2. Damage caused by the earthquake and tsunami hitting Fukushima NPSs

(1) Seismic ground motion and tsunami height observed at Fukushima Dai-ichi NPS

1) Matters related to seismic ground motion

a Seismic ground motion observation system and observation records

The seismic ground motion observation system of Fukushima Dai-ichi NPS, as shown in Figure III-2-1, consists of seismometers installed on the first basement and the second floor of the reactor buildings, seismometers in underground down-hole array (five seismometers in each part hole) at two parts in the south and north of the site and observation record device. Seismometers observe acceleration time history of two horizontal and vertical components.

Seismometers are installed at 53 points in Fukushima Dai-ichi NPS. Seismic ground motion was recorded at 29 points out of them. However, according to TEPCO's investigation, records of acceleration time history were interrupted at around 130 to 150 seconds at seven points. TEPCO's investigation revealed that the cause was failure of recoding device software.

Table III-2-1 shows the list of maximum acceleration of seismic ground motion observed in three components (east-west, north-south and vertical) at the base mat level of the reactor buildings. Maximum acceleration in horizontal direction was 550 Gal at Unit 2 (east-west) and that in vertical direction was 302 Gal at Unit 2.

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

In the seismic back check, the standard seismic ground motion Ss (Ss-1 to Ss-3) are established to envelop the seismic ground motion caused by plate boundary earthquake off the coast of Fukushima Prefecture, intraslab earthquake[5] beneath the site, earthquake by capable fault around the site and possible earthquake from diffuse seismicity.

Table III-2-1 shows maximum response acceleration to the standard seismic ground

[5] Intraslab earthquake: The earthquake caused by a fault rupture within a descending oceanic crust.

motion Ss at the site where seismometers were installed at the base mat level on the first basement level of the reactor buildings. The table shows that observed maximum acceleration is mostly smaller than maximum response acceleration to the standard seismic ground motion Ss. However, maximum acceleration observed in east-west direction at Units 2, 3 and 5 is larger than maximum response acceleration to Ss. Figure III-2-2(a) shows acceleration time history of east-west component in Unit 2.

Figure III-2-2(b) shows the comparison chart between the response spectra of observed seismic ground motion at the base mat level of the reactor building of Units 2, 3 and 5 and the response spectra at the base mat level of the building, inputting the standard seismic ground motion Ss into the base mat. The Figure shows that the response spectra of observation records of Units 2, 3 and 5 exceeds the response to Ss with a period of 0.2 to 0.3 second.

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

The Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities was revised in 2006. Under the revised Guide, considering the residual risk, the standard seismic ground motion Ss exceedance probability is referred from the standpoint that the possibility of seismic ground motion exceeding the standard seismic ground motion Ss is undeniable. NISA instructed TEPCO to conduct seismic back check (evaluation of Ss adequacy and safety of facilities) based on revision of the Guide. TEPCO evaluated the standard seismic ground motion Ss exceedance probability according to the seismic hazard evaluation procedures of the Seismic PSA Implementation Standards of the Atomic Energy Society of Japan as a part of seismic back check, and reported to NISA.

Figure III-2-3 shows the uniform hazard spectra of Fukushima Dai-ichi NPS. In the Figure, Ss-1H and Ss-2H response spectra are also shown. The figure shows exceedance probability of the standard seismic ground motion Ss is within the range of 10^{-4} to 10^{-6} per year.

2) Matters related to tsunami

a Tide level observation system and observed records

The tide level observation system consists of tide gauge and observation recording device. The tide gauge is installed in quiet area in harbor, and the tide level observation recoding device is installed in the data transfer building. According to the press conference of TEPCO (April 9), initial major tsunami arrived at around 15:27 (41 minutes later of mainshock occurrence) and tsunami height was approximately 4 m height. Though secondary major tsunami arrived at 15:35, the water level is unknown due to tide gauge failure. Maximum scale of the gauge is 7.5 m.

The site height of Fukushima Dai-ichi NPS is 10 m at Units 1 to 4, and 13 m at Units 5 and 6. At Fukushima Dai-ichi NPS, tsunami rushed from the offshore area in front of the site, and most part of the site where main buildings were placed was flooded. TEPCO reported about the inundation height based on the results of trace investigation at flooding. The results of the report are shown in Figure III-2-4. The inundation height of the ocean-side site such as reactor buildings of Units 1 to 4, turbine buildings, etc. is O.P. approximately +14 to 15 m at points H to K in the Figure(O.P.: Onahama Port base tide level for construction). Experts estimate that the tsunami height caused by this earthquake is more than 10 m from the picture (refer to Fig. III-2-5) showing the overflow status of tsunami seawall (10 m) released by TEPCO. It is hence assumed that tsunami height at the sea water pump is more than 10 m.

The average ground subsidence level is approximately 0.8 m along the coast area of Miyagi to Fukushima prefectures in this earthquake, and it is necessary to consider that the site height may change by ground subsidence when hit by tsunami.

b Comparison between design basis tsunami height and observed tsunami height

As shown in Figure III-2-6, in the application document for establishment permit, subject tsunami source is Chile Earthquake (M9.5 in 1960) and the design basis tsunami water level is 3.1 m. In 2002, TEPCO evaluated the design tsunami height based on the “Tsunami Assessment Method for Nuclear Power Plants in Japan (2002)” of the Tsunami Evaluation Subcommittee, the Nuclear Civil Engineering Committee, Japan Society of Civil Engineers (hereafter referred to as Tsunami Assessment Method of JSCE), assessing off the coast of Fukushima Prefecture Earthquake (M7.9 in 1938) shown in Figure III-2-6 as M8.0 voluntary, and the highest water level of each Unit was set as 5.4 to 5.7 m. According to the evaluation, elevation of Unit 6 sea water pump motor of emergency diesel generator was raised up 20 cm and also that of sea water pump motor for High Pressure Core Spray was raised up 22 cm.

Tsunami Assessment Method of JSCE above is also reflected in IAEA Tsunami Hazard Guide DS417. However, the tsunami recurrence period is not identified in the method,

At the 32nd Joint Working Group for Earthquake, Tsunami, Geology, and Foundations under the Seismic and Structural Design Subcommittee (June 24, 2009) held in order to conduct examination related to earthquake, it was pointed out that although the investigation report about tsunami by the Jogan earthquake in 869 was made by National Institute of Advanced Industrial Science and Technology and Tohoku University, the earthquake causing the tsunami was not dealt with. Regarding this, NISA requested TEPCO at the 33rd Joint Working Group (July 13, 2009) to take into account the Jogan earthquake for evaluating design tsunami height when new knowledge on the tsunami of the Jogan earthquake is obtained.

c Probabilistic tsunami hazard evaluation and exceedance probability of design basis tsunami height

The Tsunami Assessment Subcommittee of JSCE is at work on consideration about probabilistic tsunami hazard analysis method. As a part of the consideration, the tsunami hazard assessment method and the trial assessment of tsunami exceedance probability (Fig. III-2-7) are already announced but not yet completed. Other trial assessment of tsunami hazard is also announced.

