3. Seismic and tsunami damage to other NPSs

(1) Seismic ground motion and tsunami height observed at Onagawa NPS

1) Seismic ground motion

a Seismic ground motion observation system, its observation records and observed ground motions

The seismic observation system is composed of seismometers and recording devices. Seismometers are installed at four points (on the rooftop, the refueling floor, i.e. the 5th floor, the 1st floor and the base mat) of the reactor building of Unit 1, at four points (the same as of Unit 1, except the refueling floor, i.e. the 3rd floor) of Unit 2, and at four points (the same as of Unit 2) of Unit 3, respectively. They are also installed at the upper part of the bedrock on the site (representing the base stratum). These seismometers are designed to observe acceleration time history of two horizontal and one vertical components.

Table III-3-1 shows the maximum acceleration values of seismic ground motions in three components, i.e. horizontal east-west and north-south and vertical components, which were observed on the base mats of the reactor buildings. On the base mat level, the maximum horizontal acceleration value was 607 Gal at Unit 2 (in the north-south direction), and the maximum vertical acceleration value was 439 Gal at Unit 1.

b Comparison between standard seismic ground motion Ss and observed seismic ground motion

The standard seismic ground motion Ss (Ss-B, Ss-D and Ss-F) is established to envelop the seismic ground motions of an assumed consecutive Miyagi-ken Oki earthquake, intraslab earthquake beneath the site, and the possible earthquake from diffuse seismicity.

Table III-3-1 shows the maximum response acceleration values for the standard seismic ground motion Ss at the level of seismometers located inside the buildings. It can be seen that most of the observed maximum acceleration values are below the maximum response acceleration for the standard seismic ground motion Ss. However, the observed maximum acceleration values on the base mat level at Unit 1 (in the east-west and north-south directions), Unit 2 (in the north-south direction), and Unit 3 (in the north-south direction) somewhat go beyond the maximum response acceleration for the standard seismic ground motion Ss. The observed vertical maximum acceleration values on the base mat level at all units are below the maximum response acceleration for the standard seismic ground motion Ss.

Figure III-3-1 shows a comparison between response spectra of the observed seismic ground motions at the upper part of the bedrock on the site and response spectra for the standard seismic ground motion Ss. Response spectra of the observed seismic ground motions exceed response spectra for the standard seismic ground motion Ss in the periodic band between 0.2 and 1.0 sec.

c Probabilistic seismic hazard assessment and exceedance probability of standard seismic ground motion Ss

Figure III-3-2 shows the evaluation of the annual exceedance probability of DBGM Ss for Onagawa NPS. Response spectra for Ss-Dh are also shown in the figure. The exceedance probability for Ss is between 10^{-3} and 10^{-5} per year.

2) Tsunami

a Tide level observation system and observed records

The tide level observation system is composed of a tide gauge and recording devices. The tide gauge is installed in a quiet area in the harbor, and the tsunami recording devices are installed in the buildings.

Figure III-3-3 shows the tsunami time history recorded by the tide gauge. From the record, it can be seen that the first big wave arrived at about 15:29 (43 min after the main shock). The observed tsunami height was about 13 m relative to O.P. (O. P.: the reference surface for construction of Onagawa NPS), which did not exceed the height of the site, i.e. 13.8 m relative to O.P. (the real height of the site is 14.8 m, adjusted to sinking by about 1 m due to crustal deformation, according to the Geographical Survey Institute QE, see Figure III-3-4). Although seawater was found to have entered the sea-facing side of the site, it did not reach the major buildings.

b Comparison between design basis tsunami height and observed tsunami height

The design basis tsunami height is evaluated as 9.1 m, for the Keicho Sanriku Earthquake (M8.6 in 1611), according to the application for establishment permit, and as 13.6 m, for the Meiji Sanriku Earthquake (M8.3 in 1896), based on the tsunami evaluation method of the Japan Society of Civil Engineers (2002) mentioned previously. Thus, the design basis tsunami heights were higher relative to those tsunami height observed above.

3) Damage

a External power supply

Units 1 to 3 are connected to a transmission network: two power lines of 275 kV system from the Ishinomaki transforming station, about 25 km away from the site; two power lines of 275 kV system from the Miyagi central switchyard, about 65 km away from the site; and one power line of 66 kV system from the Onagawa nuclear transforming station.

The seismic intensity of the main shock was estimated to be upper 6 (in Japanese scale) near the Ishinomaki transforming station, and lower 6 near the Miyagi central switchyard. The power transmission from three lines of the 275 kV systems and one line of the 66 kV system were disrupted due to the seismic ground motion. Of the power receiving equipment on the NPS site, a start up transformer of Unit 1 failed, thereby losing its function. On March 12, as the start up transformer came back online, the power was switched to the external regular power supply (275 kV) and the normal power supply system was returned.

b Seawater pump and emergency power supply

Figure III-3-5(a) and Figure III-3-5(b) show the layout of intake channel, seawater pump, seawater pump room, and heat exchanger room of the component cooling system. As shown in the figure, the seawater pump room is located on the higher site, which is 14.8 m high, about 100 m away from the coast, and is structurally designed to prevent being submerged by a run-up tsunami. Inside the room, the tide gauge is installed with an opening. This tide gauge is designed to allow the automatic stop of the seawater pimp in short of seawater due to the backrush of a tsunami.

