Arrival times of tsunami at the Fukushima Daiichi Nuclear Power Station site

1. Overview

In the “Fukushima Nuclear Accidents Investigation Report,” TEPCO used the time of about 15:27 on March 11, 2011, as the time of the first wave arrival and about 15:35 as the time of the second wave arrival. These are the times when the waves arrived at the wave height meter, about 1.5 km off the site. But this wave height meter had no time correction function in its built-in clock. There was a possibility of incorrect time recording; thus it was not possible to specify the exact times of the tsunami arriving at the Fukushima Daiichi Nuclear Power Station site.

The following analyses and evaluations were newly done in order to provide the exact timings of the tsunami arrivals at the Fukushima Daiichi Nuclear Power Station site.

Analysis I: Accuracy of times recorded by the wave height meter

Analysis II: Analysis of tsunami arrival timing based on continuous photos taken (the built-in camera clock is corrected, along with the wave form time history recorded by the wave height meter) (Note)

(Note): The description was corrected on August 20, 2019, based on the error in the location of the wave height gauge [1].

In addition, the conditions that are considered more realistic have been revised and reexamined at this time (see page 42 in Attached Earthquake Tsunami-1-12).

Analysis III: Tsunami arrival timing based on the plant data recorded

In addition to the above, analyses and evaluations using tsunami numerical simulations were conducted this time. Analysis II above is summarized as Analysis II (1), and the analyses and evaluations using the tsunami numerical simulation are summarized as Analysis II (2).

As a result, it was concluded that the tsunami (second wave) that hit the Fukushima Daiichi Nuclear Power Station site arrived between 15:35 to 15:36.

It should be noted that the above analyses and evaluations do not explain the accuracy in seconds.

2. Definitions of terminology

To analyze the wave height meter records and photos in detail, the following definitions were used for the terms related to the tsunami that hit the Fukushima Daiichi Nuclear Power Station.

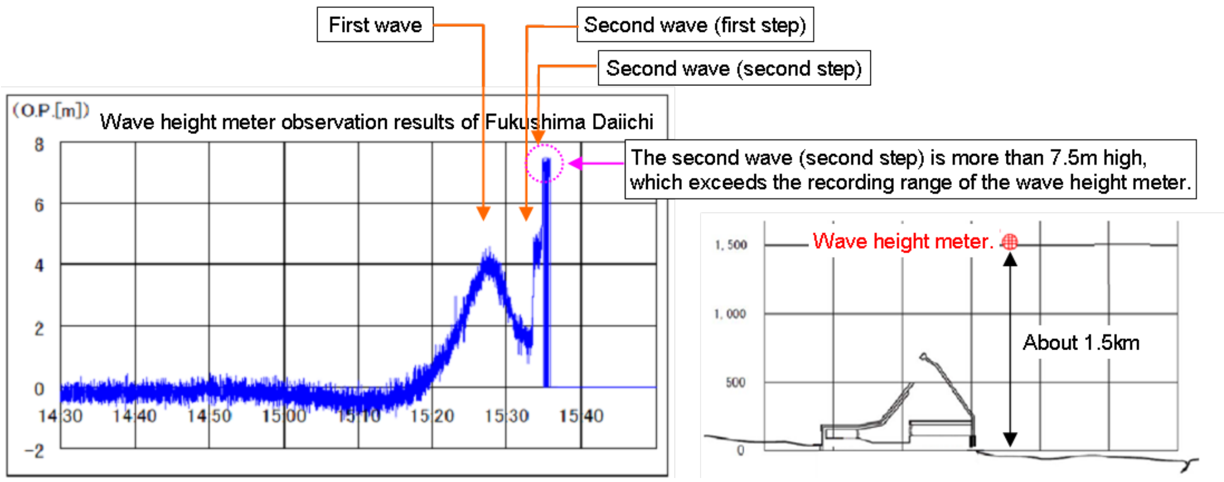


Figure Wave height meter observation results and the positional relation between the Fukushima Daiichi Nuclear Power Station site and the wave height meter

See "10. Supplement" in the main report for the description of O.P.

3. Approach for the analyses

The following approach has been taken to analyze the tsunami arrival timing at the Fukushima Daiichi Nuclear Power Station site. The results of analyses are given in later sections: the results of Analysis I and Analysis II (1) as “Analysis by the use of wave height meter records and photos”, those of Analysis II (2), as "Analysis using tsunami numerical simulation” and those of Analysis III as “Analysis using plant data.”

In Analysis I, the accuracy of the wave height meter built-in clock was analyzed, which was known to have inaccuracies. Seismometers installed on each unit of the Fukushima Daiichi Nuclear Power Station, which had been calibrated on each hour, were used as the reference and compared with the water pressure wave time history recorded on the wave height meter for the necessary time calibration.

In Analysis II, the timing of the tsunami passing over the wave height meter after its correction by Analysis I and the estimated tsunami velocity were used to estimate the tsunami arrival timing when the tsunami reached the southern breakwater bend.

There is a photo of the second tsunami (first peak) arriving at the southern breakwater bend. The times of the continuous photos recorded have been corrected by comparing the time recorded on the camera and the estimated tsunami arrival time to the southern breakwater bend obtained above.

In Analysis II (2), the tsunami arrival time was estimated by utilizing the numerical tsunami simulation that accurately reproduces the time history waveform of the tsunami recorded by the wave height gauge.

In Analysis III, the tsunami arrival time was estimated based on the recorded plant data (times when the seawater pumps, power panels and diesel generators lost their functions).

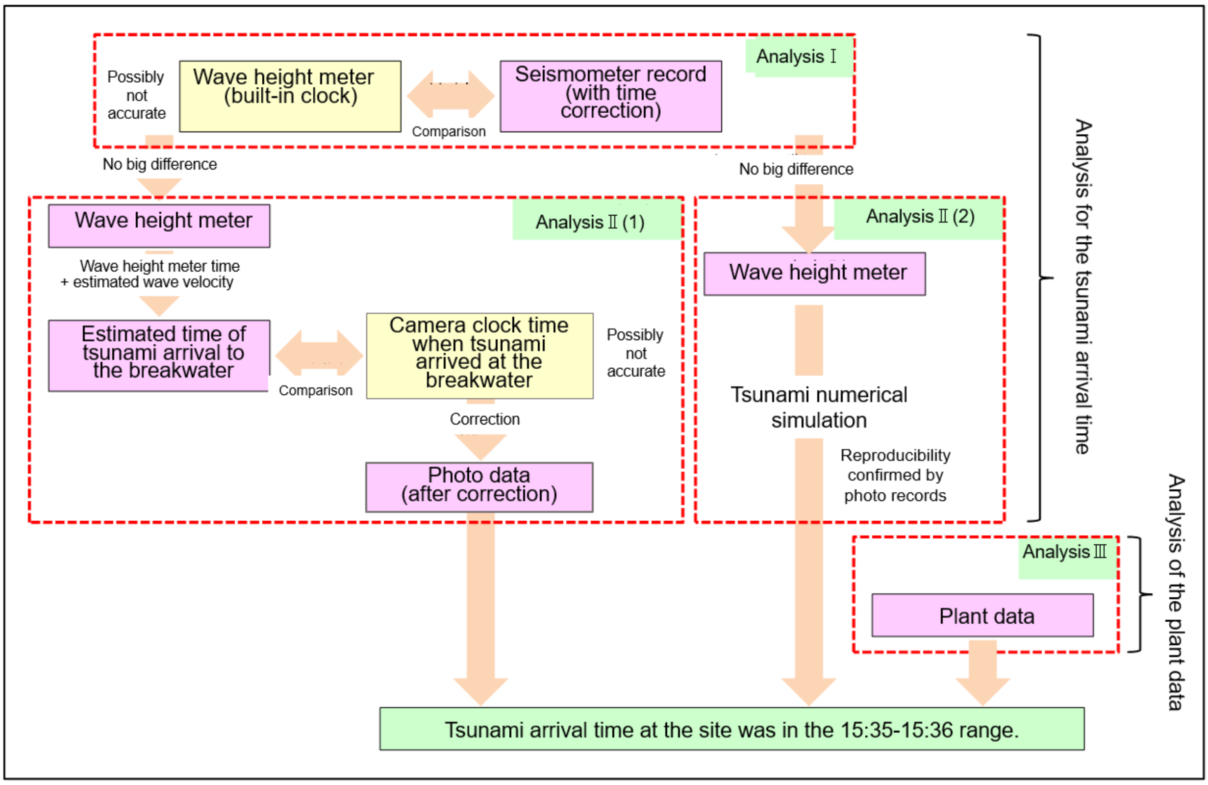


Figure　Approach to analyses of the tsunami arrival times at the site

4. Analysis using wave height meter records and photos

4.1. Purpose

The purpose was to analyze the time when the tsunami hit the site, using the tsunami time history recorded on the wave height meter located 1.5 km off the Fukushima Daiichi Nuclear Power Station site and the continuous photos taken on land.

4.2 Analysis of time data recorded on the wave height meter built-in clock (Analysis I)

Timing accuracy has been verified by comparing the slight initial motion recorded on the seismometers of each unit and the water pressure wave (responding to the seismic ground motion) recorded on the wave height meter.

Fluctuation noticed in the graph generated by the wave height meter can be considered to be due to the seismic motions, that is, the time when the seismic motion reached the wave height meter can be regarded as around 14:46:54 to 14:47:00 according to the wave height meter built-in clock.

On the other hand, the seismometers installed on each unit (their built-in clocks were calibrated on the hour) recorded that the seismic ground motion started at 14:48:48 to 14:48:52. As the seismic wave propagation speed is regarded as several kilometers per second or more, the time needed for propagation over 1.5 km is almost negligible, which was the distance separating the wave height meter and the seismometers at the power station.

From deliberations above, the wave height meter built-in clock seemed to be about 4 to 10 s fast, when compared with the median value of the seismometers records of 14:46:50 as the seismic motion starting time. Thus, wave height meter timing would be considered to have no big discrepancy.

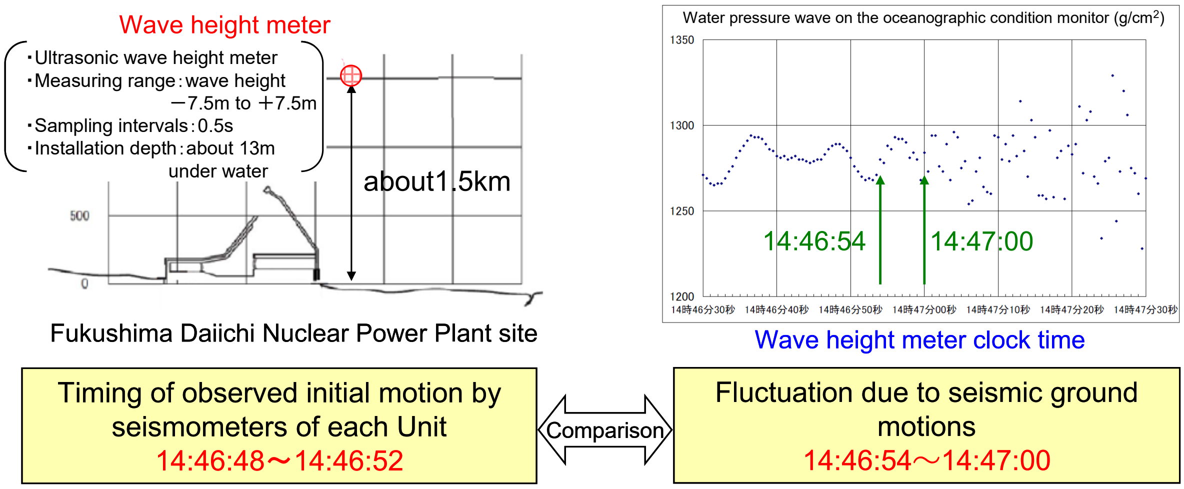


Figure Comparison between timing of observed motion by seismometers and fluctuation on wave height meter measurement

4.3 Analysis of photos (Analysis II (1))

(1) Continuous photo-taking

There were 44 continuous photos for Analysis II. The first 1st to 27th shots were taken from the northern side window of the main control room (hereinafter referred to as the “MCR”) of the central radioactive waste treatment building. When viewed from the MCR window, the wall on the right side and the Unit 4 turbine building block part of visibility as shown in the attached figure: most of the southern breakwater is visible, but only the tip of the northern breakwater and only the portion from the Unit 2 reactor building to the south of the eastern seawall bank are in the view.)

The property information of each photo specifies timing of each shot as recorded by the built-in camera clock. In the following descriptions of (2) to (6), relative time difference (in minutes:seconds) from the first shot was used to specify the timing of each shot taken.

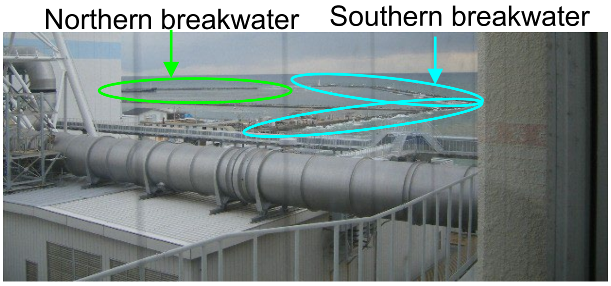
Relative locations of each shot are shown in [Appendix 1] and all 44 shots are arranged in [Appendix 2].

(2) Gradual dropping of sea level

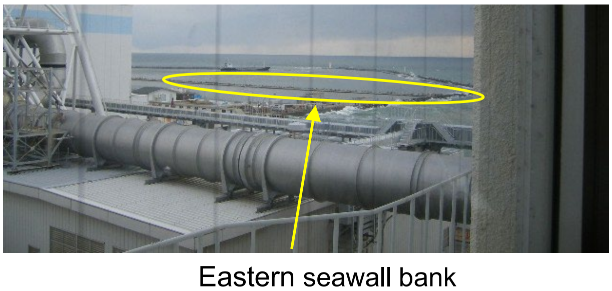
The sea level conditions on the southern breakwater show a gradual sea level drop over the time span of 1 min 26 s from Shot 1 to Shot 4. The sea level clearly declines over the following 3 min 34 s from Shot 4 to Shot 5.

Excluding Shot 1, the sea level in the harbor seemed to be declining gradually at least from Shot 2 to Shot 5 (4 min 26 s or longer).

1（00:00）

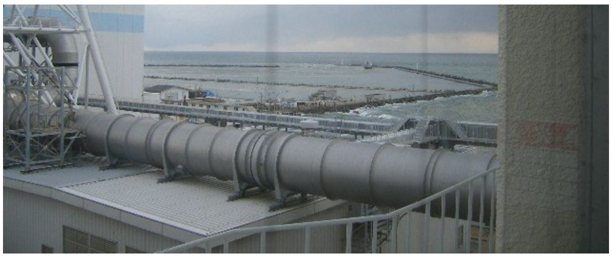


2（00:34）



3（01:02）

4（01:26）



5（05:00）

(3) Clear recognition of bores

Shot 7 clearly shows the approach of the bore-type tsunami. At this moment the bore had not yet reached the main part of the southern breakwater and the lighthouse on its tip; the bore was clearly outside the harbor. Judging from the positions of the bore and a ship in the photo, Shot 7 was taken immediately after the ship had passed the bore.

In Shot 8, the bore reached the southern breakwater and the lighthouse on its tip was behind the tsunami, so that at this moment the bore had reached the bend of the southern breakwater.

When having a look at portions that were not flooded on the land side base of the southern breakwater and the eastern seawall bank, Shot 5 and Shots 6 to 8 have similar conditions of not being flooded. Therefore, it may be understood that the tsunami bore, on the order of several meters in height as seen in Shots 7 and 8, reached that point immediately after the gradual drop of the sea level.