3) Matters related to damage

a Matters related to external power supply system outside the site

Figures III-2-8(a) and III-2-8(b) show the transmission network of external power supply of Fukushima Dai-ichi NPS and the damage situation. As shown in the Figures, the Okuma Nos. 1 and 2 power transmission lines (275 kV) from Shin Fukushima Power Substation connected to the normal high voltage switchboards of Units 1 and 2 via the switchyards for Units 1 and 2, and in addition, TEPCO nuclear line (66 kV) from Tohoku Electric Power Co., Inc. connected to the normal high voltage switchboard of Unit 1 via the switchyards for Units 1 and 2. As to Units 3 and 4, the Okuma Nos. 3 and 4 transmission lines (275 kV) connected to the normal high voltage switchboard of Units 3 and 4 via the switchyards for Units 3 and 4 as well. For Units 5 and 6, the Yorunomori Nos. 1 and 2 transmission lines (66 kV) connected to the normal high voltage switchboard of Units 5 and 6, too.

In addition, the normal high voltage switchboard of Unit 1, the normal high voltage switchboard of Unit 2, and the normal high voltage switchboard of Units 3 and 4 were connected mutually, and electric power interchange was possible. However, the switchyard for the Okuma No. 3 transmission line in the switchyards of Units 3 and 4 was under construction on the day when the earthquake occurred, and as a result, external transmission line in the total of six lines was connected to Fukushima Dai-ichi NPS. The Shin Fukushima Power Substation is located approximately 8 km from the site, and the seismic intensity of this earthquake is estimated to be 6 upper.

The earthquake caused damage to the breakers of the switchyards of Units 1 and 2. As to TEPCO nuclear line from Tohoku Electric Power, although it is not possible to estimate the cause, cables were damaged. Concerning Units 3 and 4, in addition to the Okuma No. 3 transmission line under construction, the breakers of Nos. 3 and 4 transmission lines on the side of Shin Fukushima Power Substation failed. In addition, for Units 5 and 6, one transmission line tower (tower No. 27) connecting to the switchyards of Units 5 and 6 was collapsed. As a result, all external power supplies of Units 1 to 6 were lost.

b Sea water system pump and emergency power supply system in the site

As to the sea water pump facilities for component cooling (height: 5.6 to 6 m) at Fukushima Dai-ichi NPS, all Units were flooded by tsunami as shown in Figure III-2-4. Whether or not they were damaged by wave power is under investigation. In addition, the Emergency Diesel Generators and switchboards installed in the basement floor of the reactor buildings and the turbine buildings (height: 0 to 5.8 m) were flooded except for Unit 6, and the emergency power source supply was lost. Regarding Unit 6, two out of three Emergency Diesel Generators were installed in the first basement of the reactor building and was flooded, but one Generator installed on the first floor of Diesel Generator building was not flooded and the emergency power supply was possible.

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

1) Matters related to seismic ground motion

a Seismic ground motion observation system, and observation records and observation seismic ground motion

The seismic ground motion observation system of Fukushima Dai-ni NPS is basically similar to that of Fukushima Dai-ichi NPS previously described in 2 (1). The seismometers are installed at 43 points in Fukushima Dai-ni NPS. All of these seismometers recorded the acceleration time history data of the seismic ground motion by this earthquake. However, in the same way as Fukushima Dai-ichi NPS, recording of acceleration time history was interrupted at around 130 to 150 seconds at 11 points due to failure of recoding device software.

Table III-2-2 shows observation records of maximum response acceleration in three components, two horizontal (east-west and north-south) and one vertical components, on the base mat of reactor building. Maximum acceleration in horizontal direction was 277 Gal at Unit 3 (north-south direction) and that of vertical direction was 305 Gal at Unit 1.

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

The standard seismic ground motion Ss (Ss-1 to Ss-3) are established to envelop the seismic ground motion caused by plate boundary earthquake off the coast of Fukushima Prefecture, intraslab earthquake beneath the site, earthquake by capable fault around the site and possible earthquake from diffuse seismicity. Table III-2-2 shows maximum response acceleration to the standard seismic ground motion Ss at the site where seismometers were installed at the base mat level on the first basement level of the reactor buildings. The table also shows that maximum acceleration of observation records of all Units were smaller than maximum response acceleration to the standard seismic ground motion Ss.

Figure III-2-9 shows the acceleration time history and the response spectra of observed seismic ground motion at the base mat level of the reactor building of Unit 3 whose acceleration in horizontal direction was highest. The figure also shows the response spectra on the base mat level inputting the standard seismic ground motion Ss into the base mat. The figure implies that the response spectra obtained from observation records fall below the response spectra inputting the standard seismic ground motion Ss

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

Figure III-2-10 shows the uniform hazard spectra of Fukushima Dai-ni NPS. The response spectra of Ss-1H and Ss-2H are also shown. The Figure shows that the exceedance probability of the standard seismic ground motion Ss is within the range of 10^{-4} to 10^{-6} per year.

2) Matters related to tsunami

a Tide level observation system and observed records

The tide level observation system of Fukushima Dai-ni NPS is basically similar to that of Fukushima Dai-ichi NPS previously mentioned in section 2.(1). According to the press conference of TEPCO on Apr. 9, initial major tsunami arrived at around 15:23 (37 minutes later of main shock occurrence) and next major tsunami at 15:35. After that, the circumstance is not clear.

Because the tide gauge was damaged, the observation records were not preserved. As a result, tsunami time history and maximum tsunami height were not clear.