The observed tsunami height was 13 m, and despite the land sinking, the tsunami did not cause the seawater pump room (on the site as high as 13.8 m, adjusted to sinking by about 1 m) to be directly submerged. However, as the water level rose due to the tsunami, the water level in the underground intake pit also rose as shown in Figure III-3-5, caused by the siphon phenomenon. This resulted in seawater overflowing through the opening of the tide gauge into the seawater pump room. Then the seawater flowed from the pump room, via the trench, into the basement floors of the reactor buildings, causing the heat exchanger room of the component cooling water system in the second basement to be submerged. In addition, the component cooling water pump of Unit 2 was also submerged, which thereby caused the cooling function of emergency diesel generators to be lost, with two units stopped out of those three generators.

Tohoku Electric Power Company Inc. took measures to prevent the piping penetrations and the cable tray penetrations from the seawater pump room to the trench from being submerged. They stated that the company would remove the water gauge in the seawater pump room and relocate it to an improved area to prevent exposure to water, and they would also set up a flood barrier around the seawater pump room.

4) Integrity assessment of the reactor buildings in the main shock and its aftershocks

a In the wake of the main shock

Response spectra observed on the position corresponding to the surface of the base stratum exceeded response spectra of the standard seismic ground motion Ss in a certain periodic band.

NISA directed Tohoku Electric Power Company Inc. to prepare an "inspection and evaluation plan" of equipments and piping systems by Unit and implement the plan.

Tohoku Electric Power Company conducted an integrity assessment of the reactor buildings, based on the same procedures as the integrity assessment for the building structure of the Kashiwazaki-Kariwa Nuclear Power Station after the Chuetsu-oki Earthquake in July 2007. The response analyses on the reactor buildings of Units 1 to 3 were made with the observed acceleration records as the input of seismic ground motion. Figure III-3-6 shows the shear strain and shear force at the building by floor for each Unit. It can be seen that shear strain at each floor was below the JEAG4681-2008 evaluation criteria (2.0×10^{-3}), and shear force was also below the elasticity limit. A ratio between the evaluation criteria and shear strain results at each floor was around 2.5 to 5.6.

JNES has conducted an integrity assessment of the reactor buildings of Units 1, 5, 6 and 7 at the Kashiwazaki-Kariwa Nuclear Power Station in wake of the Chuetsu-oki Earthquake. The ratio between the evaluation criteria and shear strain was the same or more as the above.

b In the wake of the aftershocks

An aftershock on April 7 around the Onagawa NPS had a magnitude of 7.1, at a depth of about 66 km, and was estimated to be an intraslab earthquake. NISA directed Tohoku Electric Power Company, as of April 13, to analyze the seismic observation data obtained from the aftershock, and confirm the seismic safety of important safety-related equipments. Tohoku Electric Power Company, as of April 25, reported the analysis results of the above seismic observation data. The report stated that: the observed maximum vertical acceleration at the Unit 2 reactor building (on the 3rd floor, the rooftop) and the Unit 3 reactor building (on the 3rd floor) exceeded the maximum response acceleration for the standard seismic ground motion Ss; the observed response spectra exceeded horizontal response spectra for the standard seismic ground motion Ss in a certain periodic band; and the reactor buildings maintained their functions.

(2) Seismic ground motion and tsunami height observed at Tokai Dai-ni NPS

1) Seismic ground motion

a Seismic ground motion observation system, observation records and observed ground motions

The seismic observation system is composed of seismometers and recording devices, and is installed at eight points (one on the 5th, 4th and 2nd floors, respectively, and five on the base mat of the second basement) of the reactor building. These seismometers are designed to observe the time history of seismic acceleration in two horizontal and vertical directions.

Table III-3-2 shows maximum acceleration values of observed seismic ground motions, in horizontal and vertical directions, at the reactor building. On the base mat level, maximum horizontal acceleration was 214 Gal (north-south direction), and maximum vertical acceleration was 189 Gal.

b Comparison between standard seismic ground motion Ss and observed seismic ground motion

Standard seismic ground motion Ss (Ss-D and Ss-1) is decided to envelop the seismic ground motions of an interplate earthquake in Kashima-nada, an intraslab earthquake in the south of Ibaraki Prefecture, earthquakes caused by near-field active faults and possible earthquake from diffuse seismicity.

Maximum acceleration of the observed seismic ground motions was below maximum response acceleration for the standard seismic ground motion in application document for construction approval (Hereinafter, referred to as the design basis seismic wave in application document for construction approval) and the standard seismic ground motion Ss for the purpose of seismic back-check. Floor response spectra observed on the second basement to 6th floors exceeded floor response spectra for the design basis seismic wave at the construction approval in a certain periodic band (between about 0.65 and 0.9 sec.). However, spectra of observed seismic ground motion was below that for the design basis seismic wave at the construction approval around equipment important to seismic design and main equipment in the piping system having their own natural periods.

c Probabilistic seismic hazard assessment and exceedance probability of standard seismic ground motion Ss

Figure III-3-7 shows the evaluation of the annual exceedance probability of DBGM Ss for Tokai Dai-ni NPS. Response spectra for $Ss\text{-}D_H$ are also shown here. It can be seen that the exceedance probability for standard seismic ground motion Ss is approximately between 10^{-4} and 10^{-5} per year.