In other words, it can be judged that water drop in Shots 1 to 5 was after the peak of the first wave, and the bore in Shots 7 and 8 was the second wave (first step).

There were four shots, 5 to 8, during 1 min 20 s. Then it was judged that these shots could catch the arrival of second wave (first step) and there was nothing more missing.

6（05:12） Lighthouse on the tip of the southern breakwater

7（06:08） Southern breakwater bend

Tsunami bore

8（06:20）

(4) Water column due to tsunami

Shots 9 to 12 show tsunami bore running along the southern breakwater, i.e., the second tsunami (first step).

In Shot 11 the base area of the southern breakwater is covered by the tsunami water, while the bore cannot be confirmed to have reached the eastern seawall bank. Therefore, the brown water column seen is due to the tsunami which did not come from the harbor area (from east) but from southeast into the front side of Unit 4. But it cannot be judged from this shot only whether it resulted when the tsunami collided with some structures after running up to the 4-m ground level above O.P. (O.P. : Onahama Port construction standard surface, hereafter described as 4-m ground level) or it ran through a water discharge canal and rose from its opening. The location can be considered to be around the border between the 4-m ground level and 10-m ground level, because the column appeared immediately northeast of a hut on the 10-m ground level in front of the Unit 4 building.

In Shots 11 and 12, a wave, probably the second wave (second step), can be seen off the coast. The water column in Shot 11, therefore, can be considered to have risen when the second wave (first step) in the order of several meters in height as observed in Shots 6 to 8 reached the area near the border between the 4-m ground level and 10-m ground level.

The time difference between Shot 8, showing the arrival of the second tsunami (first step), and Shot 12 is 48 s, and it can be considered that no phenomenon has been overlooked and consequently the water column was generated due to the second wave (first step).

9（06:36）

Eastern seawall bank

10（06:42）

Second wave (1st step)

11（07:04）

12（07:08）

Second wave (2nd step)

(5) The arrival of the highest wave (second wave (second step)) in the harbor

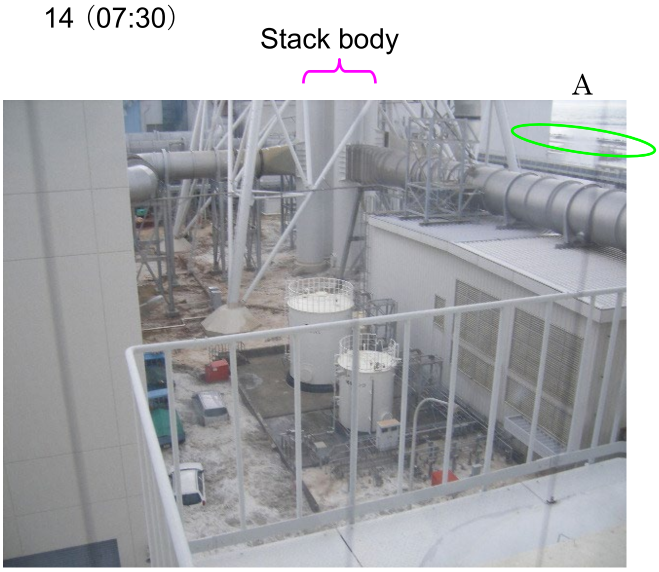
Shot 13, 20 s after Shot 11 with the water column, shows inundation to the 10-m ground level.

On the upper right of Shot 14, 6 s after Shot 13, a structure, probably the eastern seawall bank, can be recognized (A). This timing will be around the time when the second wave (first step) in the order of several meters height as recognized in Shots 7 and 8 reached the 10-m ground level. In Shots 15 and 16, the base of the stack is seen (B), and no big tsunami run-up like those in Shots 17 and 18 is visible. Based on these observations, it can be understood that in Shots 13 to 16 the second wave (second step) in the order of 10 meters high had not reached the 10-m ground level yet and that the run-up to the 10-m ground level recognized in Shots 13 and 14 by the second wave (first step) was a limited scale.

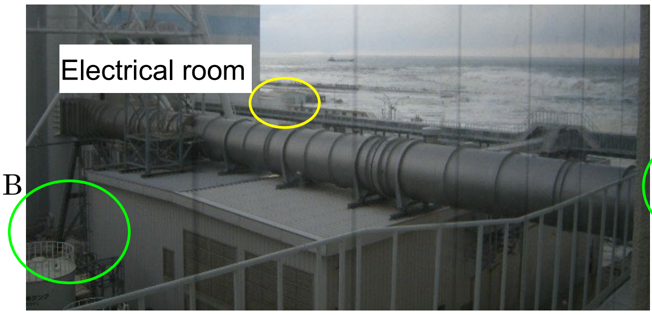
In Shot 15, 12 s after Shot 14, tsunami water covers the southern and northern breakwaters. In Shot 16, taken 14 s after Shot 15, the eastern seawall bank is also covered by the tsunami water in addition to the southern and northern breakwaters and big bores are recognized in the harbor.

13（07:24）

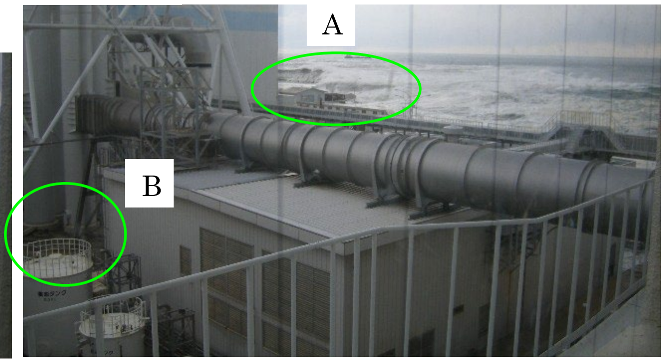
14（07:30）



15（07:42）



16（07:56）



(6) The arrival of the highest wave (second wave (second step)) at the 10-m ground level

In Shot 17, taken 14s after Shot 16, a large amount of seawater flows over the 10-m elevation level and continues in the scenes of Shots 18 and 19. The scene inside the harbor is not clear in Shot 17. In Shots 18 and 19, the elevated sea surface can be confirmed, but breakwaters and seawall bank cannot be recognized. This means that, besides the second wave (first step), there was another wave that was big enough to flood completely the breakwaters and seawall bank.

Shot 18 was taken 24 s after Shot 16 which shows a massive tsunami rushed into the harbor. Further, in Shots 18 and 19, the electrical room on the 10-m ground level is almost completely flooded; which had been seen in Shots 15 and 16. As this electrical room was 5.15 m high, tsunami in Shots 18 and 19 can be regarded as about O.P. +15 m.

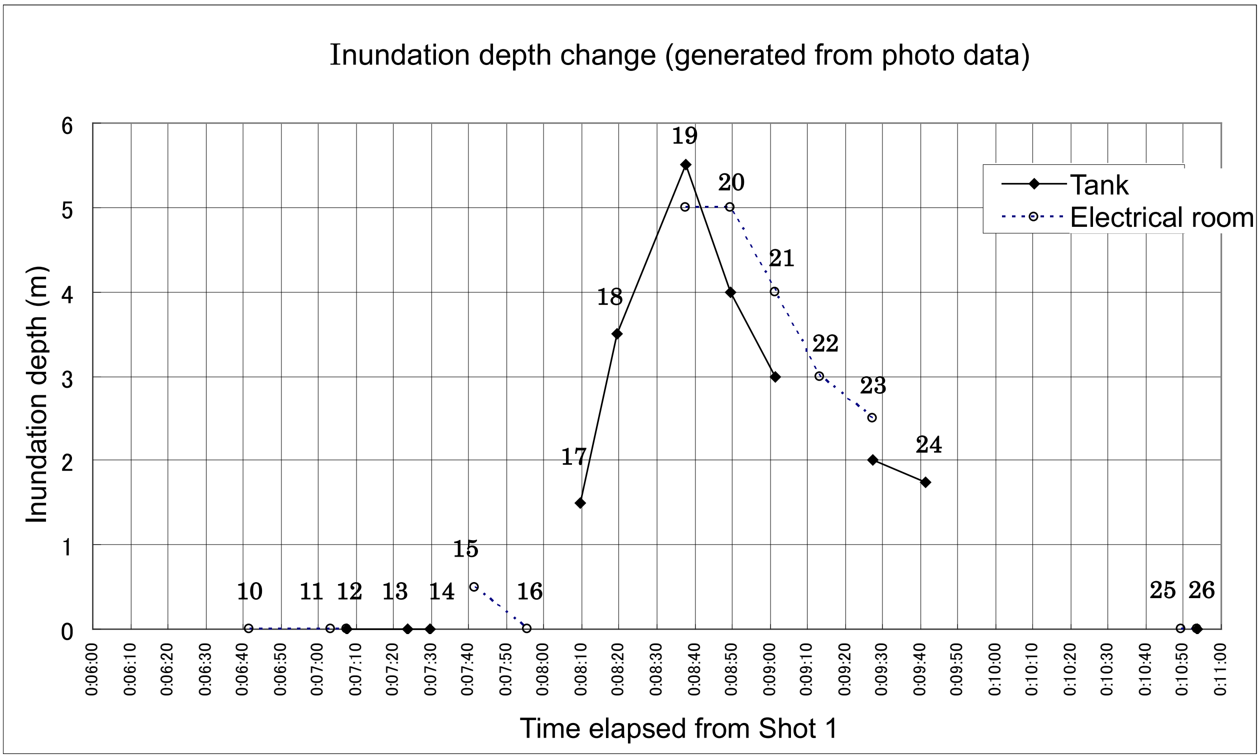
From these examinations, it can be concluded that at around the time Shot 18 was taken the second wave (second step) of about O.P. +15 m high had reached the areas near all reactor buildings of the Fukushima Daiichi Nuclear Power Station site.

The time history chart of the tsunami level on the wall of a light oil tank and the electrical room in these shots indicates that the run-up of the tsunami in Shots 13 to 16 was a limited scale and the run-up became large scale from just before Shot 17. This observation agrees with the results of the photo analysis.

17（08:10）

18（08:20）

19（08:38）


Inundation depth change (generated from photo data)
Inundation depth (m)
Time elapsed from Shot 1
Tank
Electrical room
0
1
2
3
4
5
6
0:06:00
0:06:10
0:06:20
0:06:30
0:06:40
0:06:50
0:07:00
0:07:10
0:07:20
0:07:30
0:07:40
0:07:50
0:08:00
0:08:10
0:08:20
0:08:30
0:08:40
0:08:50
0:09:00
0:09:10
0:09:20
0:09:30
0:09:40
0:09:50
0:10:00
0:10:10
0:10:20
0:10:30
0:10:40
0:10:50
0:11:00
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26

4.4. Estimation of propagation time of tsunami from the wave height meter location to the southern breakwater bend and correction of times when photo were taken

As mentioned before, the bore of the second wave (first step) reached the southern breakwater bend in Shot 8, which allows correction of the time when the shot was taken. The procedure is:

(a) Identification of the distance from the wave height meter to the southern breakwater bend;

(b) Calculation of time needed for the second wave (first step) propagation from the wave height meter to the southern breakwater bend; and

(c) Identification of the time of Shot 8 taken by adding time (b) above to the time of the second wave (first step) arrival at the wave height meter.

(a) Distance from the wave height meter to the southern breakwater bend

The distance from the wave height meter to the south breakwater bend was about 700 m. The way this distance was obtained is summarized in [Reference 3].

(b) Time needed for the second wave (first step) propagation from the wave height meter to the southern breakwater bend

The sea depth where the wave height meter was installed was about 13 m. The water depth in the direction of the tsunami travel from the wave height meter was about 8 m, when the wave front arrived at the bend of the south breakwater.

By the use of an approximation formula: $c = (gh)^{1/2}$ for tsunami propagation velocity and Green's Rule, $H_2/H_1 = (h_1/h_2)^{1/4}$, for tsunami height, time required for propagation from the wave height meter location to the harbor area can be estimated as follows. Details are in [Appendix 4].

a. Propagation time calculated from the estimated velocity based on the still water depth

To get a slight overestimation, the propagation time was estimated using the still water depth. As a result, the propagation time of about 70 s was obtained from the wave height meter to the southern breakwater bend.

b. Propagation time calculated from the estimated velocity based on the total water depth

To get a more realistic estimation, the propagation time was estimated using the total water depth (= still water depth + tsunami amplitude). The wave amplitude was set as 4.5 m, which is the average value of the second wave (first step) recorded on the wave height meter. As a result, the propagation time of about 57 s was obtained from the wave height meter to the southern breakwater bend.

Based on the above, the propagation time from the wave height meter to the harbor area is estimated as 57 - 70 s.

(c) Identification of the time Shot 8 was taken

The time when the second wave (first step) reached the wave height meter was about 15:33:30.

When the estimated time for propagation is added to this, the time when Shot 8 was taken is estimated to be between 15:34:27 and 15:34:40. On the other hand, the time recorded on the camera built-in clock was 15:41:36.

From the above, the built-in camera clock is estimated to be fast by 6 min 56 s to 7 min 09 s. From considerations (b)-a and (b)-b above, it is expected that 7 min 09 s is closer to reality.

4.5 Summary (Analyses I and II (1))

The following results have been obtained by examining the wave height meter records and photos in detail.

(a) The built-in camera clock was 6 min 56 s to 7 min 09 s fast. The real difference is likely to be close to 7 min 09 s.

(b) When 7 min 09 s was used for correction,(Note) Shot 1, taken at 15:35:16 according to the camera clock, was actually taken at about 15:28:07.

(Note) In previous examinations, the average in (a) was used, but this time, it was decided to use a value considered closer to the actual situation and the value was revised.

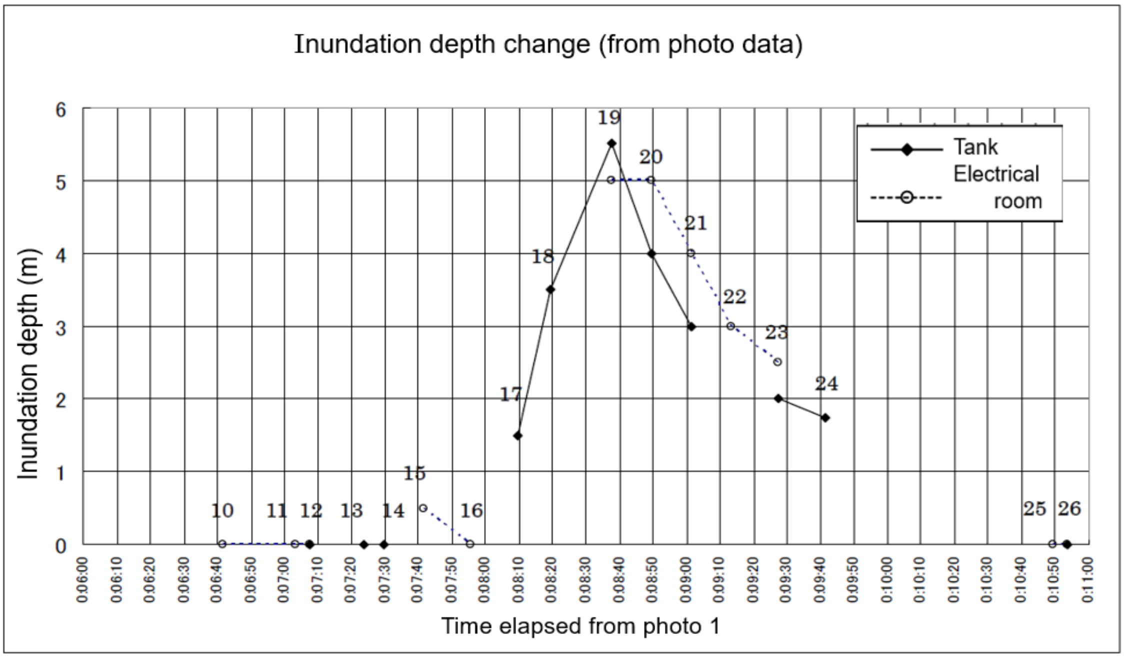
(c) With the same correction, it was at about 15:34:27, when the second wave (first step) reached the southern breakwater bend (Shot 8), and at about 15:35:31 when small scale inundation could be confirmed to have started around the tanks on the 10-m ground level (Shot 13).