TEPCO reported about the inundation height based on the results of trace investigation at flooding as well as Fukushima Dai-ichi NPS previously described in section 2.(1). Figure III-2-11(a) shows the report results. Fukushima Dai-ni NPS consists of the ocean-side area where seawater pumps, etc. are installed and the raised mountain-side area where reactor buildings, turbine buildings, etc. are installed. Tsunami at first flooded from the ocean-side area in front of the site. Afterward, as shown in the Figure, tsunami flooded from the narrow space between the south side of Unit 1 and the slope in the mountain-side area, and reached the back of the mountain-side area. There was no flooding except from the narrow place. The inundation height in the ocean-side area was O.P. approximately +6.5 to 7 m, and O.P. approximately +14 to 15 m in the mountain-side area (O.P. means base level of Onahama Port construction).

b Comparison between design basis tsunami height and observed tsunami height

In the application document for construction permit , subject tsunami source is Chile Earthquake (M9.5 in 1960) and the design basis tsunami height of each Unit is 3.1 to 3.7 m in the same way as Fukushima Dai-ichi NPS. In the previously mentioned assessment based on the Tsunami Assessment Method for Nuclear Power Plants in Japan (2002), off the coast of Fukushima Prefecture Earthquake (M7.9 in 1938) was assessed as M8.0, in the same way as Fukushima Dai-ichi NPS, and the design height of each Unit was 5.1 to 5.2 m.

3) Matters related to damage

a Matters related to external power supply system outside the site

The transmission network of external power supply of Fukushima Dai-ni NPS contain four lines including two lines of the extra high voltage switchyard on the site used in combination among Units 1 to 4 and the Tomioka Nos. 1. and 2 transmission lines outside the site (500 kV), and two lines of the Iwaido Nos.1 and 2 transmission lines (66 kV), and they connect to Shin Fukushima Power Substation, 8km upstream, and further, connect to Shin Iwaki Switchyard, approximate 40 km upper. Out of these transmission lines, power supply from Iwaido No.1 had been stopped for maintenance.

The seismic intensity in the area around Shin Fukushima Power Substation is estimated to be 6 upper. The Tomioka No. 2 transmission line (500 kV) and the Iwaido No. 2 transmission line (66 kV) to Units 1 to 4 of Fukushima Dai-ni NPS stopped transmission due to failure of devices on the side of the switchboard, caused by strong ground motion in this earthquake. However, the power supply to Units 1 to 4 was continued since the Tomioka No. 1 transmission line could supply electric power (refer to Fig.III-2-8(a)).

b Sea water system pump and emergency power supply system in the site

The sea water pump facilities for component cooling of all Units (height: 6 m) were flooded by tsunami and lost its function except Unit 3, which was not flooded and kept its function.

The Emergency Diesel Generators installed in the basement of the reactor buildings (height: 0 m) kept their functions for Unit 3 and 4, however, those for other Units lost their functions by completely flooding (Fig. III-2-11(b)).

As shown above, the sea water pump facilities for component cooling and the emergency diesel generator kept those functions only for Unit 3.

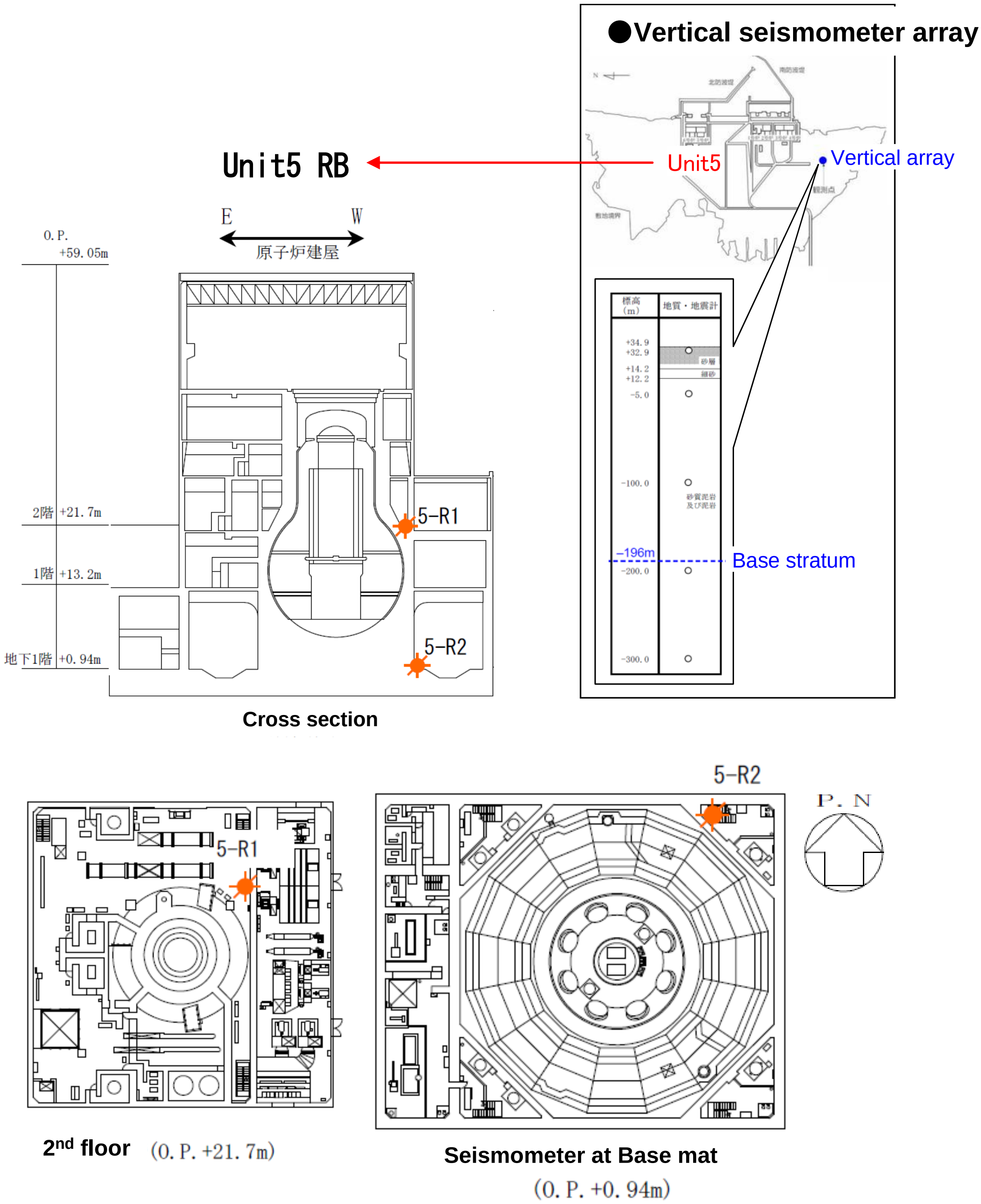
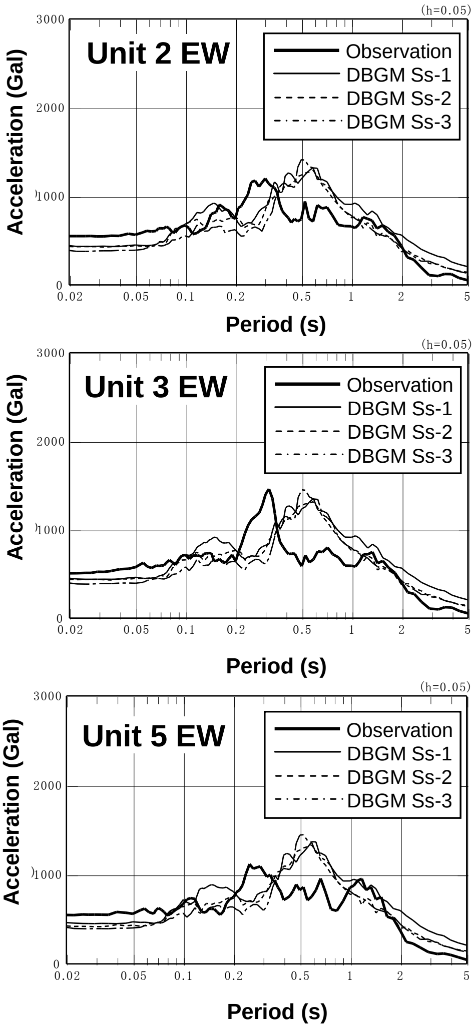