2) Tsunami

a Tide level observation system and observed records

The tide level observation system is composed of a tide gauge and recording devices. The tide gauge is installed in a moderate wave area in the harbor, but there was no record of tide gauge because the tsunami's height exceeded its measurement scale and the power supply was disrupted from 16:40, March 11 onwards. Therefore, the tsunami height along the coast near the Tokai Dai-ni is unknown. The first big wave arrived at about 15:15 (30 min after main shock), the water level was 5.4 m.

Japan Atomic Power Co. has been surveying traces of how high the tsunami ran up on the NPS site. The results are shown in Figure III-3-8. The tsunami marked traces as high as H.P. + 5.9 m (5.0 m above sea level, H.P.: the reference surface for construction of Hitachi Port) to H.P. +6.3 m (5.4 m above sea level, provisional). Based on these findings, the height of the run-up tsunami was estimated to be approximately H.P. +6.3 m (5.4 m above sea level, provisional). The tsunami did not reach H.P. +8.9 m (8 m above sea level), on which the major buildings are located.

b Relation between design basis tsunami height and tsunami observed height

Design basis tsunami height is not contained in the application document for establishment permit. It is determined as H.P. +5.8 m (4.9 m above sea level), for the Boso-oki Earthquake (M8.2 in 1677), based on the tsunami evaluation method of the Japan Society of Civil Engineers (2002).

3) Damage

a External power supply

The Tokai Dai-ni Nuclear Power Station is connected to the following transmission network: two 275 kV power lines from the Naka substation, about 15 km away from the site; and as external backup power, one 154 kV power system from the Ibaraki substation, about 8 km away from the site, via the Tokai switchyard.

The seismic intensity was estimated to be upper 6 (in Japanese scale) near the Naka substation, and lower 6 near the Ibaraki substation. Immediately after the quake, the Naka substation and the Ibaraki substation stopped functioning due to the seismic ground motion, resulting in disrupted transmission of all lines. Of the power receiving equipment on the NPS site, a main transformer and a starting transformer experienced leakage of insulation oil. On March 13, one of 154 kV external backup line came back. And on March 18, the Tokai Dai-ni switched to the external regular power supply (275 kV system) and returned to the normal power supply system.

b Seawater pump and emergency power supply

The tsunami flooded the north emergency seawater pump area in the seawater pump room, as shown in Figure III-3-8. Consequently one of three seawater pumps for emergency diesel generators was submerged, and one of three emergency diesel generators stopped. Meanwhile, the other two emergency diesel generators were able to operate, successfully ensuring emergency power supply.

When the earthquake hit the site, the north emergency seawater pump room was under leveling construction of its sidewall as protection against tsunami (H.P. +5.8 m, 4.9 m above sea level). This construction work put in place a new sidewall up to H.P. +7.0 m (6.1 m above sea level) outside the existing sidewall, but the waterproof sealing of the penetration (small holes for electric cables, etc.) of the wall had not been completed, and as a result the seawater came through the small holes into the pump room.

The height of the run-up tsunami was approximately H.P. +6.3 m (5.4 m above sea level), not going beyond the new sidewall, which was as high as H.P. +7.0 m (6.1 m above sea level).

4) Integrity assessment of the reactor building in wake of a main shock

Floor response spectra of the observed seismic ground motion exceeded the design basis seismic ground motion in the application document for establishment permit and the standard seismic ground motion Ss in a certain periodic band. An integrity assessment of the reactor building was conducted, based on the same procedures of the Onagawa as mentioned above 3.(1) 4).

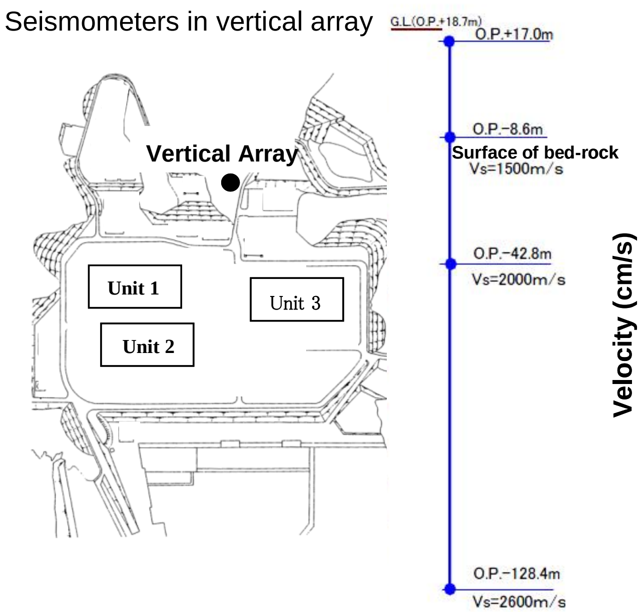
(3) Situation of Higashidori NPS at the time of the earthquake