(d) It was from about 15:35:49 to about 15:36:03 when the run-up to the tank area on the 10-m ground level stopped once (Shots 15 and 16).

(e) Further it was at about 15:36:17 when the large scale inundation could be confirmed to have started around the tanks on the 10-m ground level (Shot 17), and at about 15:36:45 when the tanks disappeared completely under water (Shot 19).

(f) The following figure shows the inundation situations of the tanks, etc. with the same time correction.

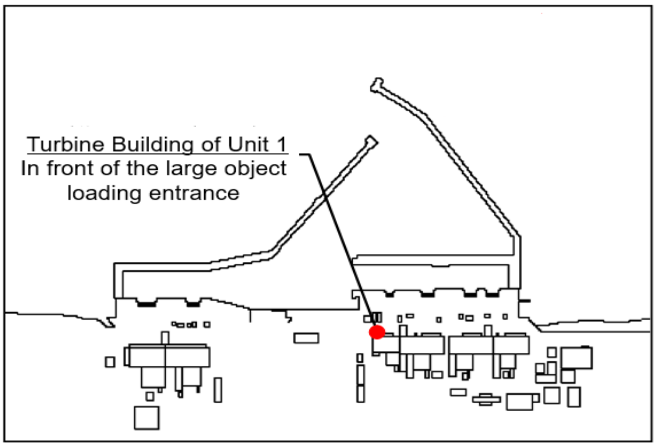
(g) Run-up of the second wave (first step) to the 10-m ground level remained as a limited one, but it can be understood that the second wave (second step) ran up to the 10-m ground level and almost completely covered the breakwaters and seawall bank.



5. Analysis using numerical simulation of tsunami (Analysis II (2))

5.1 Purpose

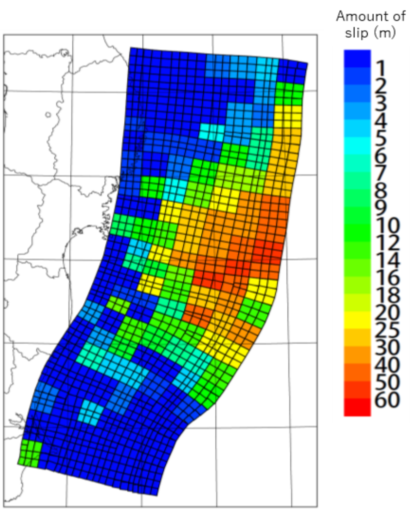
The arrival time of tsunami was estimated using numerical simulation of the tsunami, which accurately reproduces the time history waveform of the tsunami recorded by wave height meters. The tsunami arrival time was estimated at the location in front of the large item loading entrance of the turbine building of Unit 1, which is located almost in the center of the seaward side of the site.



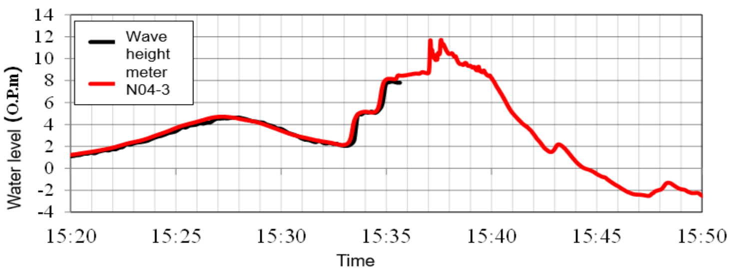
Evaluation position of tsunami arrival time

5.2 Tsunami wave source model and numerical simulation of tsunami

Numerical simulation of tsunami using a tsunami wave source model (Tsunami Wave Source Model N04-3 [2)]), which accurately reproduces the time history waveform of tsunami at the wave height meter position, in addition to the reproducibility in a wide area and at Fukushima Daiichi Nuclear Power Station and Fukushima Daini Nuclear Power Station, was used to understand in detail how tsunami arrived at the Fukushima Daiichi Nuclear Power Station.



Tsunami Wave Source Model N04-3



Comparison of waveforms with wave height meter records

Fitness to trace height values (K, k) ※

Evaluation location	N04-3	
	K	κ
Hokkaido to Chiba (3882 points)	1.00	1.34
Fukushima Dai-Ichi NPS (19 points)	1.02	1.10
Fukushima Dai-Ni NPS (71 points)	0.99	1.15

※ The geometric mean K and geometric standard deviation k by Aida (1977) are indicators of the spatial fit between the tsunami trace height and the calculated value. As criteria for reproducibility evaluation, "0.95<K<1.05" and "k<1.45" are used as a guide. When these criteria are satisfied, the reproducibility is considered good.
The reproducibility of the N04-3 tsunami wave source model over a wide area is shown in [Reference 5].

The details of numerical simulation of tsunami are shown in [Reference 6]. In order to reflect the situation more accurately at Fukushima Daiichi Nuclear Power Station at the time of the tsunami arrival, the overturning of the upper structure of the north breakwater and the roughness coefficient of the runup area were taken into account (Case 1 (basic case)). Since the time of overturning of the upper structure of the north breakwater is unknown and the roughness coefficient of the runup area is not uniform, parameter studies were also conducted without considering these factors (Cases 2 to 4).

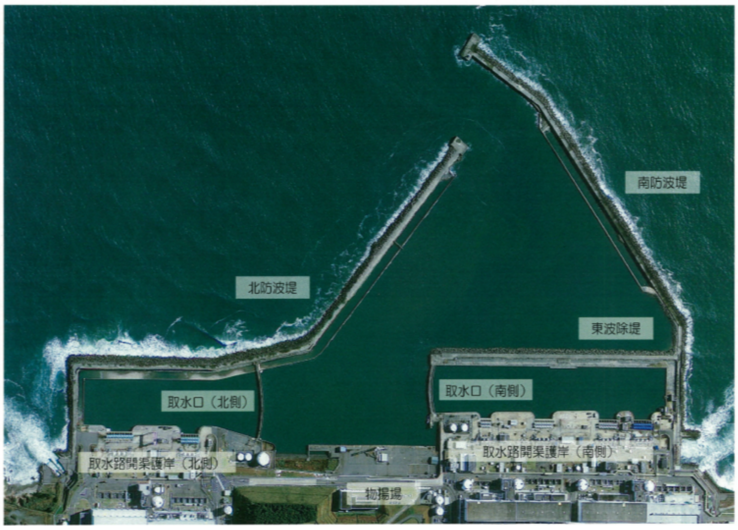
✓ Reflecting the site status: Since the upper structure of the north breakwater overturned in a wide area at the time of the earthquake, a parameter study was conducted to determine whether the upper structure had or had not overturned.

Damage to the north breakwater＊

(Left: Immediately before the tsunami overtopped the breakwater, Middle: Immediately after the tsunami overtopped the breakwater (overturned upper structure, etc.), Right: During the tsunami receding wave)

＊Source: Report of the Great East Japan Earthquake Joint Investigation (Great East Japan Earthquake Joint Investigation Report Editorial Committee, 2014.8)

✓ Reflecting the site status: Since the majority of the 1F seawall area is pavement or concrete, a parameter study was conducted to determine a pattern in which the roughness coefficient of the runup area is equivalent to concrete.

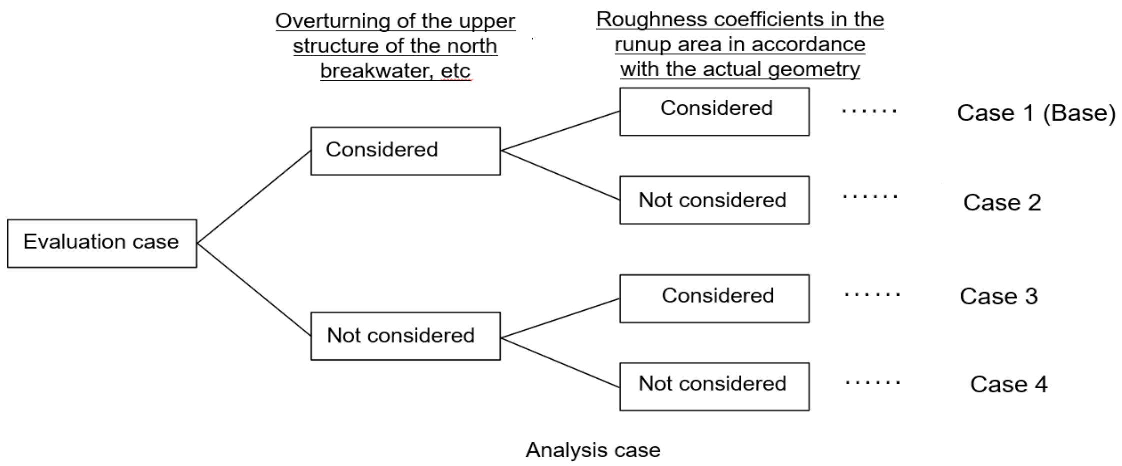


Manning's roughness coefficient

Channel shape	Channel status	n の範囲	Standard No.
Culver	cast-in-place concrete		0.015
	コンクリート管		0.013
	コルゲートメタル管（1形）		0.024
	〃　（2形）		0.033
	〃　（ペービングあり）		0.012
	塩化ビニル管		0.010
	コンクリート2次製品		0.013
ライニングした水路	鋼，塗装なし，平滑	0.011～0.014	0.012
	モルタル	0.011～0.015	0.013
	木，かんな仕上げ	0.012～0.018	0.015
	コンクリート，コテ仕上げ	0.011～0.015	0.015
	コンクリート，底面砂利	0.015～0.020	0.017
	石積み，モルタル目地	0.017～0.030	0.025
	空石積み	0.023～0.035	0.032
	アスファルト，平滑	0.013	0.013
ライニングなし水路	土，直線，等断面水路	0.016～0.025	0.022
	土，直線水路，雑草あり	0.022～0.033	0.027
	砂利，直線水路	0.022～0.030	0.025
	岩盤直線水路	0.025～0.040	0.035
自然水路	整正断面水路	0.025～0.033	0.030
	非常に不整正な断面，雑草，立木多し	0.075～0.150	0.100

Aerial view of Fukushima Daiichi Nuclear Power Plant (2009.11.15)＊

＊Source: Report on the investigation results of the tsunami generated by the 2011 off the Pacific coast of Tohoku Earthquake at Fukushima Daichi Nuclear Power Plant and Fukushima Daini Nuclear Power Plant (Part 2) (TEPCO, 2011.7)



5.3. Verification of reproducibility of numerical simulation of tsunami using continuous photographs

As shown in 5.2, the numerical simulation of tsunami can reproduce the time history waveform of tsunami recorded by wave height meters with high accuracy. In this section, we confirm whether the numerical simulation of tsunami can reproduce the arrival and runup of tsunami arriving at the site after passing the wave height meter by comparing the results of the numerical simulation of tsunami with those of the continuous photographs.

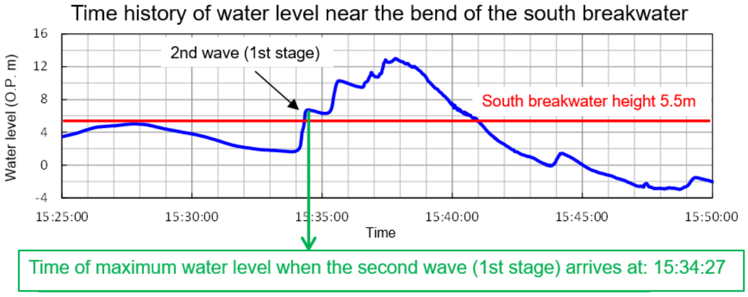
In the following, the numerical simulation of tsunami based on Case 1 (basic case) is used for examination.

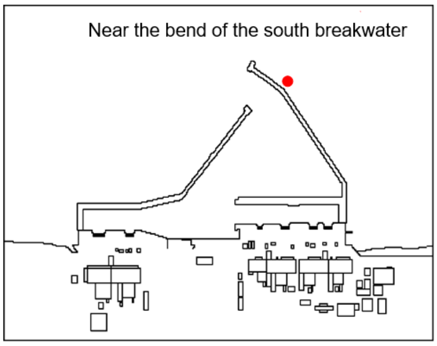
(1) Correction of the time when the photographs were taken using the results of numerical simulation of tsunami

As shown in 4.3.3 (3), the tsunami first arrived at and overflowed the area around the bend of the south breakwater in Photo 8 after the gradual decrease in water level, and the area around the bend of the south breakwater was not exposed for at least 5 min 30 s after that (until Photo 27 taken 5 min 34 s after Photo 8).

According to the time history of the water level near the bend of the south breakwater based on the numerical simulation of tsunami, a similar situation is observed only around 15:34, and it is estimated that the time when the water level reaches its maximum is 15:34:27, which is the time of Photo 8.

On the other hand, as mentioned in 4.4.(c), the internal time of the camera in Photo 8 was 15:41:36. Compared with the time estimated by the numerical simulation of tsunami, it is estimated that the time of the built-in camera clock was about 7 min and 09 s earlier than the actual time. This result is consistent with the result of the examination based on the simple calculation (4.4.1) using the distance from the wave height meter to the south breakwater bend and the estimated wave speed of tsunami, and the result is consistent with the simple calculation and the numerical simulation of tsunami.



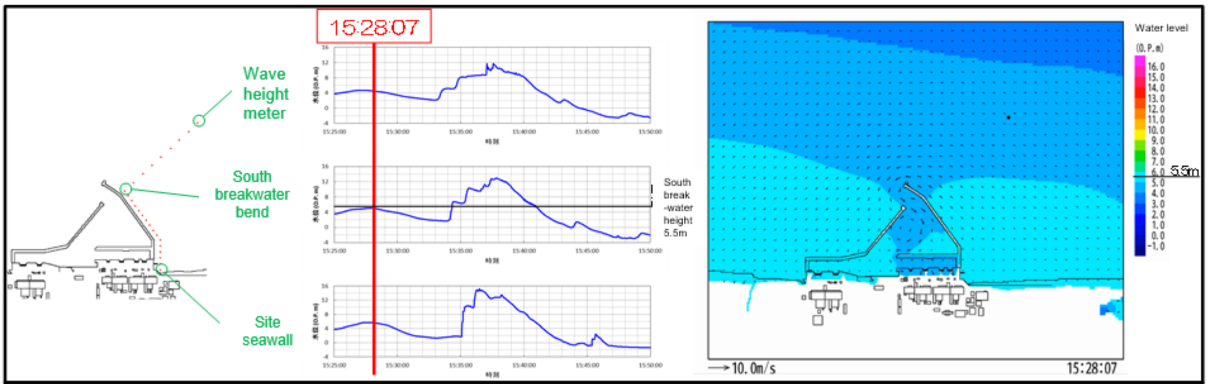


(2) Comparison of the results of the numerical simulation of tsunami with continuous photographs

When the time is corrected based on (1), the estimated time for Photo 1, which is 15:35:16 by the built-in camera clock, is about 15:28:07. Similarly, the times of Photos 2 through 19 were corrected. The results of the numerical simulation of tsunami (time history of water level and distribution of water level) are compared with a series of continuous photographs with corrected times and summarized in [Reference 7]. A summary is shown below.