Fig. III-2-1 Deployment of seismometers at Fukushima Dai-ichi NPS and R/B in unit 5.

Table III-2-1 Max. acceleration values observed in reactor buildings at Fukushima Dai-ichi NPS.

Loc. of seismometer (bottom floor of reactor bld.)		Record*1 Max. acc. (Gal)			Max. response acceleration to the DBGM Ss (Gal)		
		NS	EW	UD	NS	EW	UD
Fukushima Dai-ichi	Unit 1	460*2	447*2	258*2	487	489	412
	Unit 2	348*2	550*2	302*2	441	438	420
	Unit 3	322*2	507*2	231*2	449	441	429
	Unit 4	281*2	319*2	200*2	447	445	422
	Unit 5	311*2	548*2	256*2	452	452	427
	Unit 6	298*2	444*2	244	445	448	415

***1 These are temporal values, and may be corrected later.**
***2 Each recording was interrupted at around 130-150 s from recording start time.**



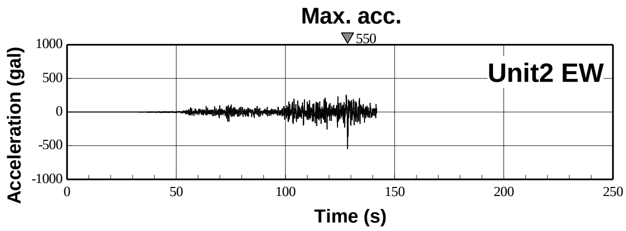


Fig. III-2-2(a) Acceleration seismogram on the base mat at R/B in Unit-2 at Fukushima Dai-ichi NPS.

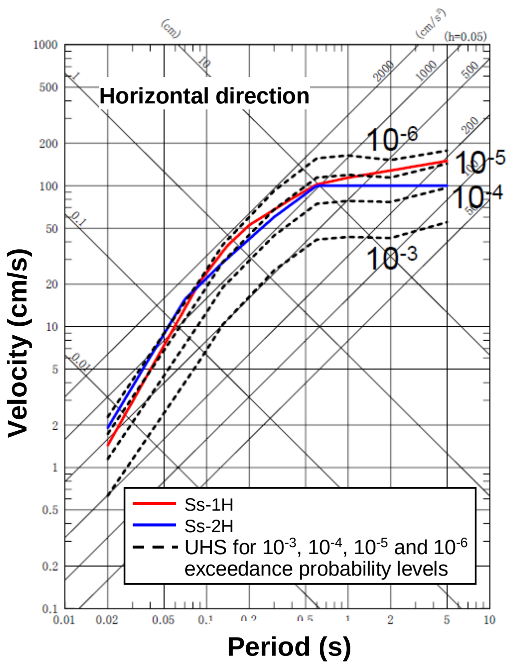
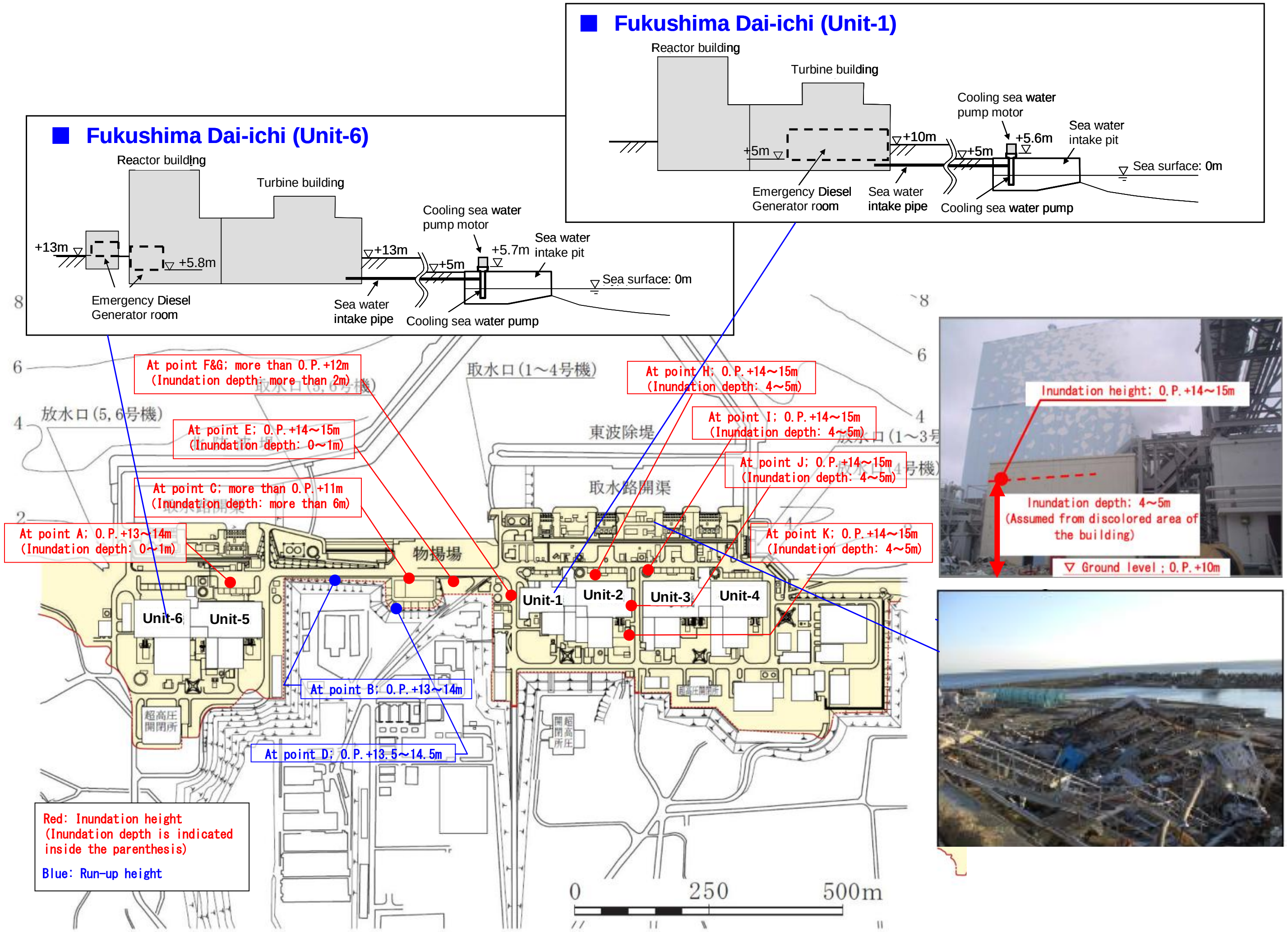


