abutment. The width of the abutment: 275 cm at the upper part and 460 cm at the lower part. (Road bridge, 3 spans continuos, 2 main girders box section, Midorimachi in Nakashibetsu town)

Photo 4 Cracking at the concrete base for the gates and shear cracks on the anti—tidal wave quaywall itself (Fishing port, Hanasaki in Nemuro city)

Photo 5 Wharf tilted and sunk and broke the concrete plate of apron (Fishing port, habomai in Nemuro city)

3.1.4 The Sanriku Haruka-oki earthquake

The greatest damage occurred along a northwest to southeast line from Matsugaoka to Ruike in Hachinohe city. As shown in Photo 6, the piers of a steel road bridge were caused to tilt over by about 20 cm toward the upstream direction. Though the bridge itself was constructed in 1931, the pedestrian bridge section was added in 1972. Damage to the bridge superstructure and the pedestrian bridge was caused by the two coming into contact with each other ; this came about because motion perpendicular to the bridge axis was strong and the movements of the two parts of the bridge were out of phase. The motion of the bridge was restrained by the presence of the pedestrian bridge, causing inclination of the bridge piers standing in the river channel.

Photo 6 Concrete pier of steel girder bridge tilted and damage a part of concrete pier of pedestrian bridge by crashing onto each other (Road bridge: costructed in 1931, pedstrian bridge: constructed more in 1972, Kumanodou — Naganawashironai Funawatasi in Hachinohe city)

Photo 7 shows how to the concrete structure of a high school building was damaged by shearing of the walls and pillars. The stirrups were broken. The longitudinal reinforcing steels were deformed and had yielded. This old structure had suffered from the Tokachi-oki earthquake (18th May 1968, magnitude 7.9), the Kushiro-oki earthquake, corrosion of the reinforcing steel were recognized at the destructive parts of earthquakes and it is clear that there had been cracks and it is clear that the reinforcing concrete had been weakened in these earthquakes. Some cracks certainly seemed to have been caused in the earlier earthquakes.

Photo 8 shows how the collapse of a road embankment subbase caused an L-shaped concrete retaining wall to slide by 3.5 m and subside by 2.5 m at Matsugaoka in Hachinohe city.

Photo 7 Concrete destroyed, broken stirrups, deformation and yield of longitudinal steel at recessed steel section past of RC pier (the first floor of 3 stories high school building in Hachinohe city)

Photo 8 Collapse of a road embankment subbase caused an L-shaped concrete retaining wall to slide 3.5 m and subside by 2.5 m (at Matsugaoka in Hachinohe city)

3.1.5 The Hyogoken-Nanbu earthquake

This was the most destructive earthquake to strike Japan since 1923 Kanto earthquake. Damage to the infrastructure of the modern city of Kobe and Awaji island, including that to many concrete structures, was particularly great because the area, which is known as the Hanshin metropolitan area, is so highly populated. Though the measured horizontal acceleration was over 800 gal at several points, the case over the horizontal acceleration of design with large range many.

As shown in Photo 9, expressway piers and girders failed and collapsed. Stirrups in RC columns failed, as did pressure welds in the main reinforcing bars. The girders forming the superstructure were heavy, consisting of PC concrete, the piers were high. It appears that large perpendicular inertial force resulted from the large amplitude of the earthquake motion. The bridge in the photo 9 has clearly reached its ultimate limit state. The traffic probelms caused by this collapsemeant. It was scrapped and quickly removed.

As shown in Photo 10, the rigid frame bridge piers of Bullet Train overpasses suffered scaling and some were destroyed. Stirrups failed and the longitudinal reinforcing steel yielded and deformed. Inertial forces were clearly very strong here too, for the same reasons as stated earlier.

Photo 9 Expressway piers and girders failed and collapsed (PC bridge constructed in 1969, at Fukae honjyo-chyo, Higashinada Ward in Kobe city)

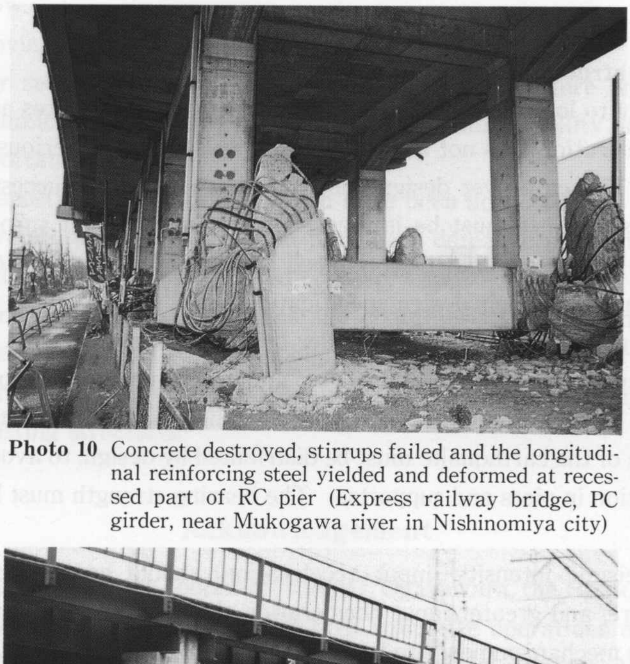

Photo 10 Concrete destroyed, stirrups failed and the longitudinal reinforcing steel yielded and deformed at recessed part of RC pier (Express railway bridge, PC girder, near Mukogawa river in Nishinomiya city)