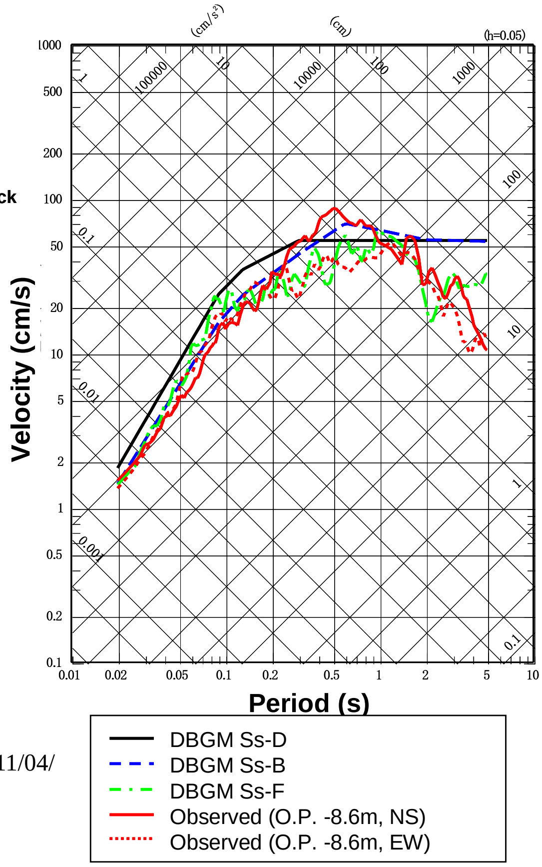
At the time of the Earthquake, the Higashidori Nuclear Power Station was in in-service inspection, and the reactor was not operated. On the site, no damage caused by seismic ground motion and tsunami was reported. The observed seismic ground motion at the reactor building was 17 Gal. The earthquake caused the external power supply (the Mutsu trunk line and Tohoku-Shiranuka line) to be lost, but an emergency diesel generator was able to operate, successfully ensuring power supply. Later the same day, at 23:59, the Tohoku-Shiranuka line was restored, which enabled the cooling of the spent fuel storage pool, etc. using the external power supply.

Table III-3-1 Max. acceleration values observed in reactor building at Onagawa NPS.

Loc. of seismometer		Record Max. acc. (Gal)			Max. response acceleration to the DBGM Ss (Gal)		
		NS	EW	UD	NS	EW	UD
Unit 1	Roof	2000	1636	1389	2202	2200	1388
	Refueling Floor(5F)	1303	998	1183	1281	1443	1061
	1ST F	573	574	510	660	717	527
	Base mat	540	587	439	532	529	451
Unit 2	Roof	1755	1617	1093	3023	2634	1091
	Ref. Floor(3F)	1270	830	743	1220	1110	968
	1ST F	605	569	330	724	658	768
	Base mat	607	461	389	594	572	490
Unit 3	Roof	1868	1578	1004	2258	2342	1064
	Ref. Floor(3F)	956	917	888	1201	1200	938
	1ST F	657	692	547	792	872	777
	Base mat	573	458	321	512	497	476

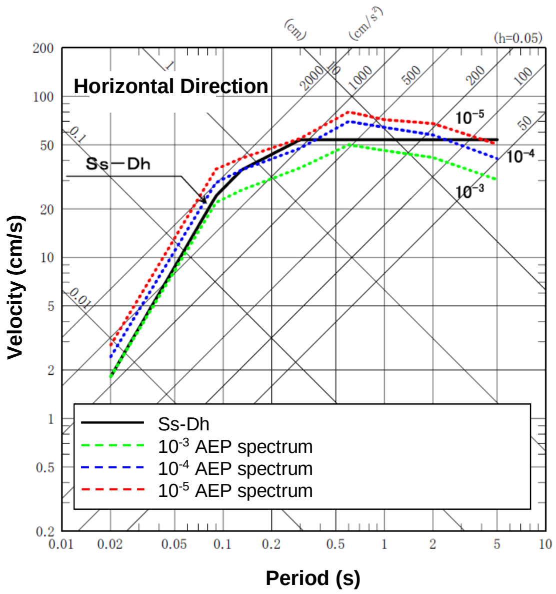
Reference: Tohoku Electric Power Co., Inc
[Online]. http://www.tohoku-epco.co.jp/ICSFiles/afieldfile/2011/04/07/110407_np_b1.pdf
Partially modified by JNES.





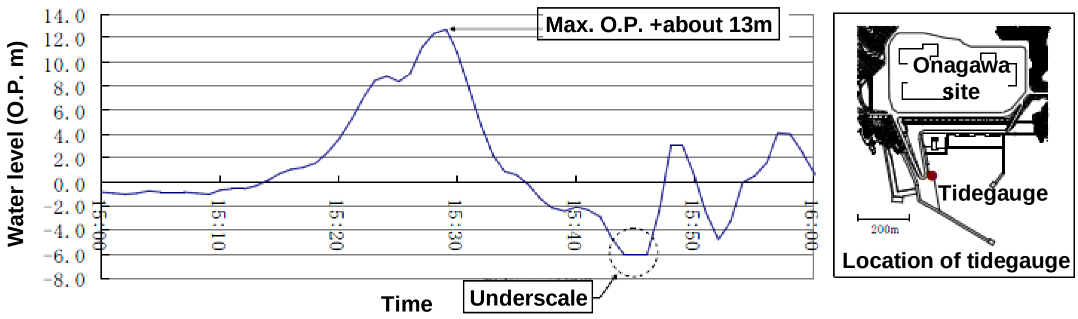
Reference: Tohoku Electric Power Co., Inc
[Online].http://www.tohoku-epco.co.jp/ICSFiles/afieldfile/2011/04/25/110425np_s.pdf
Partially modified by JNES.

Fig. III-3-1 Deployment of seismometers and comparison of observed response spectra with the DBGM Ss on a free surface (equivalent to the base stratum) at Onagawa NPS.