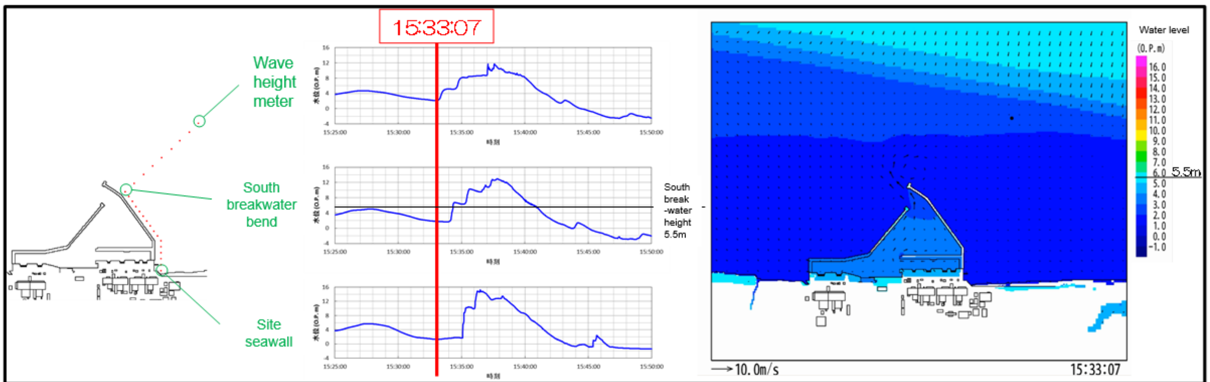
(a) Water level decline after the peak of the first wave

The water level decline after the peak of the first wave is observed from Photo 1 to Photo 5 (4.3.2 (2)). A similar water level decline is confirmed in the results of numerical simulation of the tsunami.



1 (after 00 minutes and 00 seconds)
About 15:28:07 (time after correction)
15:35:16 (camera internal time before correction)

＊Corrected by numerical simulation results

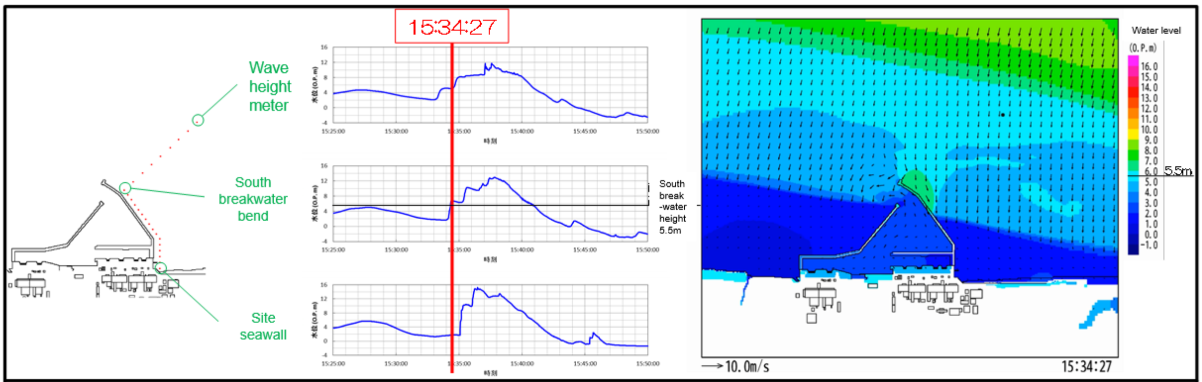


5 (after 05 minutes and 00 seconds)
About 15:33:07 (time after correction)
15:40:16 (camera internal time before correction)

＊Corrected by numerical simulation results

(b) Second wave (first step) arrives at the bend of the south breakwater

In Photo 8, the second wave (first step) is judged to have arrived at the bend of the south breakwater (4.3.3 (3)). As mentioned above, in numerical simulation of the tsunami, it is estimated that the time in Photo 8 is the time when the water level reaches its maximum when the second wave (first step) arrives at the bend of the south breakwater.

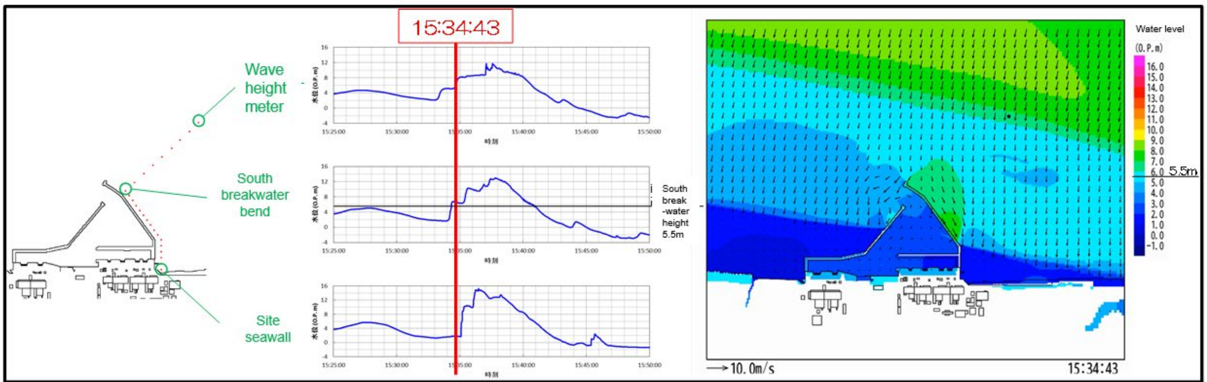


8 (after 06 minutes and 20 seconds)
About 15:34:27 (time after correction)
15:41:36 (camera internal time before correction)

＊Corrected by numerical simulation results

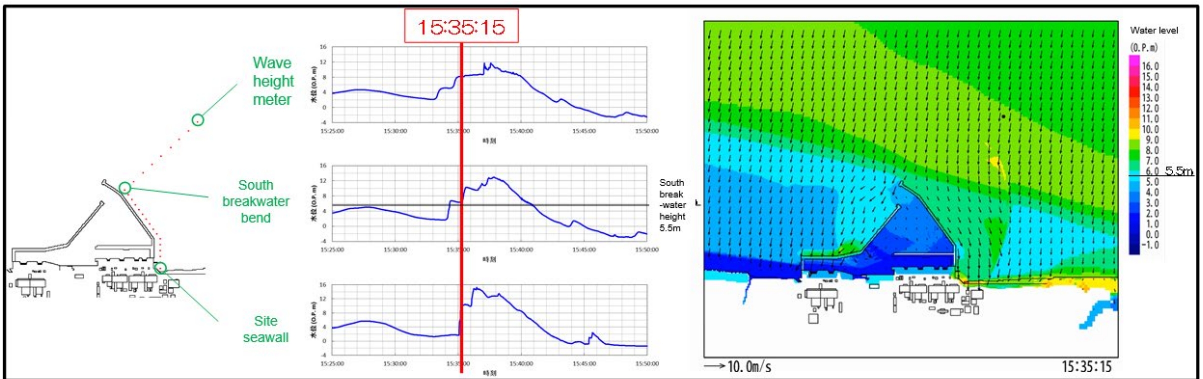
(c) Progress of the second wave (first step)

From Photo 9 to Photo 12, the second wave (first step) is seen advancing along the south breakwater (4.3.3 (4)). The same situation is confirmed in the results of numerical simulation of the tsunami.



9 (after 06 minutes and 36 seconds)
About 15:34:43 (time after correction)
15:41:52 (camera internal time before correction)

＊Corrected by numerical simulation results

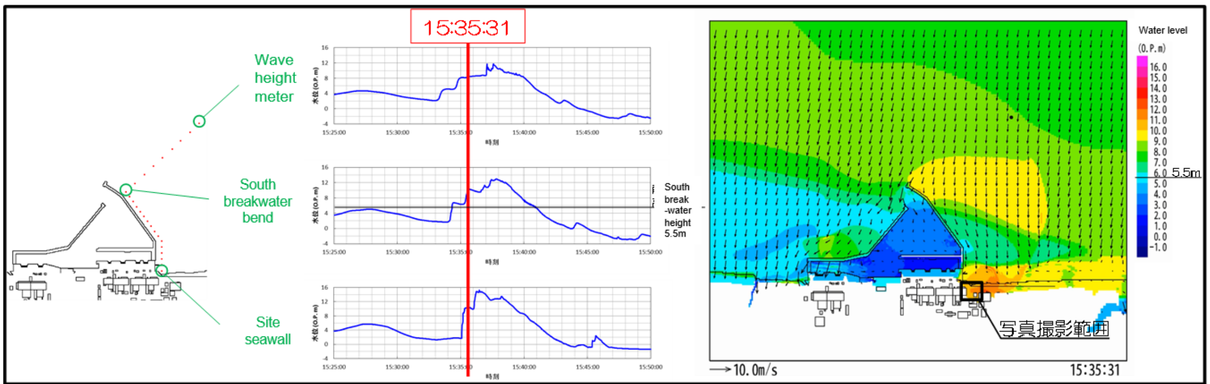


12 (after 07 minutes and 08 seconds)
About 15:35:15 (time after correction)
15:42:24 (camera internal time before correction)

＊Corrected by numerical simulation results

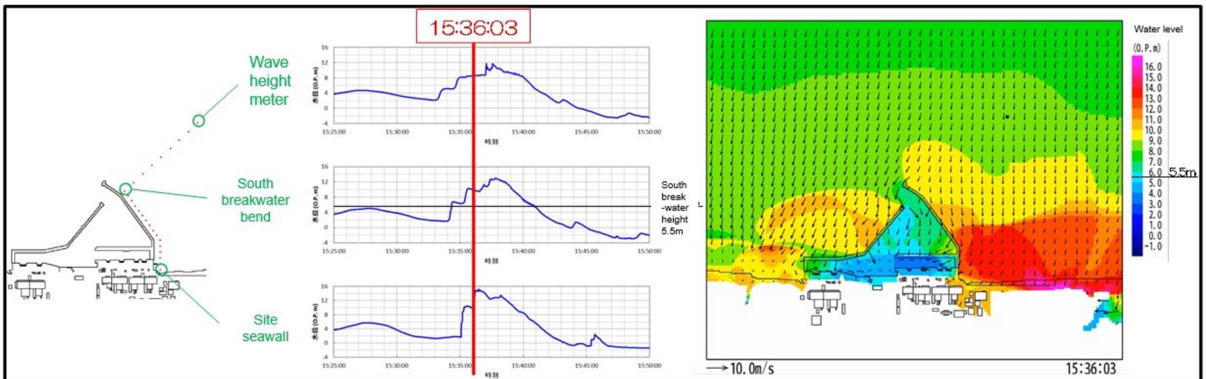
(d) Arrival of the second wave (first step) at the 10-meter plate and arrival of the second wave (second step) in the harbor

From Photo 13 to Photo 14, the second wave (first step) arrives at the 10-meter plate, and from Photo 15 to Photo 16, the second wave (second step) arrives at the harbor (4.3.3 (5)). The same situation is confirmed in the results of numerical simulation of tsunami.



13 (07:24 minutes and 24 seconds later)
About 15:35:31 (time after correction)
15:42:40 (camera internal time before correction)

＊Corrected by numerical simulation results

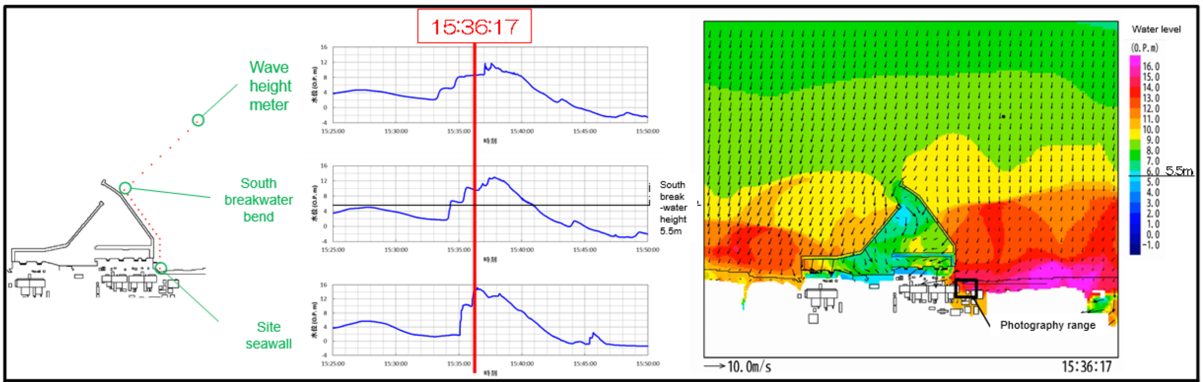


16 (07 minutes and 56 seconds later)
About 15:36:03 (time after correction)
15:43:12 (camera internal time before correction)

＊Corrected by numerical simulation results

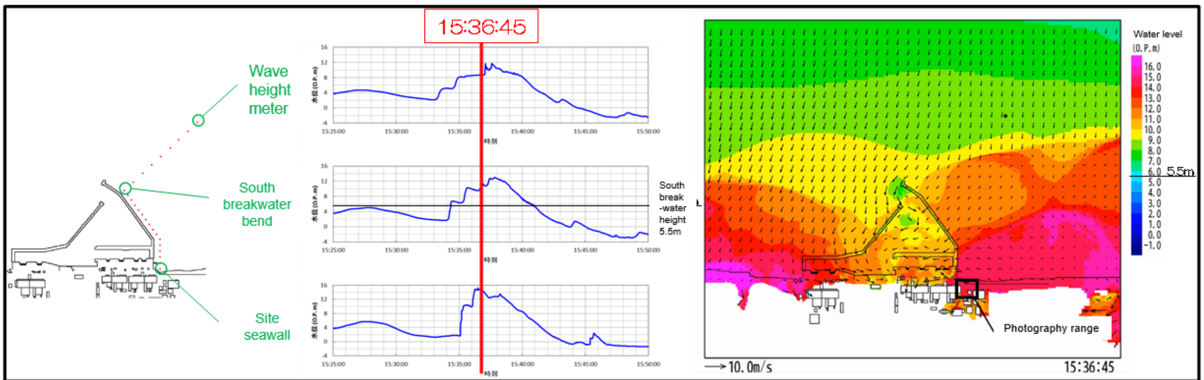
(e) Arrival at 10-meter plate of the second wave (second step)

From Photo 17 to Photo 19, the second wave (second step) arrives at the 10-meter plate (4.3.3 (6)). The same situation is confirmed in the results of numerical simulation of tsunami.



17 (08 minutes and 10 seconds later)
About 15:36:17 (time after correction)
15:43:26 (camera internal time before correction)

＊Corrected by numerical simulation results



19 (08 minutes and 38 seconds later)
About 15:36:45 (time after correction)
15:43:54 (camera internal time before correction)

＊Corrected by numerical simulation results

(3) Results of confirming the reproducibility of numerical simulation of tsunami

In numerical simulation of the tsunami, it is estimated that the time when the water level reaches its maximum when the second wave (first step) arrives at the bend of the south breakwater is the time shown in Photo 8, and the times shown in Photos 1 to 19 were corrected. The results from confirming numerical simulation of the tsunami with the corrected time series of photographs and numerical simulation of the tsunami corresponding to the time of the photographs show a good agreement with the arrival and runup of the tsunami that hit the site.

Therefore, it is concluded that the numerical simulation of the tsunami accurately reproduces the arrival and runup of the tsunami after passing wave height meters.

5.4. Estimation of arrival time of tsunami by numerical simulation

The tsunami arrival times for each case are shown below. Based on the numerical simulation of tsunami, it is estimated that the tsunami arrives at about 15:36 in front of the large item loading entrance of the turbine building of Unit 1, which is located almost in the center of the seaward side of the site.