Fig. III-2-2(b) Response spectra on the base mats at R/Bs at Fukushima Dai-ichi NPS.

Fig. III-2-3 DBGM Ss and Uniform Hazard Spectra (UHS) for Fukushima Dai-ichi NPS.

Presented by TEPCO



Reference: The Tokyo Electric Power Co., Inc. Release [Online]. http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110409e9.pdf
Partially modified by JNES.

Reference: The Tokyo Electric Power Co., Inc. Release [Online]. http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110409e9.pdf
Partially modified by JNES.

Fig. III-2-4(a) Damage of Fukushima Dai-ichi NPS due to the tsunami.

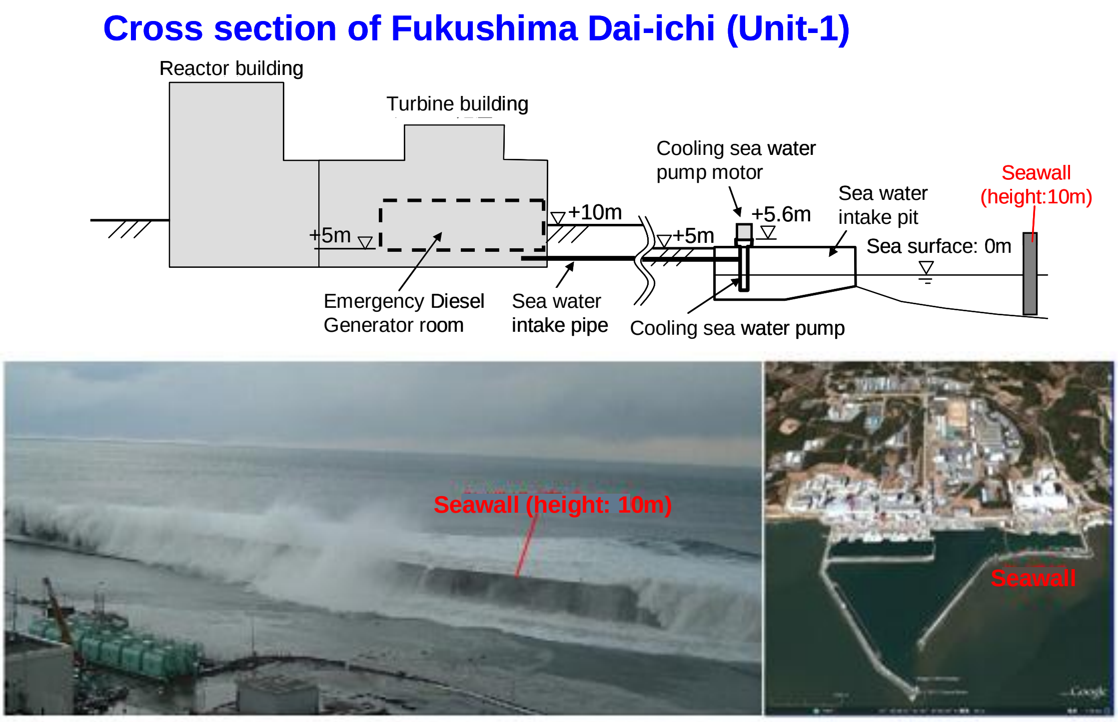
【福島第1原発　津波来襲状況　2011年3月11日　固体廃棄物貯蔵庫東側のり面(5号機の近傍(南側)から東側を撮影】＝東京電力提供

【福島第1原発への津波来襲状況　2011年3月11日　廃棄物処理建屋4階から北側を撮影】午後3時43分ごろ(2)＝東京電力提供

【福島第1原発　津波来襲状況　2011年3月11日　固体廃棄物貯蔵庫東側のり面(5号機の近傍(南側)から東側を撮影】＝東京電力提供

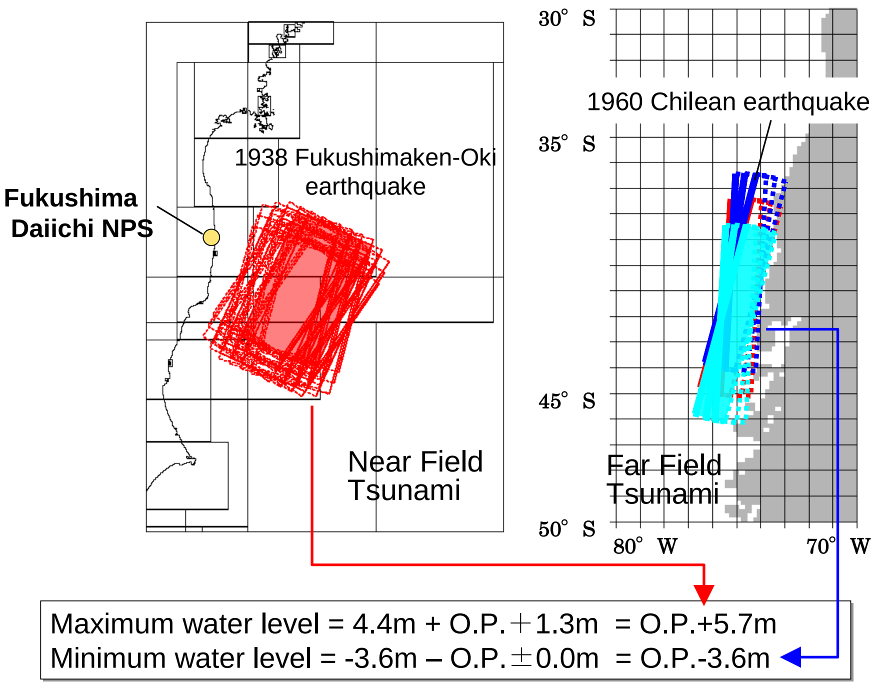
Reference: The Tokyo Electric Power Co., Inc. Release [Online].http://www.tepco.co.jp/tepconews/pressroom/110311/index-j.html