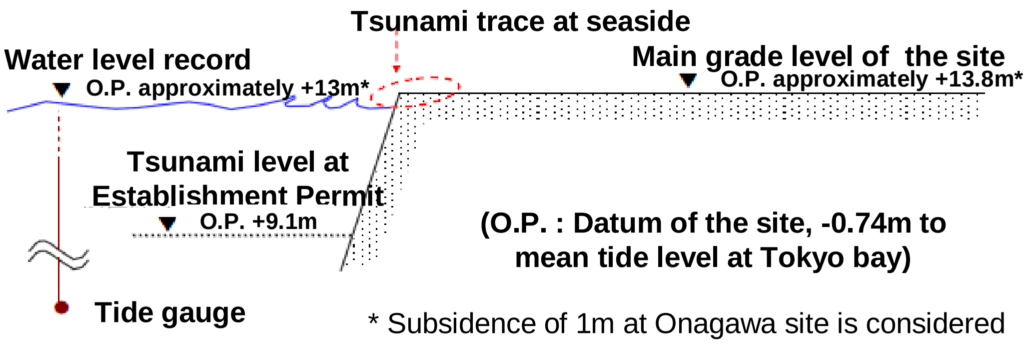
Reference: Tohoku Electric Power Co., Inc
[Online]. http://www.nisa.meti.go.jp/shingikai/107/3/2/017/17-2-1.pdf
Partially modified by JNES.

Fig. III-3-2 Annual exceedance probability (AEP) of DBGM Ss for Onagawa NPS.



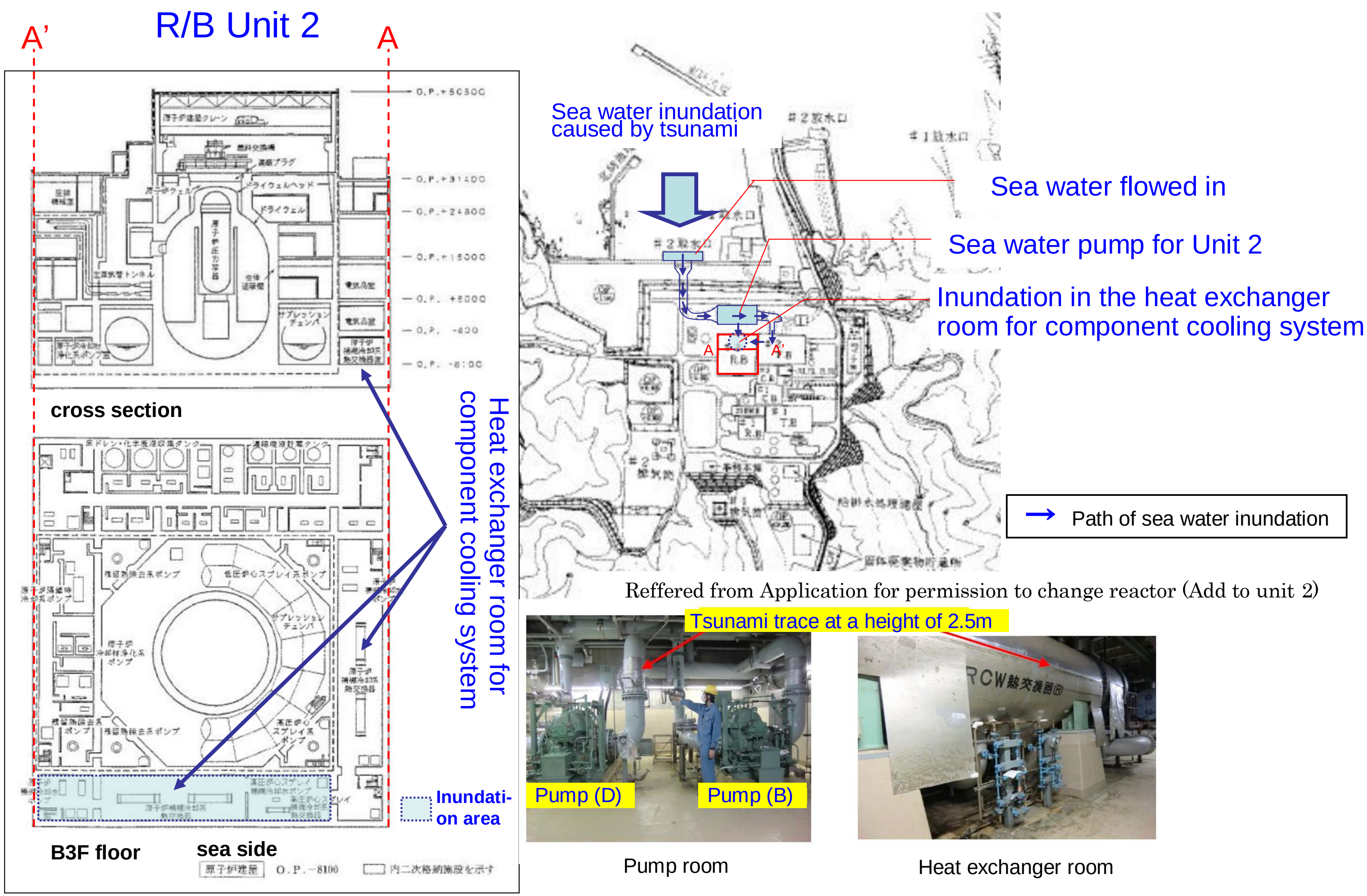
Reference: Tohoku Electric Power Co., Inc
[Online].http://www.tohoku-epco.co.jp/ICSFiles/afieldfile/2011/04/26/110407_np_t3.pdf
Partially modified by JNES.