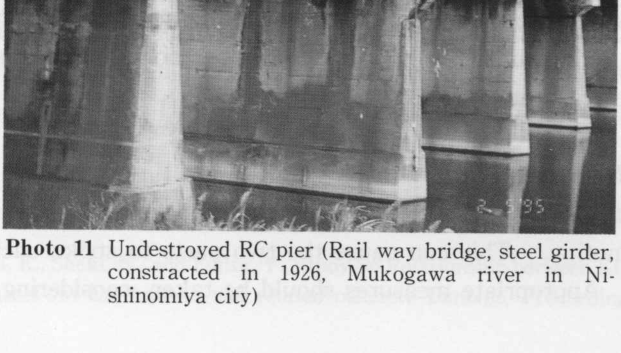

Photo 11 Undestroyed RC pier (Rail way bridge, steel girder, constracted in 1926, Mukogawa river in Nishinomiya city)

Photo 11 shows how a railroad bridge in the same area Photo 10 was scarcely damaged, despite having been in service since 1926. This bridge was returned to service immediately after earthquake. The small span and section of the girder, and the low height of piers means the inertial force were probably small. Still more the girders were caught up to direction of bridge axis and the perpendicular by top part of pier.

3.2 Study on earthquake-proofing

3.2.1 Improving for support

Damages to bridge supports were particularly conspicuous in all these earthquakes. Such damage caused bridge girders to collapse in the Hyogoken Nanbu earthquake. It is necessary to look into how these supports can be improved and fitted with devices to prevent the collapse of girder. Future structures must be made earthquake proof, and if necessary this should be studied according to 1992 manual for the earthquake-proofing of road bridge designs [5]

3.2.2 Verifying structural stability in earthquakes

It is necessary to look into structural stability during earthquakes as described bellow.

(1) The large acceleration was not always necessarily to damage seriously for structure by some condition. The case over design condition was not always necessarily to reach the limit of ultimate state. It must be influenced to sustain level of surplus of structure to design condition. It is clear that there is need to investigate the relationship between the damage to structures and their design specifications.

(2) Damage to long-span and continuous-girder bridges was conspicuous. Since the inertia of the superstructure is large in such bridges, and forces concentrate on fixed support, it should be made as light as possible, for example using light-weight concrete, PC, and SRC and so on. The force of the earthquake must be distributed by design, to avoid its concentration at particular location in piers and supports. The bearing strength must be improve by SRC pier and so on.

(3) The design seismic intensity (input acceleration) should be increased in the case of important structure, and greater input acceleration should be used in dynamic analysis.

(4) A new fail-safe mechanism needs to be developed for bridges. It must ensure that instant collapse dose not occur even if seismic force beyond the design specifications act upon the structure and damage it. The use of single columns in a structure, which may cause it to collapse when exposed to ultimate conditions, should be avoided. Rather, an appropriate structure—such as rigid frame construction—should be adopted to ensure that the structure load is supported even after the structure is damaged.

3.2.3 Inspection of structure extensions

When a structure has been extended, the old and new sections may be subject to different seismic motion. This can cause the two parts to strike each other, leading to eventual damage. Appropriate measures should be taken, considering structural balance during an earthquake, to prevent structural components coming into contact with each other.

3.2.5 Reinforcing of structures designed according to old construction codes

The specifications for Highway Bridges and their Aseismatic Design Standards were revised considerably in 1980. Many of the civil engineering structures and buildings damaged by Hyogoken Nanbu earthguake were built according to earlier versions of the specifications and standards. There is an urgent need to review the seismic performance of structure constructed according to old codes and take adequate precautions where necessary [5] .

4. Conclusion

This study of the relationship between the recent series of major earthquakes and damage to concrete structure has revealed that several issues needs to be addressed. These are elucidated below.

(1) Means of improving supports and improving base isolation.

(2) Adopting larger seismic forces in the structural design of future projects and higher acceleration in dynamic analysis, while considering the seismic stability of the structure and the structure's importance.

(3) Carrying out inspections of structures which have been added to.

(4) Inspecting and reinforcing structures that have been damaged in previous earthquakes.

(5)Inspecting structures built under outdated codes.

It is also essential to analyzed patterns and characteristics of earthquake damage to concrete. Damage data must be made public, and an extensive and detailed study of available data must be carried out with the aim of developing seismic measures for both newly built and existing structures.

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