Fig. III-2-4(b) Photos showing plant damages at the Fukushima Dai-ichi NPS.



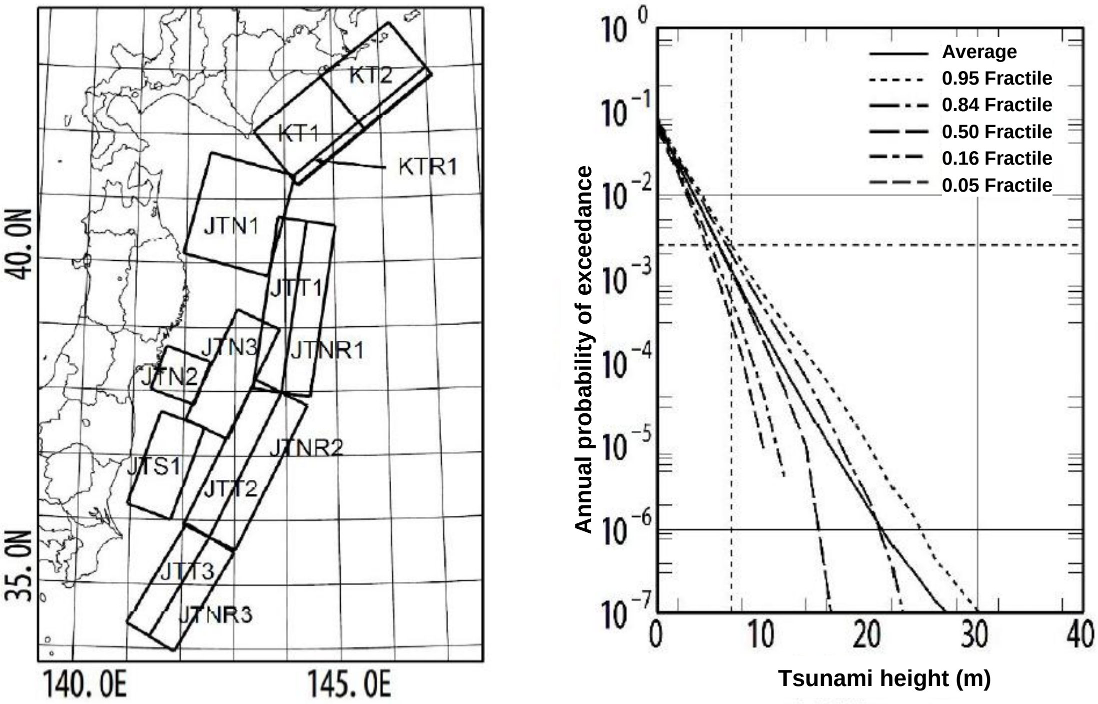
Reference: The Tokyo Electric Power Co., Inc. Release [Online].http://www.tepco.co.jp/tepconews/pressroom/110311/index-j.html

Fig. III-2-5 Tsunami getting over seawall at the Fukushima Dai-ichi NPS.



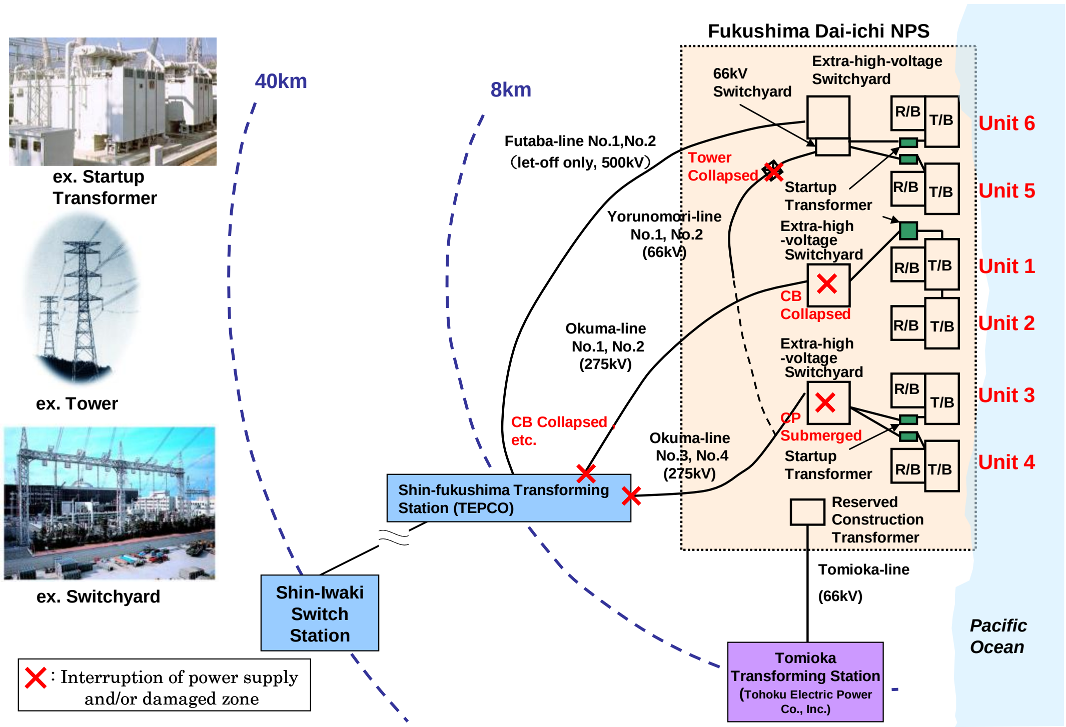
Reference: Takao (2010) [Online].
http://www.jnes.go.jp/seismic-symposium10/presentationdata/3_sessionB/B-11.pdf
Partially modified by JNES.

