Seismic Safety of Nuclear Power Plants: Lessons Learned from the 2007 Niigataken Chuetsu-Oki Earthquake

Young-Sun Choun
Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejeon, Korea. sunchun@kaeri.re.kr

1. Introduction

Nuclear power plants (NPPs) are designed to withstand earthquakes that can be anticipated to occur during their operating periods and to shut down safely in the event of a major earthquake. In Taiwan, three reactors at the Chinshan and Kuosheng NPPs shut down automatically during the 1999 Chi-Chi earthquake with a magnitude of 7.6 [1]. In Japan, one reactor at the Kashiwazaki-Kariwa NPP and three reactors at the Onagawa NPP shut down automatically during the 2004 Niigata-Chuetsu earthquake's aftershock (M=5.2) [2] and the 2005 Miyagi earthquake (M=7.2) [3], respectively.

Recently, on July 16, 2007, there was a powerful earthquake with a magnitude of 6.6 occurred in the northwest Niigata region of Japan. Since the strong ground motion significantly exceeded the design basis ground motion level, the operating reactors at the Kashiwazaki-Kariwa NPP were automatically shut down and a number of problems were identified [4].

This paper summarizes the responses and damages of the Kashiwazaki-Kariwa NPP during the 2007 Niigataken Chuetsu-Oki earthquake and then addresses the lessons learned from a seismic or structural point of view.

2. The Niigataken Chuetsu-Oki Earthquake

The Niigataken Chuetsu-Oki earthquake with a moment magnitude of 6.6 (M=6.8 according to the Japanese Meteorological Agency) occurred at 10:13 a.m. local time on July 16, 2007 with a depth of its epicenter of about 17 km, in a zone of a compressional deformation that is associated with the boundary between the Amur plate and the Okhotsk plate. At this area, the Okhotsk plate is converging to the west-northwest towards the Amur plate with a velocity of about 9 mm/yr. The Amur and Okhotsk plates are relatively small plates that lie between the Eurasian plate and the Pacific plate. The Pacific plate converges west-northwest towards the Eurasia plate at over 90 mm/yr [5].

3. Earthquake Response and Damage of the Kashiwazaki-Kariwa NPP

3.1 Outline of the Plant

The Kashiwazaki-Kariwa NPP of the Tokyo Electric Power Company, Inc., which has seven units with a total net installed capacity of 7,965 MW, is the biggest nuclear power station in the world. Five reactors which started commercial operation between 1985 and 1994 are of a BWR type with a net installed capacity of 1,067 MW each and two reactors which started commercial operation in 1996 and 1997 are of an ABWR type with a net installed capacity of 1,315 MW each [6].

The extreme design earthquake ground motions S2, which are the largest conceivable ground motion assuming an earthquake directly under a reactor, are 167 to 274 gal for different units as shown in Table 1.

3.2 Earthquake Response

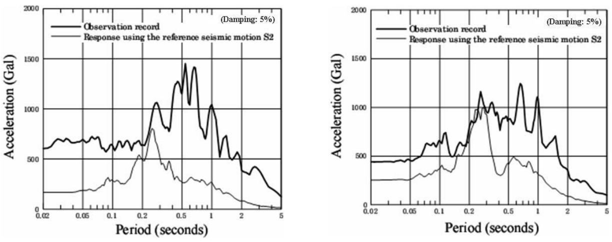
The Niigataken Chuetsu-Oki earthquake occurred with its epicenter about 16 km north of the Kashiwazaki-Kariwa NPP site. The maximum accelerations recorded at the base mat of the reactor building for each unit during the earthquake and their design values at the same locations are shown in Table 1. The maximum accelerations are measured from 267 to 680 gal in the horizontal direction and 205 to 488 gal in the vertical direction, which exceed the S2 design values in all the units. For Unit 2, the maximum acceleration recorded for the EW component was 3.6 times the value expected in the design stage.

Table 1. Maximum accelerations observed at the base mat of the reactor building [7].

(Unit: gal)

Location	Observed accelerations			Design Values, S2		
	NS	EW	UD	NS	EW	UD
Unit 1	311	680	408	274	273	(235)
Unit 2	304	606	282	167	167	(235)
Unit 3	308	384	311	192	193	(235)
Unit 4	310	492	337	193	194	(235)
Unit 5	277	442	205	249	254	(235)
Unit 6	271	322	488	263	263	(235)
Unit 7	267	356	355	263	263	(235)

* The up-down components in brackets were used in static design.