Time of tsunami arriving at the front of the large item loading entrance of the turbine building of Unit 1

Case	Overturning of the upper structure of the north breakwater etc.	Roughness coefficient of runup area	Arrival time (Unit 1 T/B large item loading entrance)
1 (Base)	○	○	15:36:45
2	○	-	15:36:51
3	-	○	15:36:55
4	-	-	15:37:00

5.5 Summary (Analysis II (2))

As the result of estimation of tsunami arrival time by utilizing the numerical simulation of tsunami with the tsunami wave source model, which accurately reproduces the time history waveform of tsunami recorded by wave height meters, the following items were confirmed.

(1) The time shown by the built-in camera clock was about 7 min and 09 s earlier than the actual time. This result is consistent with the result of the examination using the simple calculation (4.4.4) based on the distance from the wave height meter to the bend of the south breakwater and estimated wave speed of tsunami, and the simple calculation and numerical simulation of tsunami are consistent.

(2) The comparison of the numerical simulation of tsunami with the continuous photographs shows good agreement between the arrival and runup of tsunami arriving at the site and the results of the numerical simulation of tsunami. Therefore, it is judged that the numerical simulation of tsunami accurately reproduces the arrival and runup of tsunami after the passage of wave height meters.

(3) If it is estimated, by using the numerical simulation of tsunami, that the tsunami arrives at the front of the large item loading entrance of the turbine building of Unit 1, which is located almost in the center of the seaward side of the site, the arrival time is approximately in the range of 15:36.

6. Analysis using plant data (Analysis III)

6.1 Purpose

Among plant data (stored in the process computers, transient recorders, etc.) the following information was included which indicated the abnormal conditions such as flooding.

- Shutdown times of seawater pumps (circuit breakers worked when motors were flooded, etc.)
- Diesel generator (DG) operation records (voltage, current)
- Data recordings by emergency power panels

Among such information above, the seawater pumps would be the first to be affected by the tsunami, because they were located closest to the sea. The information recorded on the power panels or D/Gs installed in the main buildings can also be used as supplementary information for analyzing the exact arrival time of the tsunami to the Fukushima Daiichi Nuclear Power Station site.

6.2 Analysis of plant data

Plant data were first screened from the following criteria for appropriate utilization

- Clock calibration function is installed
- Electronic data useful to analysis were recorded
- Data at around the times of tsunami arrivals were recorded

The situation is summarized in the following table.

<table>
<tr><th></th><th>Unit 1</th><th>Unit 2</th><th>Unit 3</th><th>Unit 4</th><th>Unit 5</th><th>Unit 6</th></tr>
<tr><td>Process computers (with electronic data storage)</td><td>Not available</td><td>Yes available</td><td>Not available</td><td rowspan="2">Not available, as the system being replaced during the periodic inspection</td><td>Yes available</td><td>Not available</td></tr>
<tr><td>Transient recorders (Data recorded at around the tsunami arrivals)</td><td>Yes available</td><td>Yes available</td><td>Not available</td><td>Not available</td><td>Not available</td></tr>
</table>

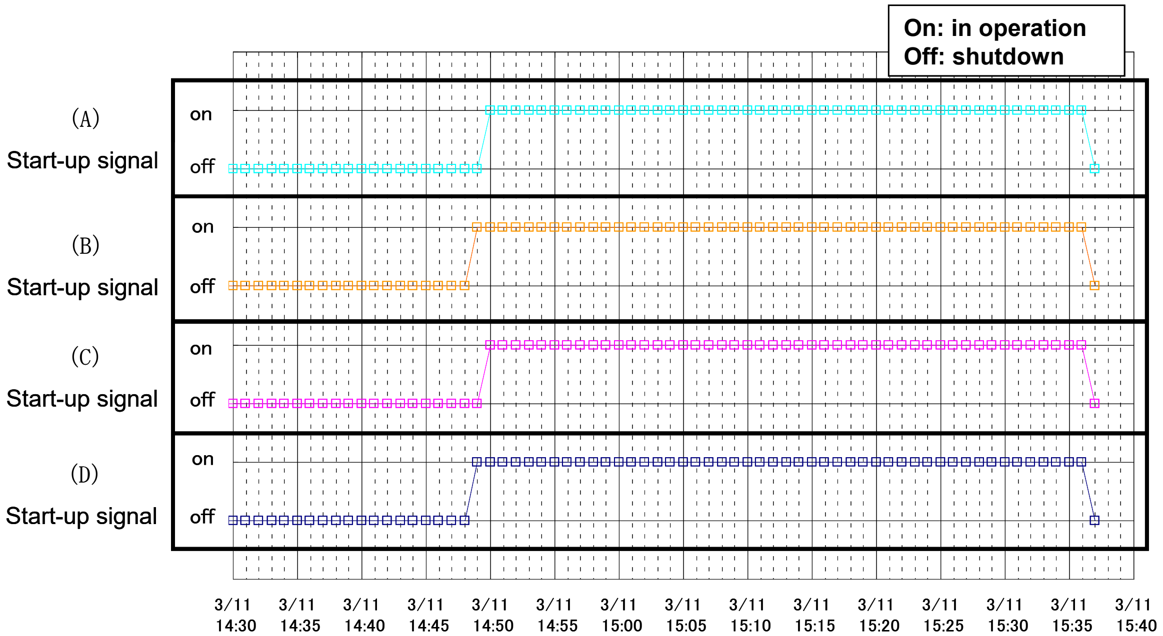
Process computers which have electronic data storage were only installed in Unit 2 and Unit 5, and it is possible to make time corrections for both. Concerning the transient recorders, the data of Unit 1 and Unit 2 are available and time correction is also possible (there was only a data sampled in one minute cycle for Unit 1). In Unit 3, some data from around 14:59:43 on March 11 were not stored and therefore the unit was excluded from the analysis. In Unit 4, the transient recorder was being replaced during the periodic inspections and no data were stored. The transient recorder in Unit 5 had no data when the tsunami arrived and was excluded from the analysis. Unit 6 was under periodic inspection and so the recording system was not in service.

From the reasons above, one minute cycle data of the transient recorder of Unit 1, and the process computer data of Unit 2 and Unit 5 were used in the analysis.

[Shutdown time of seawater pumps]

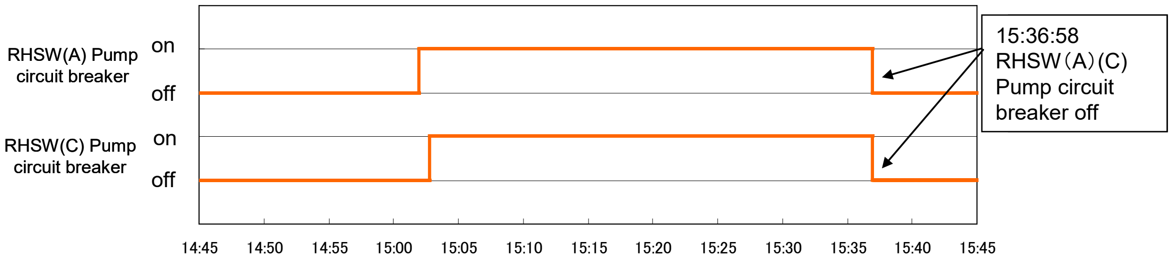
✓ Containment cooling sea water system (CCSW) pumps of Unit 1

The CCSW pumps (A) to (D) had anomalies between 15:35:59 and 15:36:59 and lost their functions, according to the one minute cycle data recorded on the transient recorder.



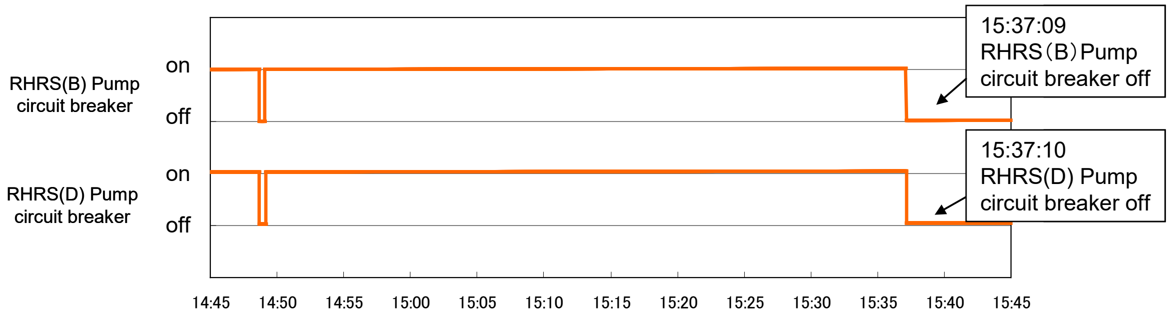
✓ Residual heat removal sea water system(RHSW) pumps of Unit 2

The circuit breakers of RHSW pumps (A) and (C) were opened and lost their operating functions at 15:36:58, according to the records in the process computer.



✓ Residual heat removal sea water system (RHRS) pumps of Unit 5

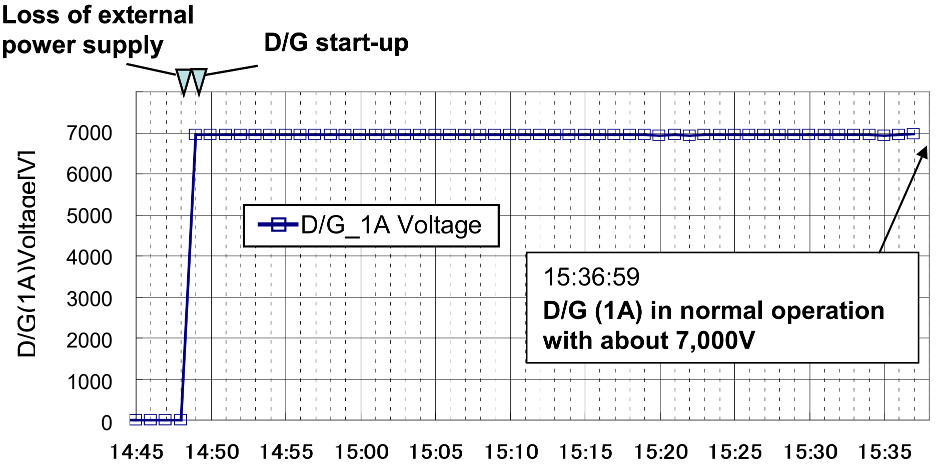
The RHRS pumps (B) and (D), which had started operation after the earthquake, had anomalies and lost operating functions at 15:37:09 and 15:37:10 according to the records in the process computer.

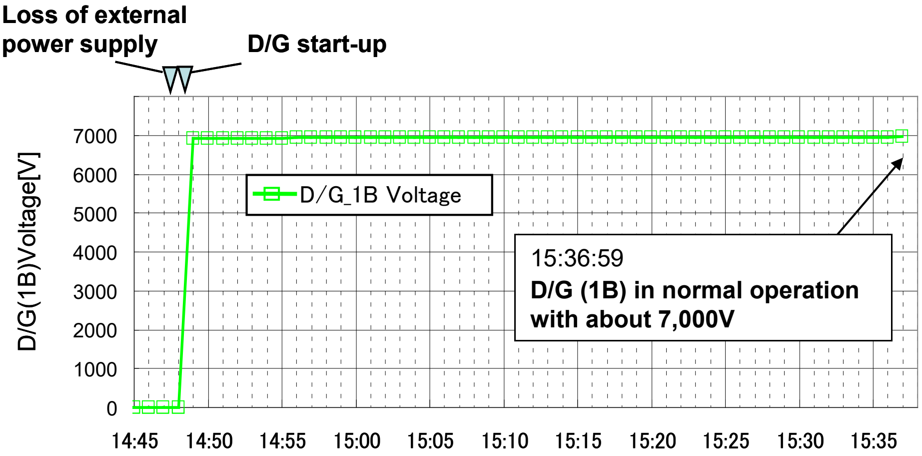

RHRS(B) Pump
circuit breaker
RHRS(D) Pump
circuit breaker
on
off
on
off
15:37:09
RHRS（B）Pump
circuit breaker off
15:37:10
RHRS(D) Pump
circuit breaker off
14:45
14:50
14:55
15:00
15:05
15:10
15:15
15:20
15:25
15:30
15:35
15:40
15:45

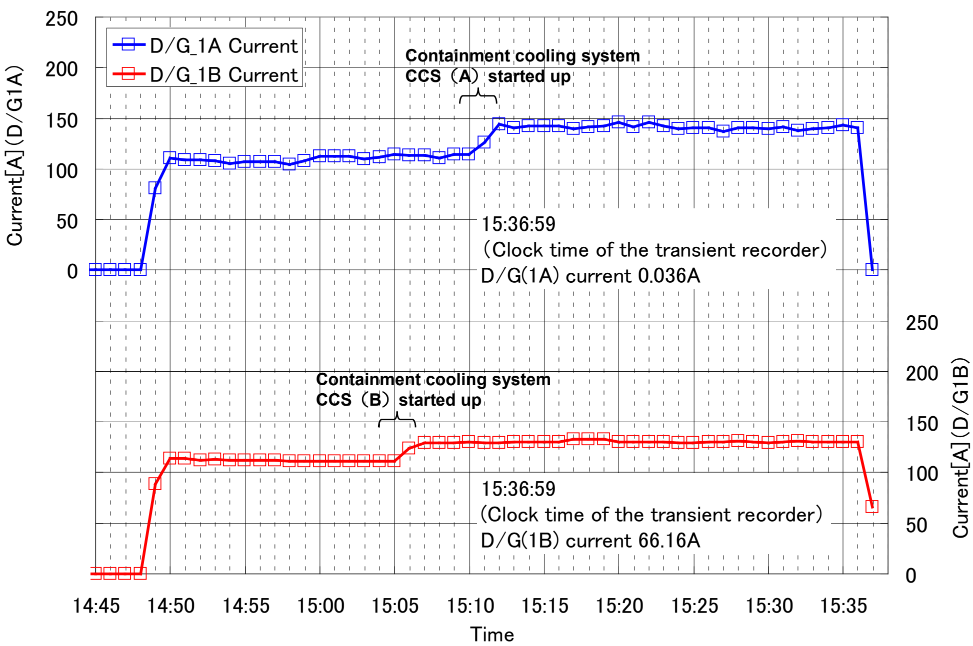
[D/G operation records (voltage, current)]

✓ D/Gs (1A) and (1B) of Unit 1

The voltage of the D/Gs (1A) (1B) of Unit 1 had been established until 15:36:59 while the transient recorder was recording data. This confirms their function losses were sometime after 15:36:59.