Fig. III-2-6 Design tsunami level evaluated by TEPCO for the Fukushima Dai-ichi NPS.

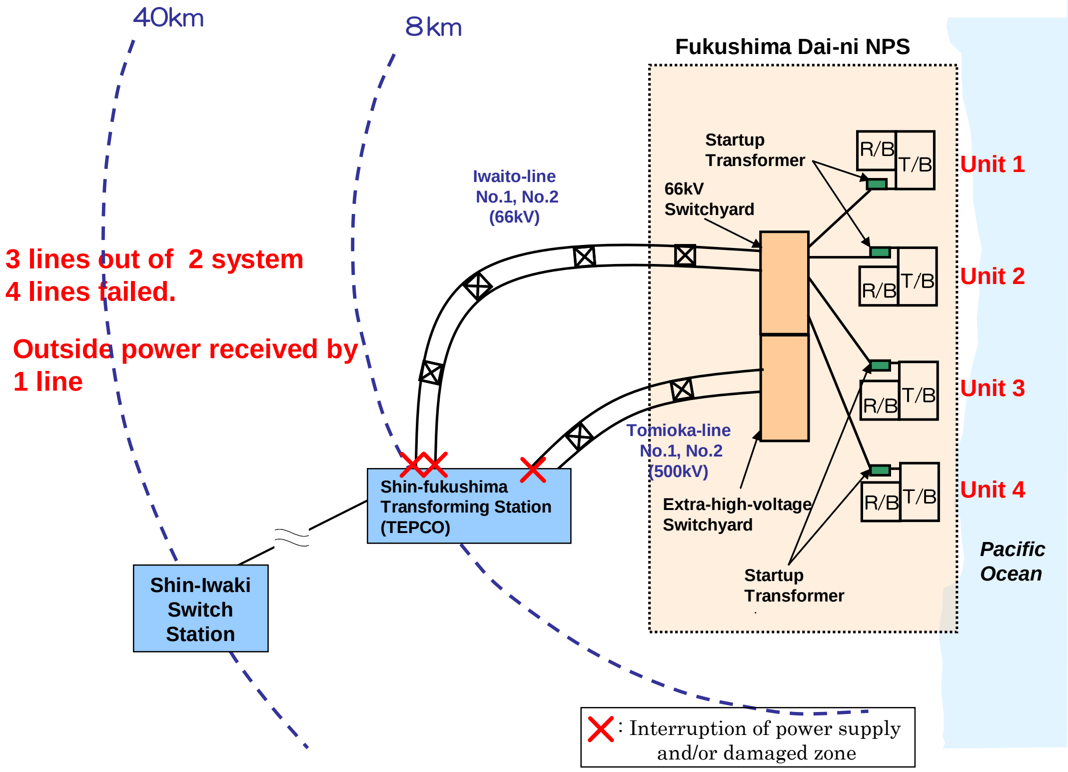


Reference: The Tsunami Evaluation Subcommittee, The Nuclear Civil Engineering Committee, JSCE (2010)
[Online].http://www.jstage.jst.go.jp/article/jscejb/63/2/168/_pdf/-char/ja/

Fig. III-2-7 Evaluation results of tsunami hazard curves based on near- and far-field tsunami sources for Yamada villages, Iwate Pref..



Reference: The Tokyo Electric Power Co., Inc. Release
[Online]. http://info.nicovideo.jp/pdf/2011-03-18_1930_touden_genpatsu.pdf
http://www.tepco.co.jp/nu/kk-np/info/tohoku/pdf/23032202.pdf



Reference: The Tokyo Electric Power Co., Inc. Release
[Online]. http://www.tepco.co.jp/nu/kk-np/tiiki/pdf/230325.pdf

Fig. III-2-8(a) Damage of external power supply systems for the Fukushima Dai-ichi and Dai-ni NPSs (1).

Okuma line 1L (O-81)
Circuit Breaker damaged

Okuma line 2L (O-81)
Circuit Breaker damaged

Okuma line 3L, Ground wire (disconnected)

Okuma line 3L & 4L, Steel structure for lead-in (tilted)

Yorunomori line, Cable in substation (subsidence)

Landslide of slope

Overview of landslide

Collapsed tower

Reference: The Tokyo Electric Power Co., Inc. Release
[Online]. http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110516e23.pdf
http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110516e19.pdf
http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110516e20.pdf

Fig. III-2-8(b) Damage of external power supply systems of the Fukushima Dai-ichi and Dai-ni NPSs (2).

Table III-2-2 Max. accelerations values observed in reactor buildings at the Fukushima Dai-ni NPS.

Loc. of seismometer (bottom floor of reactor bld.)		Record*1 Max. acc. (Gal)			Max. response acceleration to the DBGM Ss (Gal)		
		NS	EW	UD	NS	EW	UD
Fukushima Dai-ni	Unit 1	254	230*2	305	434	434	512
	Unit 2	243	196*2	232*2	428	429	504
	Unit 3	277*2	216*2	208*2	428	430	504
	Unit 4	210*2	205*2	288*2	415	415	504

***1 These are temporal values, and may be corrected later.**
***2 Each recording was interrupted at around 130-150 s from recording start time.**

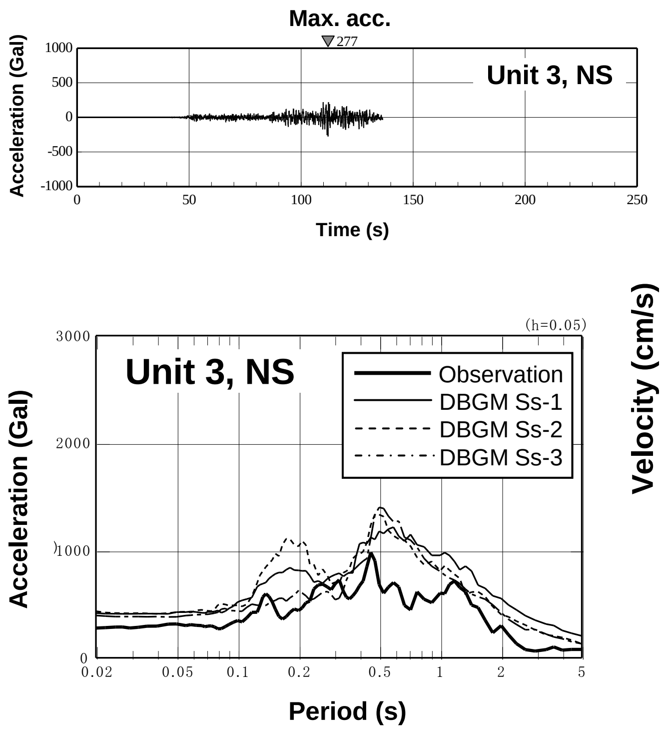


Fig. III-2-9 Acceleration seismogram and response spectra on the base mat at R/B in Unit-3 at the Fukushima Dai-ni NPS.