Fig. III-3-3 Time history of water level changes observed at Onagawa NPS.



Reference: Tohoku Electric Power Co., Inc
[Online].http://www.tohoku-epco.co.jp/ICSFiles/afieldfile/2011/04/26/110407_np_t3.pdf
Partially modified by JNES.

Fig. III-3-4 Outline of tsunami arrival at Onagawa NPS.

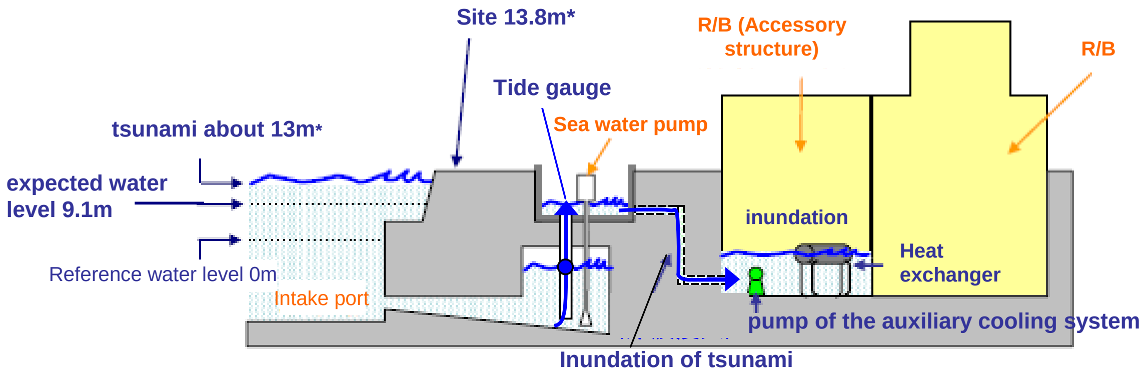


Reference (Photos): Tohoku Electric Power Co., Inc [Online]. http://www.tohoku-epco.co.jp/ICSFiles/afieldfile/2011/04/26/110426_siryou.pdf

Partially modified by JNES.

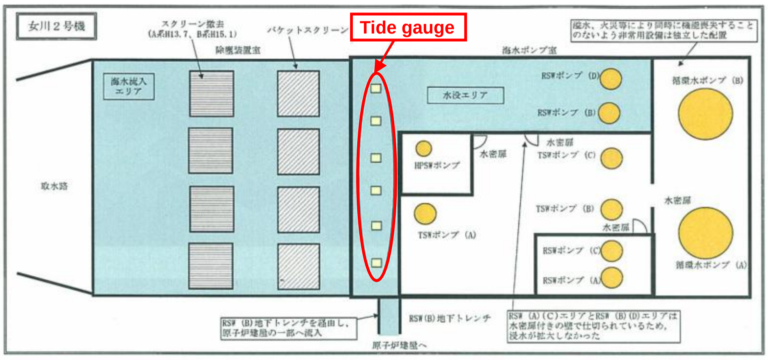
Fig. III-3-5(a) Inundation in the heat exchanger room for a component cooling system (1) at Onagawa NPS.

[Inundation pathway to Heat exchanger (B) room for component cooling system]

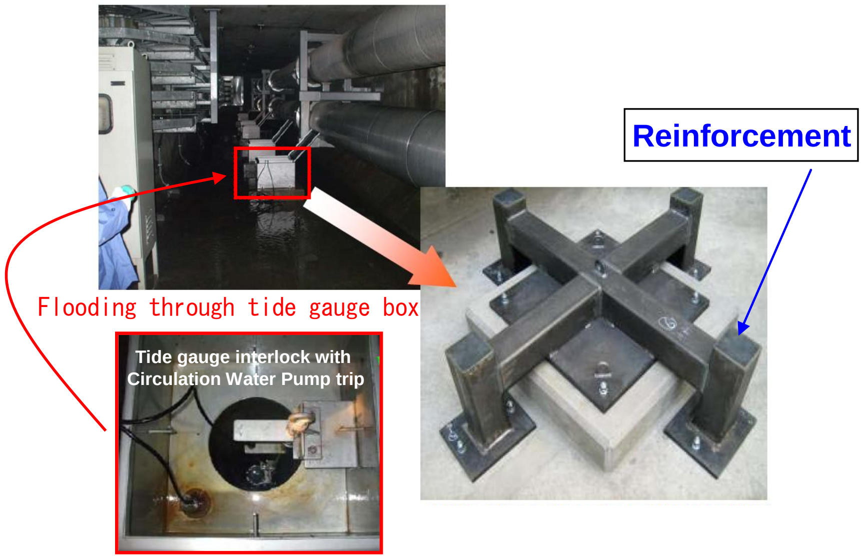


*Subsidence of 1m at Onagawa site is considered

[Installation position of tide gauge interlock with Unit 2 Circulation Water Pump trip]



[Tsunami countermeasure for tide gauge]



Reference: NISA [Online].
http://www.meti.go.jp/press/2011/05/20110530001/20110530001.pdf
Partially modified by JNES.