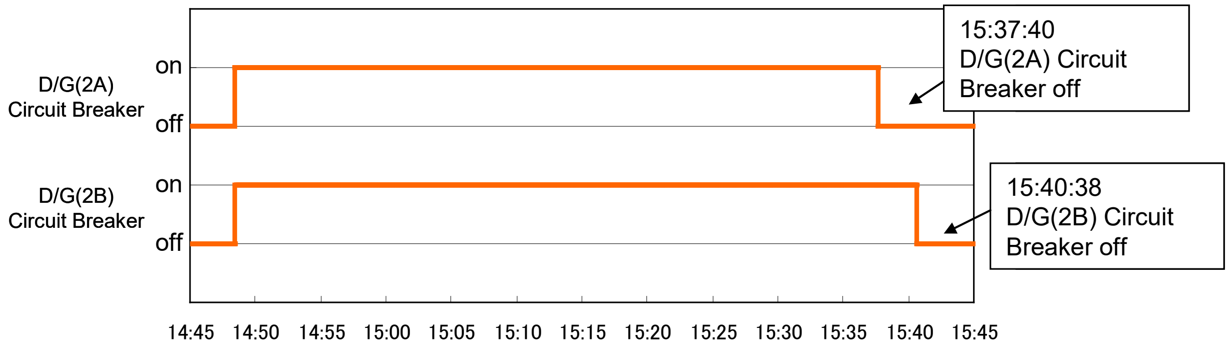


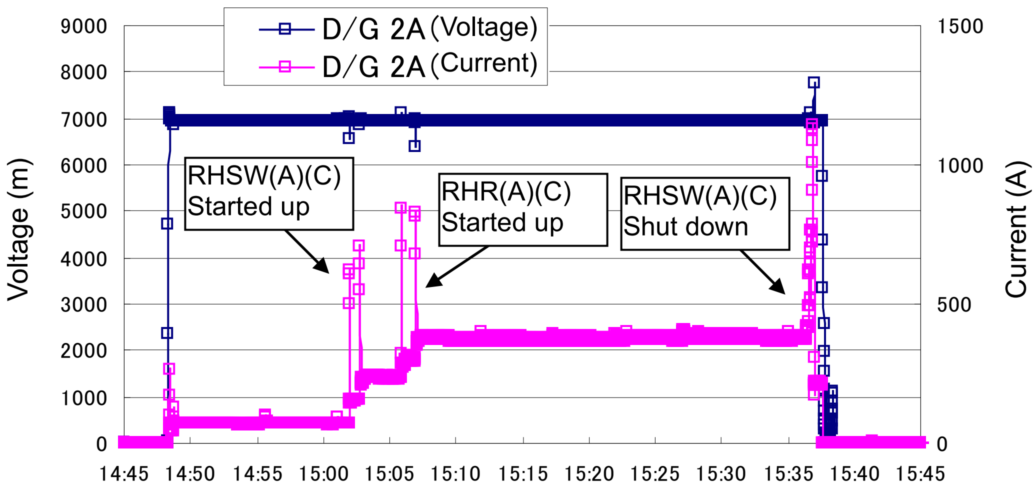
✓ D/Gs (2A) and (2B) of Unit 2

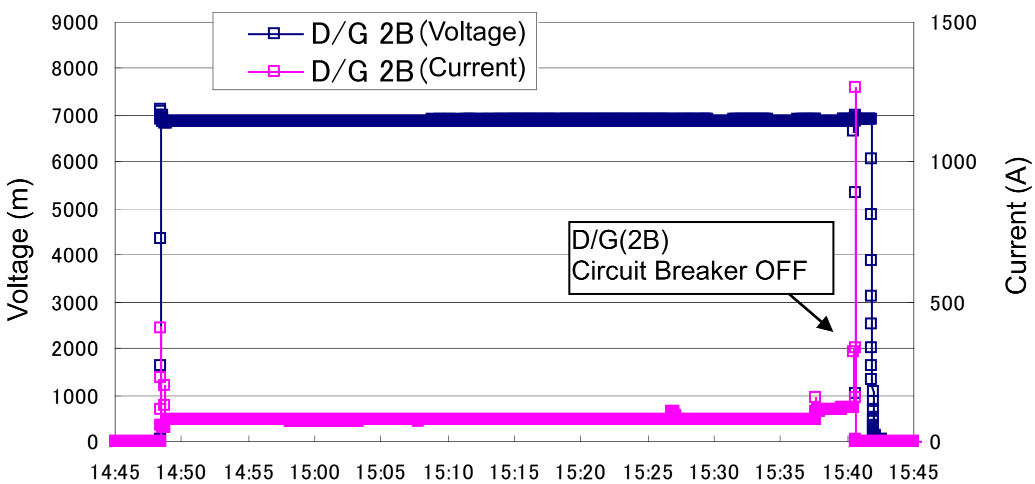
The power receiving circuit breaker of D/G (2A) opened at 15:37:40, according to the data recorded on the process computer.

The D/G (2A) was confirmed in a later investigation to have been flooded. The function loss is assumed to be due to flooding of the D/G body or its related facilities.

The D/G (2B) was installed in another building (the common pool building) and its body was not damaged. But its breaker opened at 15:40:38. The function is assumed to have been lost due to the effect of damage to its related facilities or flooding of the emergency power panels to which the D/G (2B) was supplying power.



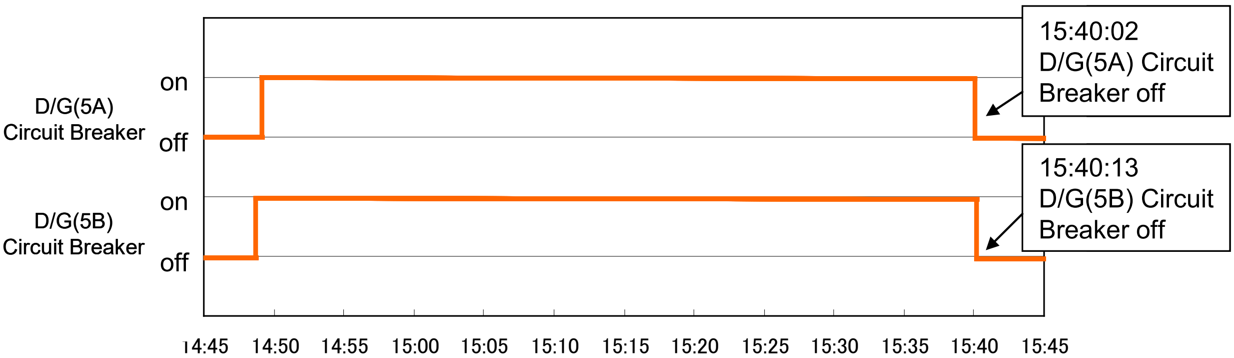


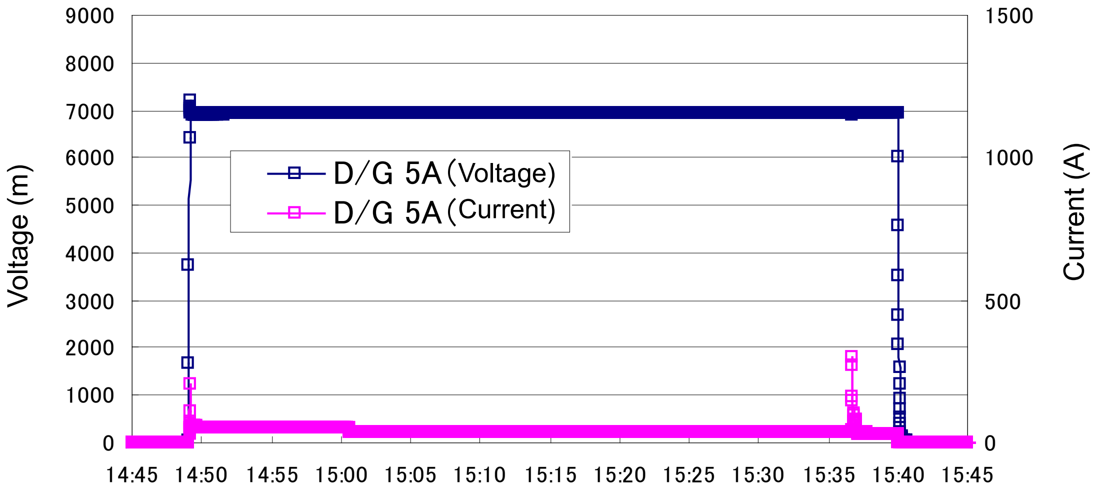


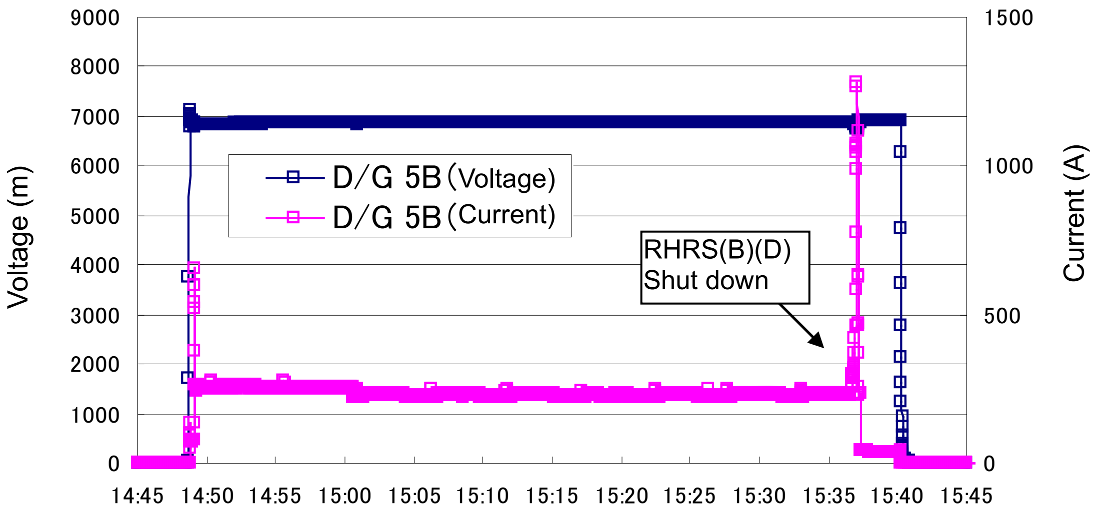
✓ D/Gs (5A) and (5B) of Unit 5

The D/Gs (5A) (5B) had anomalies at around 15:40 and lost their function, according to the data recorded on the process computer.

The bodies of D/Gs (5A) (5B) were confirmed in later investigation to have had no damage by flooding. The function is assumed to have been lost due to damage of their related facilities or flooding of the emergency power panels.



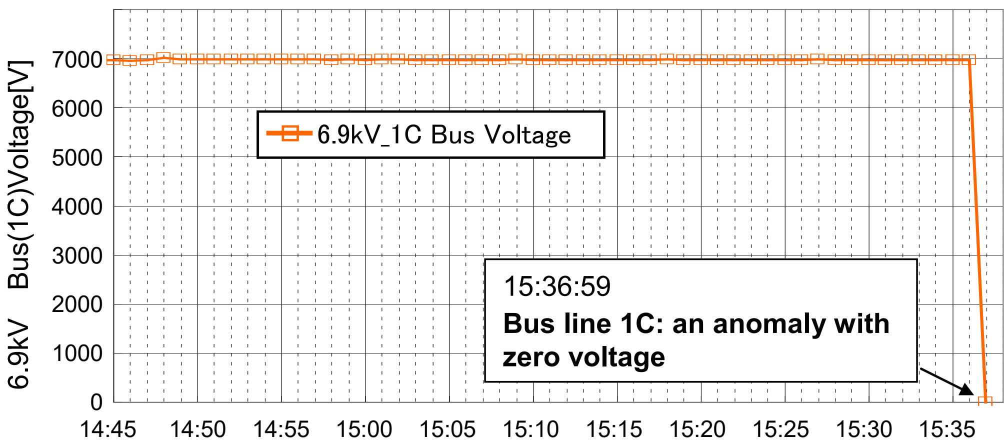


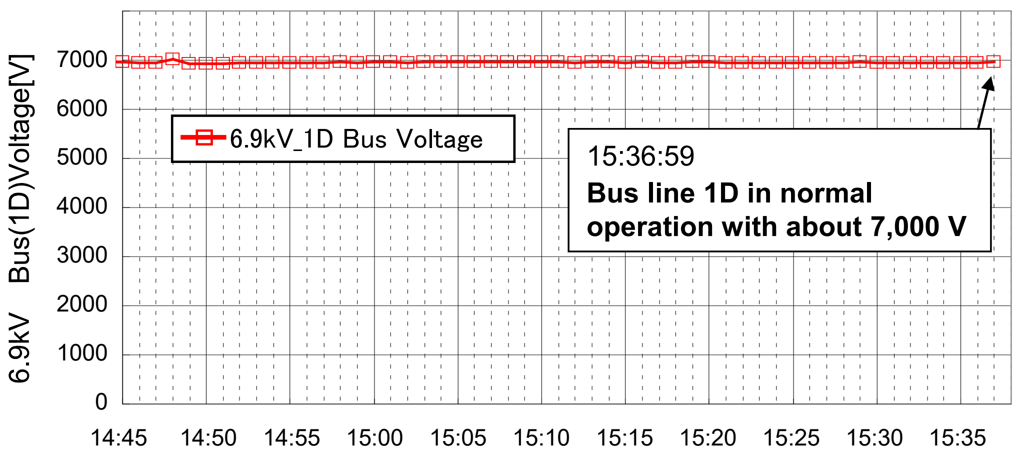


[Emergency power panels]

✓ Emergency power panels 1C and 1D of Unit 1

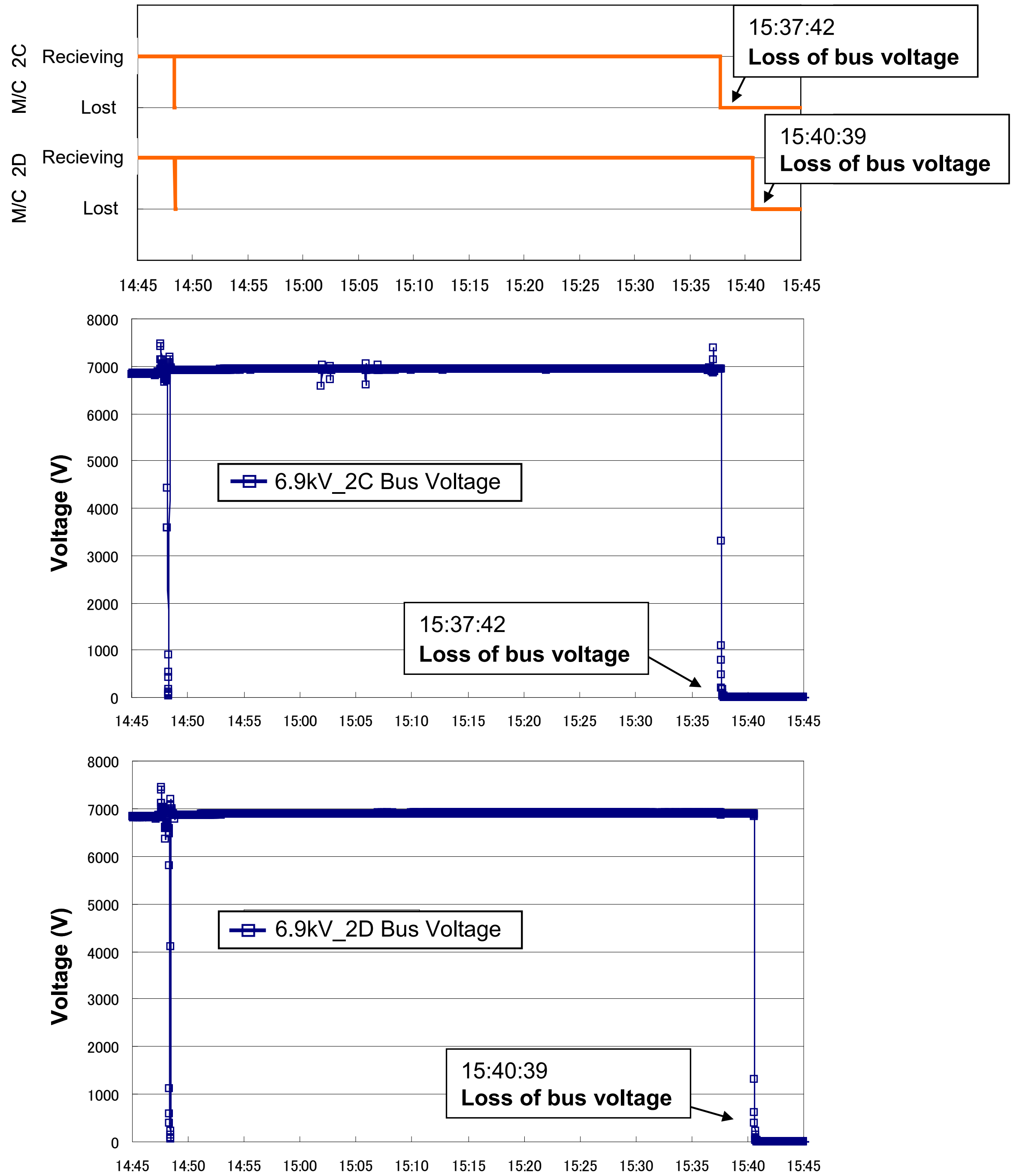
The emergency power panel 1C lost the emergency bus voltage between 15:35:59 and 15:36:59, while the emergency bus voltage of the emergency power panel 1D has been established until 15:36:59, according to the one minute cycle data recorded on the transient recorder. This confirms the function losses of the emergency power panel 1D was sometime after 15:36:59.