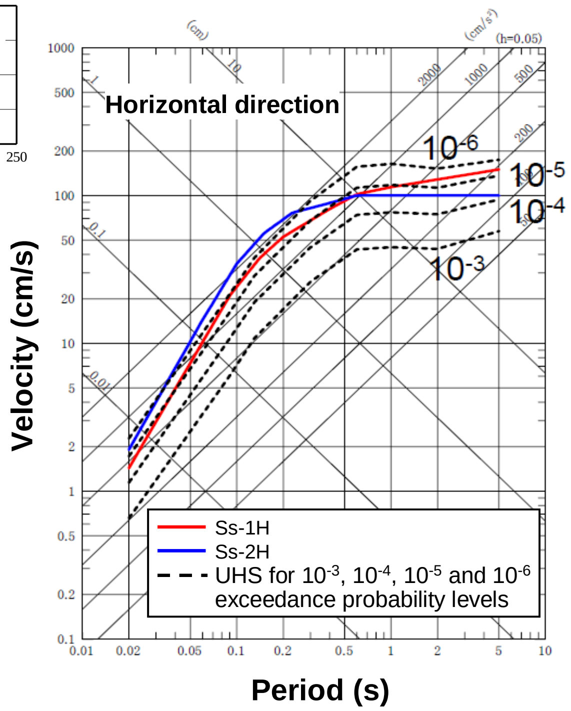
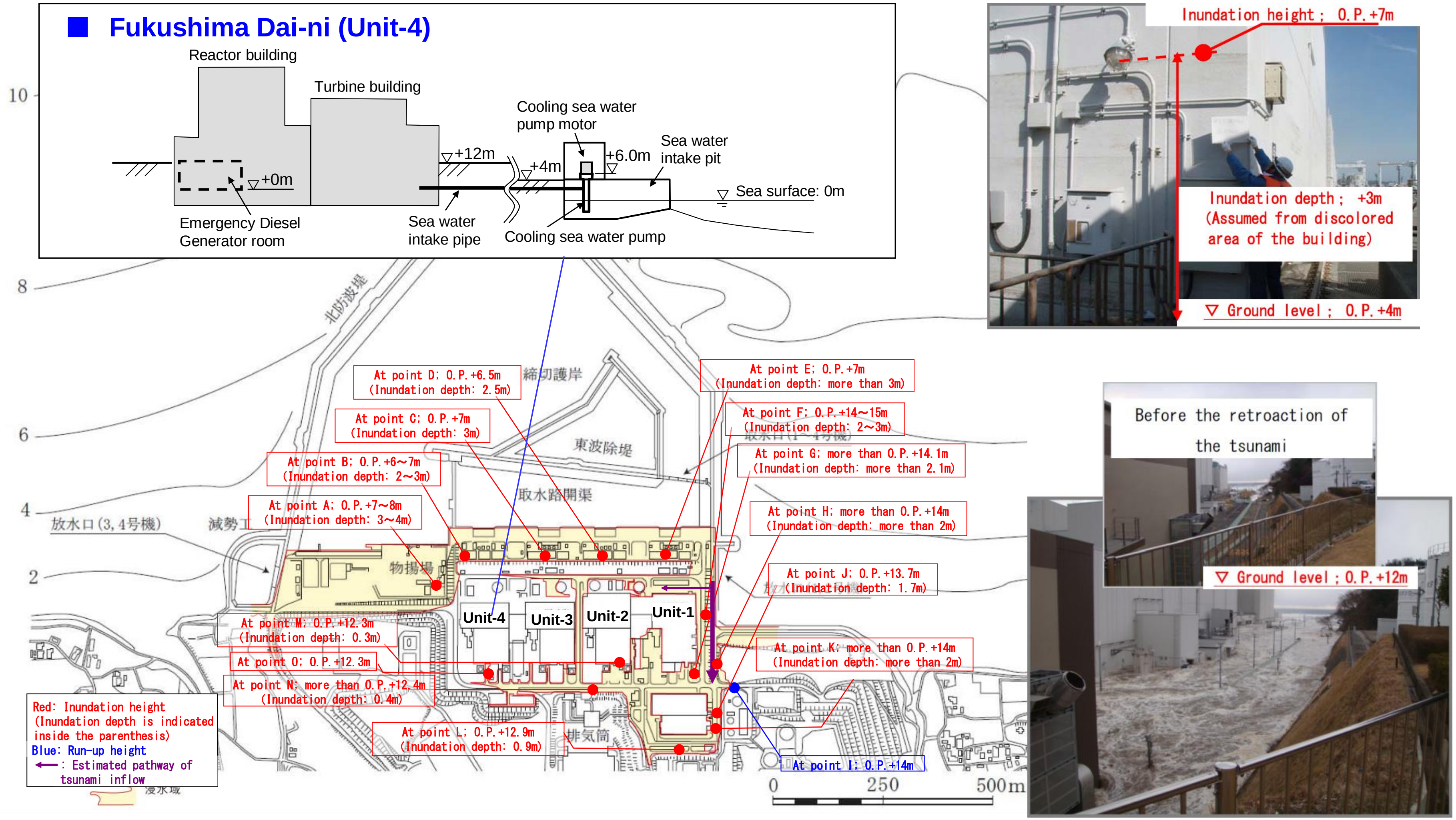


Fig. III-2-10 DBGM Ss and Uniform Hazard Spectra (UHS) for the Fukushima Dai-ni NPS.

Presented by TEPCO



Reference: The Tokyo Electric Power Co., Inc. Release [Online]. http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110409e10.pdf
Partially modified by JNES.

Fig. III-2-11(a) Damage of Fukushima Dai-ni NPS due to the tsunami.

Damages of heat exchanger room and heat exchanger (Unit 1)

Damages of reactor building and emergency diesel generator (Unit 1)

Presented by TEPCO

Fig. III-2-11(b) Damage of Fukushima Dai-ni NPS due to the tsunami.