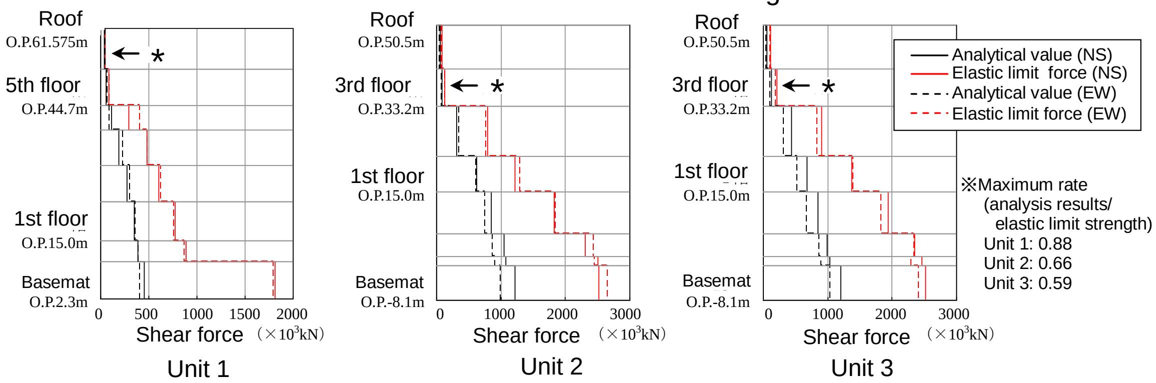
Fig. III-3-5(b) Inundation in the heat exchanger room for component cooling system (2) at Onagawa NPS.

Max. shear strain response of shear resisting at R/B

		Analytical result	Standard Value*	(Comparison) DBGM
Unit 1	NS	0.36×10^{-3}	2.0×10^{-3}	0.65×10^{-3}
	EW	0.35×10^{-3}		0.56×10^{-3}
Unit 2	NS	0.49×10^{-3}		1.15×10^{-3}
	EW	0.28×10^{-3}		0.55×10^{-3}
Unit 3	NS	0.81×10^{-3}		0.99×10^{-3}
	EW	0.18×10^{-3}		0.41×10^{-3}

* Standard values are established in JEAC4601-2008 (Japanese seismic design code for nuclear power plants; Japan Electric Association).
They are twice the value of ultimate shear strain for reinforced concrete shear walls as safety factor.

Shear force of R/B aseismic resisting at each floor



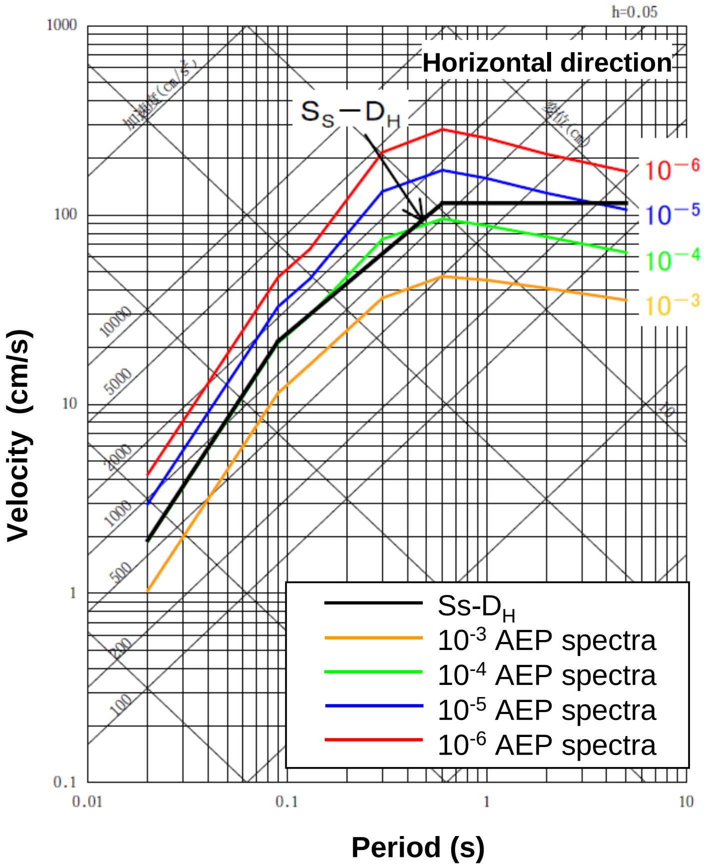
Reference: Tohoku Electric Power Co., Inc
[Online]. http://www.tohoku-epco.co.jp/ICSFiles/afieldfile/2011/04/07/110407_np_t1.pdf
Partially modified by JNES.

Fig. III-3-6 Verification of shear strain and shear force acted on seismic walls at each floor in R/Bs of Onagawa NPS.

Table III-3-2 Maximum accelerations values observed in reactor buildings at Tokai Dai-ni NPS.