(a) Unit 2 (b) Unit 5

Figure 1. Acceleration response spectra for the base mat of the reactor building (EW component) [8].

3.3 Earthquake Damage

At the time of the earthquake, three reactors (Units 3, 4, and 7) were in operation, one reactor (Unit 2) was in the process of starting its operation after a periodic inspection, and the other three reactors (Units 1, 5, and 6) were shut down for a planned periodic inspection. As a result of the earthquake, four reactors (Units 2, 3, 4, and 7) were shut down automatically.

As a result of the post-earthquake visual observations, a total of 65 problems had been identified [9]. Main events were reported as follows [10]:

- Overflow of water containing radioactive materials from the spent fuel storage pools onto the operating floor of the reactor buildings (All Units)
- Displacement of the ducts connected to the main exhaust stacks (Units 1-5)
- Flooding with 2,000 cubic meters of water in the Reactor Combination Building due to damage to the fire protection system's piping (Unit 1)
- Fire at an electrical transformer outside a building due to the relative movement of the ground (Unit 3)
- Release of radiation-contaminated water into the sea (Unit 6)
- Damage to the couplings of the drive axis for the overhead crane in the reactor building (Unit 6)
- Detection of iodine and radioactive particulate matter by the monitor of the main exhaust stack (Unit 7)

4. Lessons Learned

There is a significant contribution to the seismic hazard by an active fault in the vicinity of the site or the near region. The Niigataken Chuetsu-Oki earthquake was caused by the movement of an approximately 30 km long and 25 km deep fault, which was not considered during surveys carried out for the design of the Kashiwazaki-Kariwa NPP. After all, there was a significant exceedance of the design basis earthquake level by the observed accelerations at the base mat elevation of the reactor buildings for a very wide range of spectral periods as shown in Figure 1. Also, the design acceleration response spectra did not represent the rich contents for a long-period range in comparison with the response spectra obtained from the observed acceleration records. Thus, during an evaluation of the seismic hazard at the site, capable and active faults near the site must be taken into account. The design basis earthquake level has to be determined and updated continuously with a consideration of the latest geological environment.

Although there was a significant exceedance of the design basis level, the safety-related facilities of the plant suffered little damage and appeared to show a good performance to shut down the reactors automatically. This indicates that significant uncertainties were included at each step for evaluating a seismic hazard, and a sufficient safety margin due to the applied conservatisms was included at the time of the design of the plant. Therefore, for obtaining the realized seismic hazard and the seismic capability of facilities, it is necessary to identify and quantify the sources of uncertainties and conservatisms involved in the derivation of the seismic design basis and in the process of the seismic design. To maintain a reliable safety function of the safety-related facilities, the efforts for reducing the uncertainties involved in the seismic hazard and seismic design, and for obtaining the real seismic capacities of facilities representing the final seismic design as well as an aging accelerated by an earthquake-induced damage are needed. Otherwise, it is necessary to introduce a reliable seismic design concept such as a seismic isolation system.

Near-fault ground motions containing a large velocity pulse can cause severe damage to structures. Thus, on occasion, a reactor may be shut down automatically even though peak ground accelerations do not exceed the design values. Because of this possibility, it can be said that the acceleration response spectra may not be the only representative of the energy content of a ground motion. Therefore, additional representations of a ground motion by considering energy contents should be provided, and a reevaluation of the automatic shutdown criteria of the rector should be carried out.

5. Conclusion

In the event of a strong earthquake, the safety-related structures, systems, and components (SCCs) of NPPs must have their safety functions to shut down the operating reactors safely without any release of radioactive material. For this, first of all, seismic design criteria for NPPs have to be updated continuously with a consideration of the latest geological environment, especially active faults in the vicinity of a site, and of the new advanced knowledge related to the seismic hazard and the seismic performance of nuclear facilities. Seismic safety research for reducing the uncertainties during an evaluation of a seismic hazard and structural performance should be strengthened. In addition, development of an advanced seismic design concept with a high reliability should be performed for ensuring the safety function of the safety-related SCCs during an unexpected strong earthquake.

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