✓ Emergency power panels 2C and 2D of Unit 2

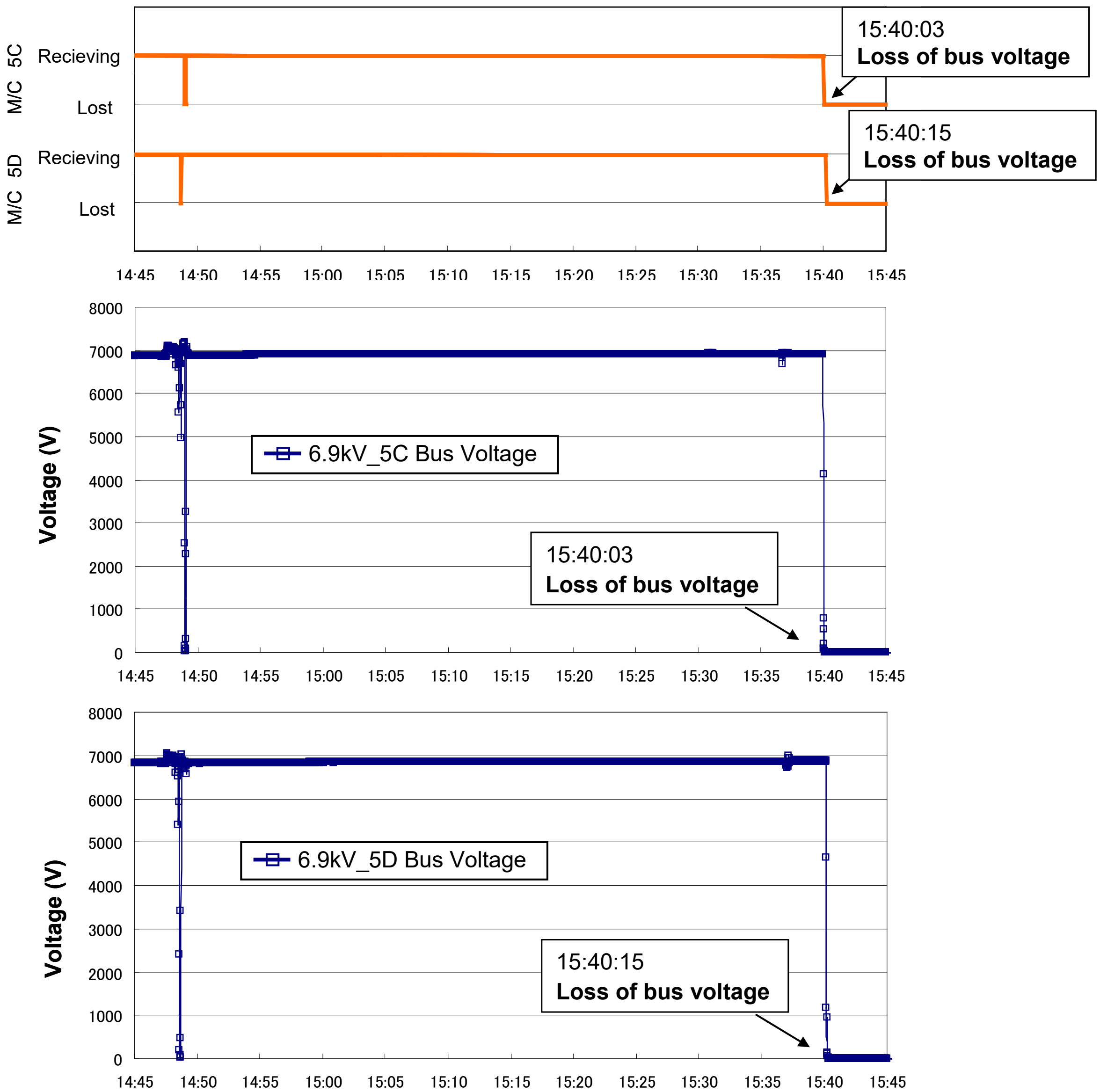
The emergency power panel 2C lost the emergency bus voltage at 15:37:42, while the emergency power panel 2D lost it at 15:40:39, according to the data recorded on the process computer for emergency power panels.



✓ Emergency power panels 5C and 5D of Unit 5

The emergency power panel 5C lost the emergency bus voltage at 15:40:03, while the emergency power panel 5D lost it at 15:40:15, according to the data recorded on the process computer.

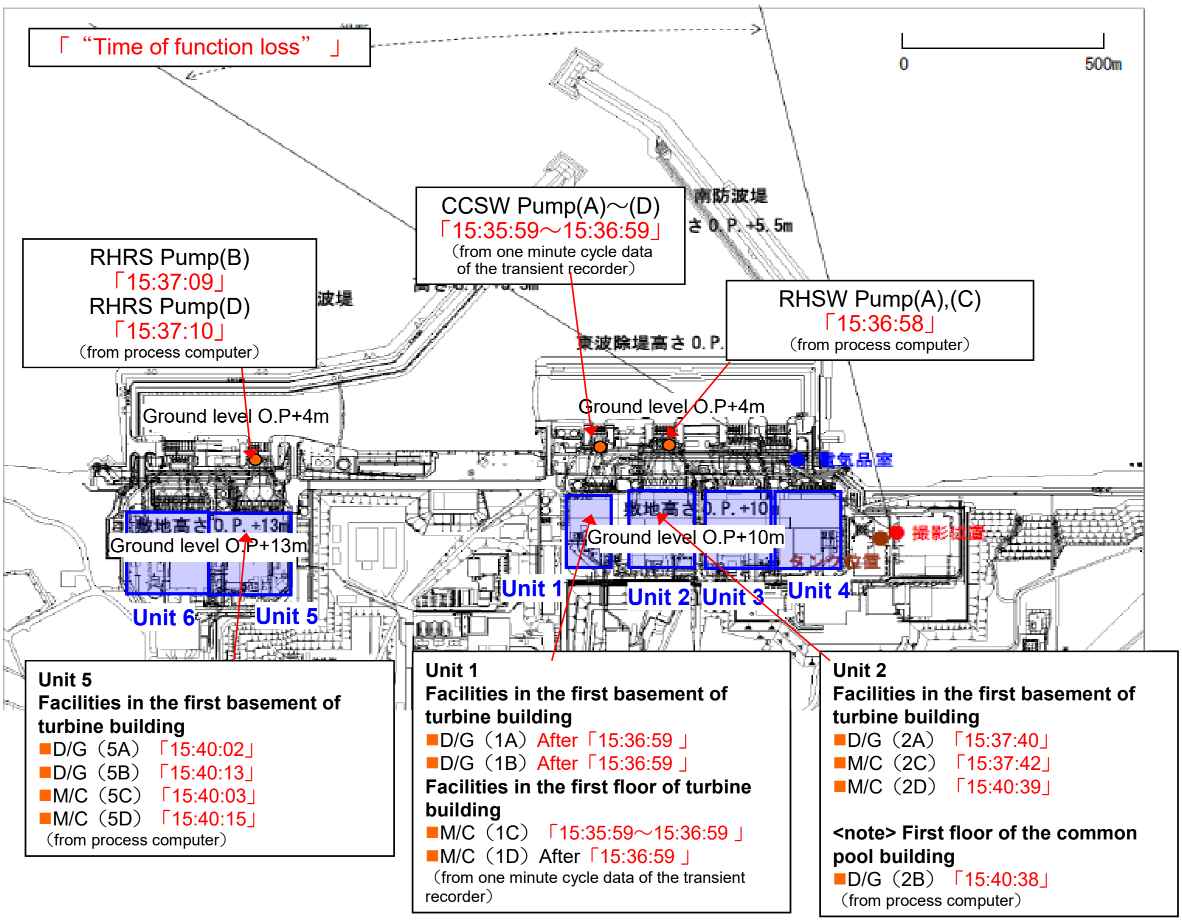
The D/Gs showed no anomalies in a post-accident investigation. The loss of function is assumed to have been caused by that of the metal-clad switchgear (M/C) or D/G related facilities, which were flooded.



6.3. Summary of analysis by the use of plant data (Analysis III)

Seawater pumps closest to the sea (installed on the 4-m ground level) lost their function mostly at the 15:36 level, which is thought to be due to the arrival of tsunami second wave at the site.

In other main buildings, the timing of function loss varied depending on the installed locations, but the emergency bus function was lost mostly at around 15:40 caused by tsunami, resulting in the loss of all AC power supplies.



7. Conclusion

The results of Analyses I, II (1), II (2) and III can be summarized as follows.

Analysis I showed no big timing errors in the wave height meter.

Analysis II (1) showed the photo-taking timing by the camera had an error of about 7 min 09 s. Timing correction of photos led to the following judgments.

- ✓ Around 15:35:31: small scale inundation could be confirmed around the tanks on the 10-m ground level due to the tsunami second wave (first step).
- ✓ Around 15:36:17: large scale inundation could be confirmed around the tanks on the 10-m ground level due to the tsunami second wave (second step).

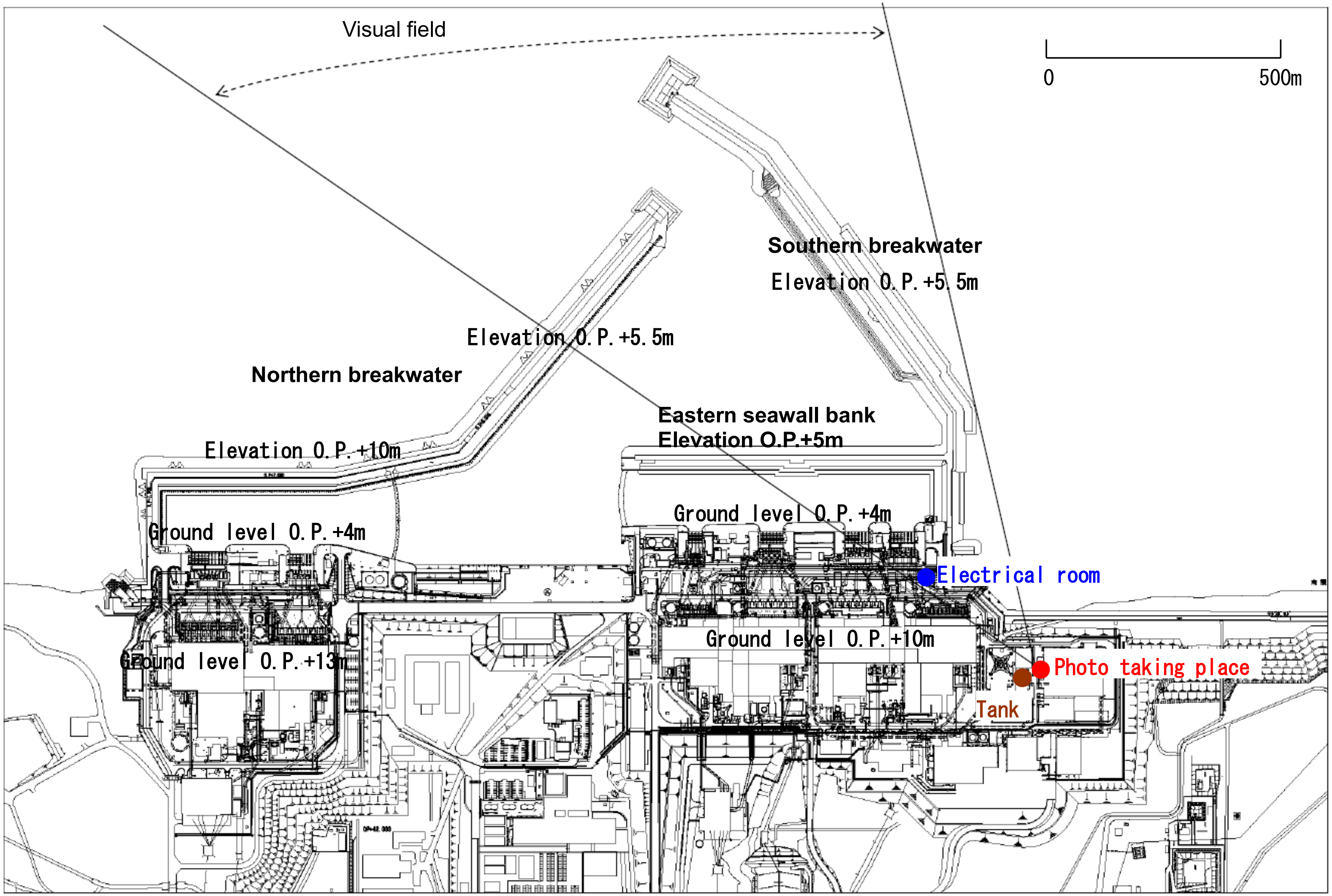
As a result of Analysis II (2), it is judged that the time of the photographs is off by about 7 min and 09 s, as described above. The results of numerical simulation of tsunami are as follows.

- ✓ 15:36: the tsunami arrives at the front of the large item unloading entrance of the turbine building of Unit 1, which is located almost in the center of the seaward side of the site.

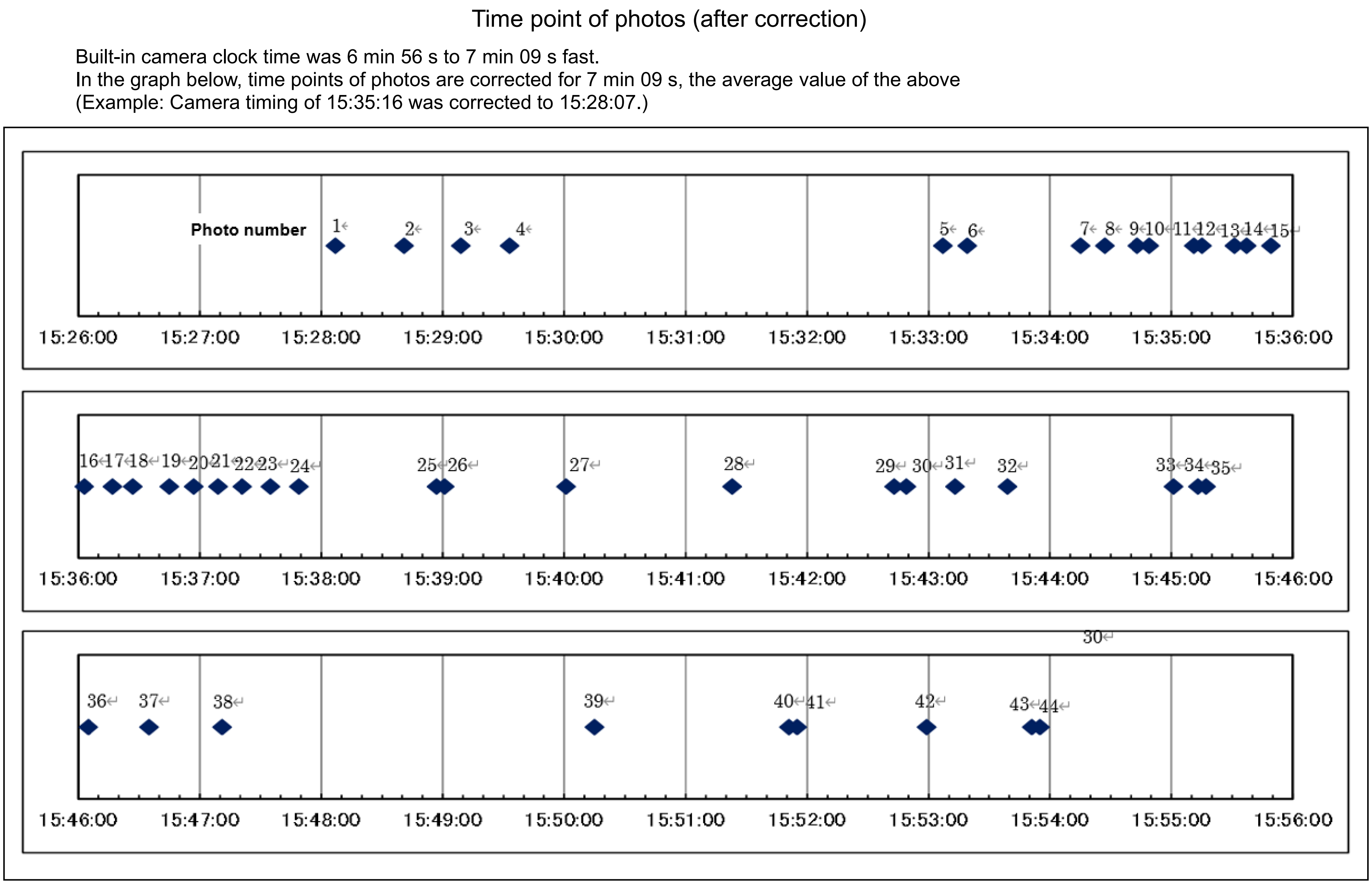
Analysis III based on the plant data indicated that the second tsunami reached the site at around 15:36. Furthermore seawater pumps closest to the sea lost their function mostly at around 15:36 due to the arrival of the second tsunami. Then the emergency bus function was lost mostly at around 15:40 after the arrival of the second tsunami at the site, resulting in the loss of all AC power supplies.