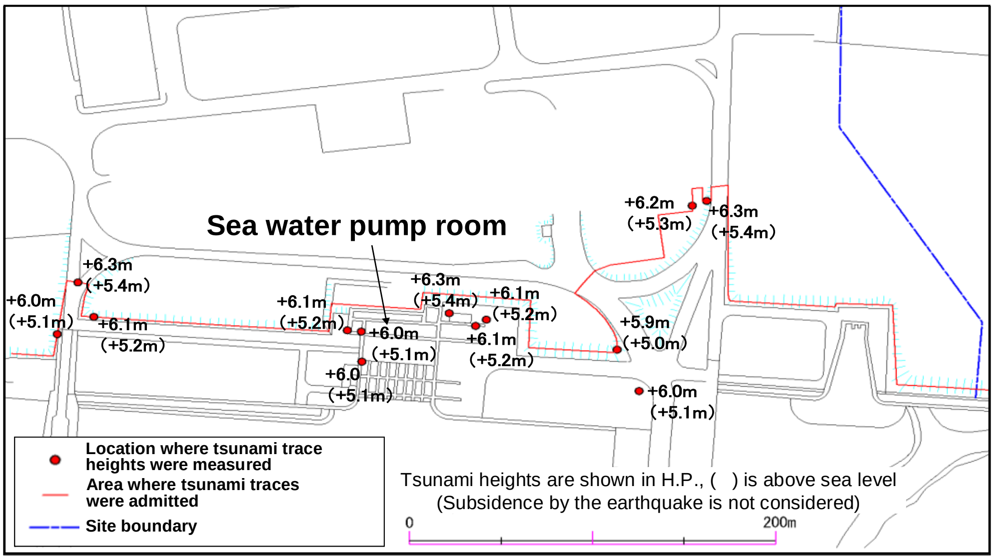
Loc. of seismometer		Record			Max. acceleration at construction (Gal)		Max. response acceleration to the DBGM Ss (Gal)		
		Max. acc. (Gal)							
		NS	EW	UD	NS	EW	NS	EW	UD
Reactor building	6 F	492	481	358	932	951	799	789	575
	4 F	301	361	259	612	612	658	672	528
	2 F	225	306	212	559	559	544	546	478
	Base mat (B2F)	214	225	189	520	520	393	400	456

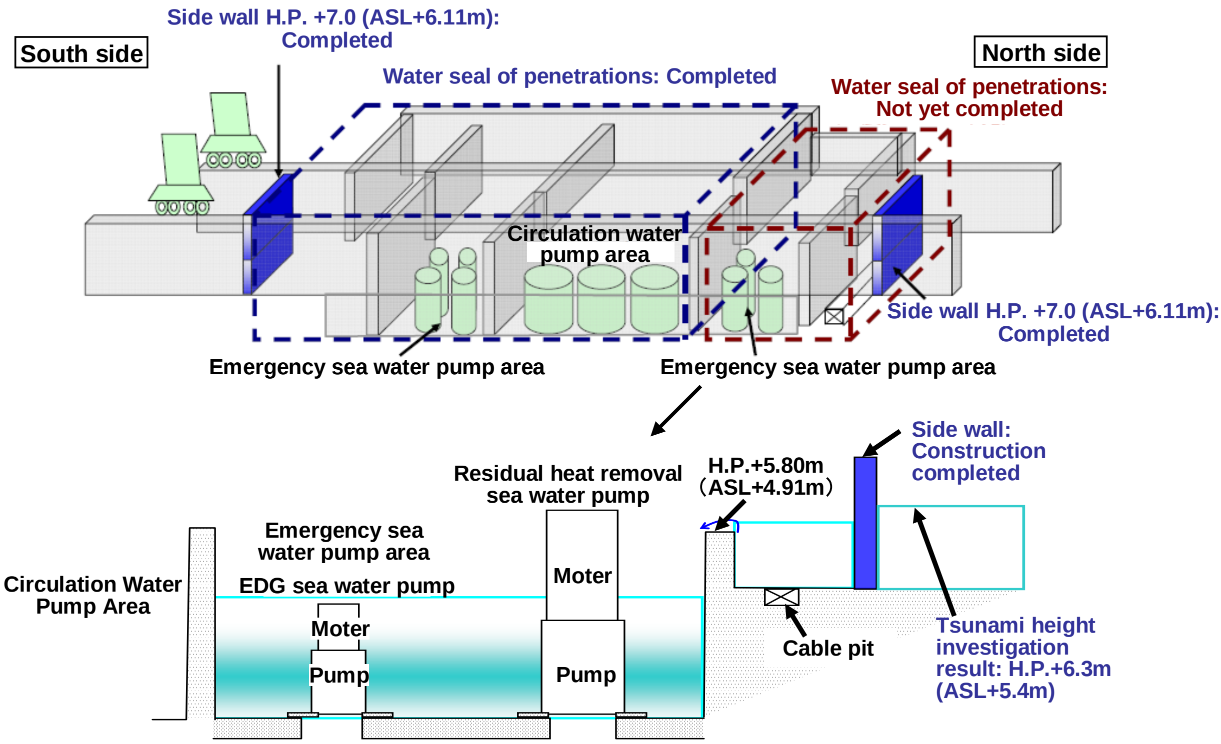
Reference: The Japan Atomic Power Company
[Online]. http://www.japc.co.jp/news/bn/h23/230407.pdf
Partially modified by JNES.



Reference: The Japan Atomic Power Company
[Online]. http://www.nisa.meti.go.jp/shingikai/107/3/1/006/6-2-1-1.pdf
Partially modified by JNES.

Fig. III-3-7 Annual exceedance probability (AEP) of DBGM Ss for Tokai Dai-ni NPS.





Reference: The Japan Atomic Power Company [Online]. http://www.japc.co.jp/news/bn/h23/230407.pdf Partially modified by JNES.

Fig. III-3-8 Map of the areas with tsunami traces identified at Tokai Dai-ni NPS.