TEPCO believes from the above analysis (photo-taking timing, numerical simulation of tsunami and plant data) that the tsunami reached the site between 15:35 to 15:36.

【Appendix 1】Positional relation of continuous photos



【Appendix 2】All 44 continuous photos



Legend above photo

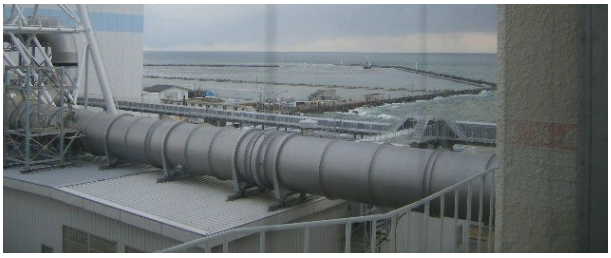
Photo number (time elapsed from Shot 1)
Time after correction (corrected time)
Time before correction (built-in camera clock time)

1（00 min 00 s later）
about 15:28:07（corrected time）
15:35:16（built-in camera clock time）

2（00 min 34 s later）
about 15:28:41（corrected time）
15:35:50（built-in camera clock time）

3（01 min 02 s later）
about 15:29:09（corrected time）
15:36:18（built-in camera clock time）

4（01 min 26 s later）
about 15:29:33（corrected time）
15:36:42（built-in camera clock time）



5（05 min 00 s later）
about 15:33:07（corrected time）
15:40:16（built-in camera clock time）

6（05 min 12 s later）
about 15:33:19（corrected time）
15:40:28（built-in camera clock time）

7（06 min 08 s later）
about 15:34:15（corrected time）
15:41:24（built-in camera clock time）

8（06 min 20 s later）
about 15:34:27（corrected time）
15:41:36（built-in camera clock time）

9（06 min 36 s later）
about 15:34:43（corrected time）
15:41:52（built-in camera clock time）

10（06 min 42 s later）
about 15:34:49（corrected time）
15:41:58（built-in camera clock time）

11（07 min 04 s later）
about 15:35:11（corrected time）
15:42:20（built-in camera clock time）

12（07 min 08 s later）
about 15:35:15（corrected time）
15:42:24（built-in camera clock time）

13（07 min 24 s later）
about 15:35:31（corrected time）
15:42:40（built-in camera clock time）

14（07 min 30 s later）
about 15:35:37（corrected time）
15:42:46（built-in camera clock time）

15（07 m 42 s later）
about 15:35:49（corrected time）
15:42:58（built-in camera clock time）

16（07 min 56 s later）
about 15:36:03（corrected time）
15:43:12（built-in camera clock time）

17（08 min 10 s later）
about 15:36:17（corrected time）
15:43:26（built-in camera clock time）

18（08 min 20 s later）
about 15:36:27（corrected time）
15:43:36（built-in camera clock time）

19（08 min 38 s later）
about 15:36:45（corrected time）
15:43:54（built-in camera clock time）

The above photos are reproduced ones of those in the text body.

20（08 min 50 s later）
about 15:36:57（corrected time）
15:44:06（built-in camera clock time）

21（09 min 02 s later）
about 15:37:09（corrected time）
15:44:18（built-in camera clock time）

22（09 min 14 s later）
about 15:37:21（corrected time）
15:44:30（built-in camera clock time）

23（09 min 28 s later）
about 15:37:35（corrected time）
15:44:44（built-in camera clock time）

24（09 min 42 s later）
about 15:37:49（corrected time）
15:44:58（built-in camera clock time）

25（10 min 50 s later）
about 15:38:57（corrected time）
15:46:06（built-in camera clock time）

26（10 min 54 s later）

about 15:39:01（corrected time）

15:46:10（built-in camera clock time）

27（11 min 54 s later）

about 15:40:01（corrected time）

15:47:10（built-in camera clock time）

28（13 min 16 s later）

about 15:41:23（corrected time）

15:48:32（built-in camera clock time）

29（14 min 36 s later）

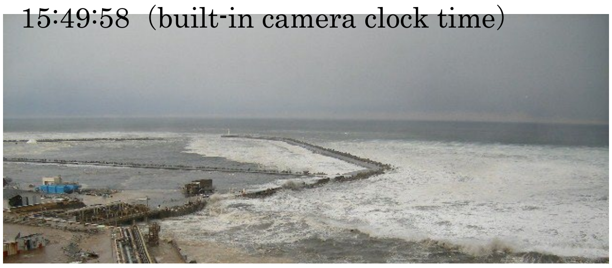
about 15:42:43（corrected time）

15:49:52（built-in camera clock time）

30（14 min 42 s later）

about 15:42:49（corrected time）

15:49:58（built-in camera clock time）



31（15 min 06 s later）

about 15:43:13（corrected time）

15:50:22（built-in camera clock time）

32（15 min 32 s later）

about 15:43:39（corrected time）

15:50:48（built-in camera clock time）

33（16 min 54 s later）

about 15:45:01（corrected time）

15:52:10（built-in camera clock time）

34（17 min 06 s later）

about 15:45:13（corrected time）

15:52:22（built-in camera clock time）

35（17 min 10 s later）

about 15:45:17（corrected time）

15:52:26（built-in camera clock time）

36（17 min 58 s later）

about 15:46:05（corrected time）

15:53:14（built-in camera clock time）

37（18 min 28 s later）

about 15:46:35（corrected time）

15:53:44（built-in camera clock time）

38（19 min 04 s later）
about 15:47:11（corrected time）
15:54:20（built-in camera clock time）

39（22 min 08 s later）
about 15:50:15（corrected time）
15:57:24（built-in camera clock time）

40（23 min 44 s later）
about 15:51:51（corrected time）
15:59:00（built-in camera clock time）

41（23 min 48 s later）
about 15:51:55（corrected time）
15:59:04（built-in camera clock time）

42（24 min 52 s later）
about 15:52:59（corrected time）
16:00:08（built-in camera clock time）

43（25 min 44 s later）
about 15:53:51（corrected time）
16:01:00（built-in camera clock time）

44（25 min 48 s later）

about 15:53:55（corrected time）

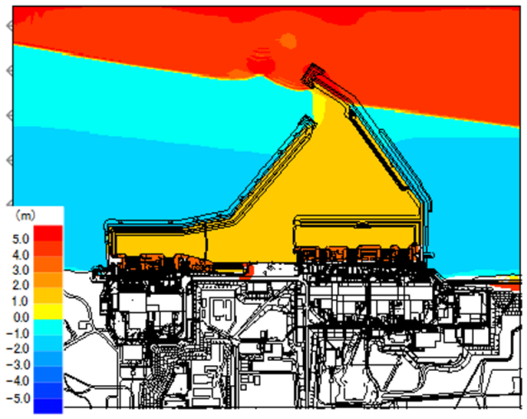
16:01:04（built-in camera clock time）

[Appendix 3] Setting of distance value from the wave height meter to the southern breakwater bend

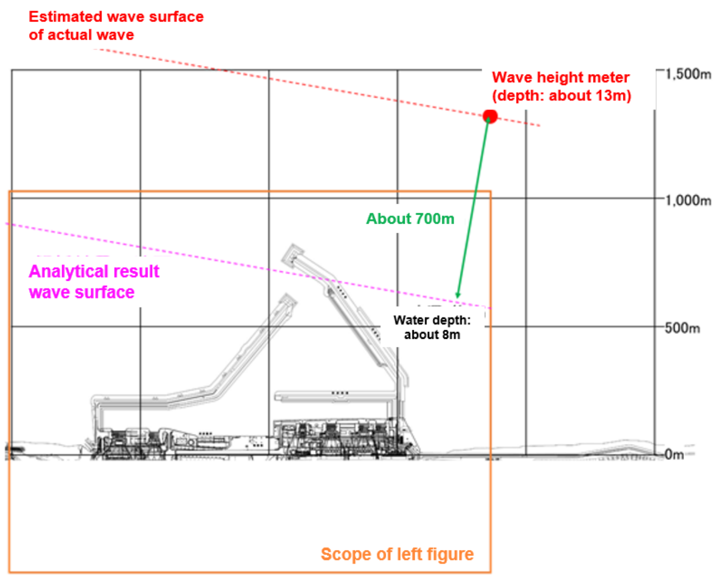
In this examination, the distance was set as 700 m from the wave height meter to the south breakwater bend.

According to the numerical simulation of the tsunami, the wave surface is angled as shown in the figure below. Since the direction of the wave front is governed by the seafloor topography, it can be concluded that the numerical simulation of tsunami is almost equal to the actual direction of the wave front.

In previous examinations, the distance between the wave height meter and the bend in the south breakwater (about 900 m) was taken as a straight line distance, which was estimated to be longer than the actual tsunami travel distance, but this time the distance was revised to the above distance, which is considered closer to the actual one.



Analytical result (Bird's eye view)



[Appendix 4] Propagation time of the second wave (first step) from the wave height meter to the southern breakwater

a. Propagation time calculated from estimated velocity based on the still water depth

The still water depth h was used to estimate propagation time on the longer side in the following approach, without considering the tsunami amplitude.

- The distance of about 700 m was divided into 14 sections of 50 m each.
- The water depth at the location of the wave height meter was about 13 m. The water depth in the direction of the tsunami travel from the wave height meter when the wave surface arrives at the bend of the south breakwater was about 8 m. The slope of the sea bottom was assumed to be constant along this distance.
- The wave propagation velocity in each section was obtained by combining the approximation formula $c = (gh)^{1/2}$ and the average seabed depth in each section.
- Time needed for tsunami to propagate over each section was calculated.
- As the Table on the next page shows, the tsunami propagation time from the wave height meter location to the southern breakwater bend was obtained as about 70 s.

b. Propagation time calculated from estimated velocity based on the total water depth

The total water depth (= still water depth + tsunami amplitude) was used to obtain a more realistic propagation time.

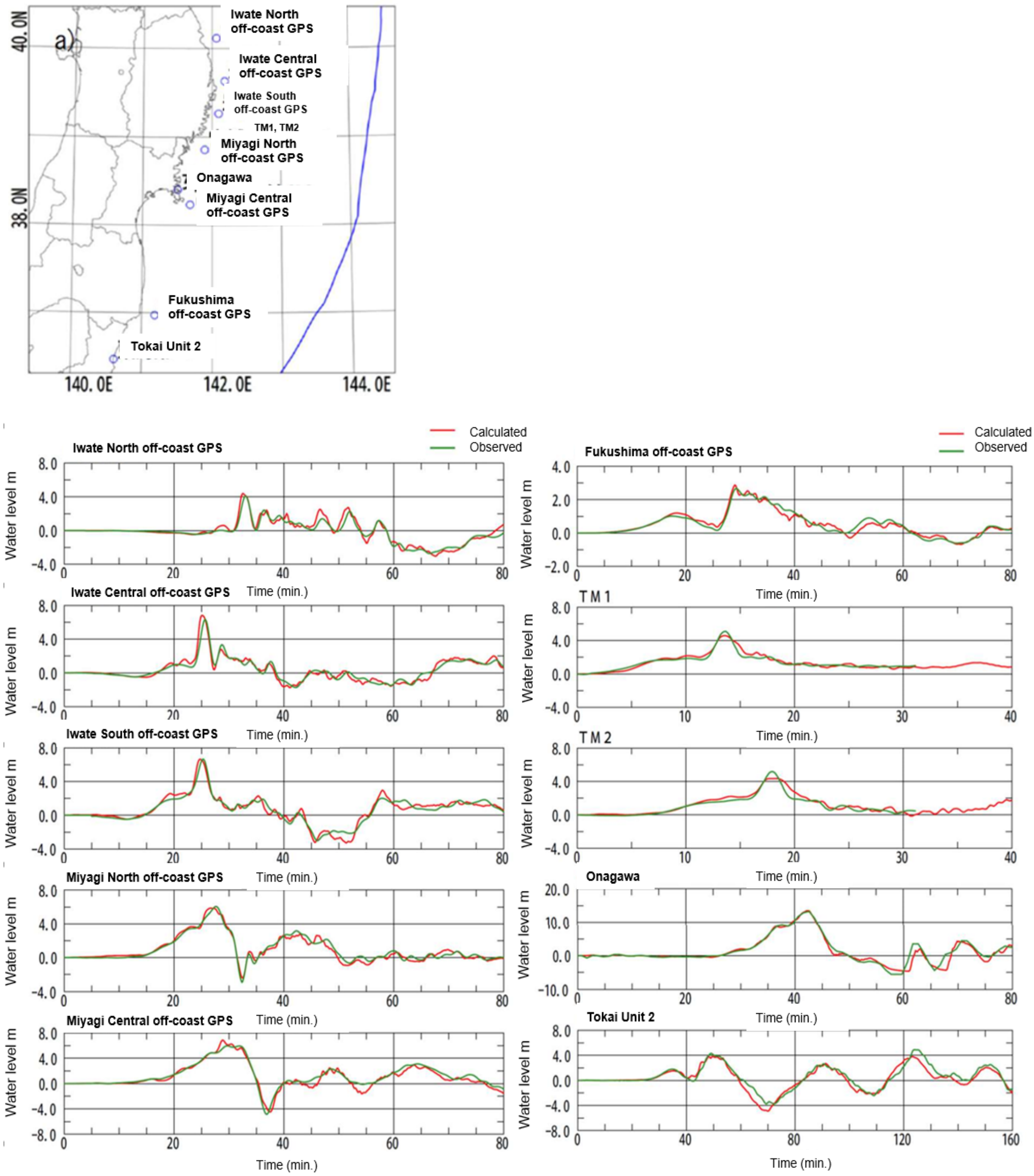
- The tsunami amplitude H_2 was calculated in each section using Green's Rule: $H_2/H_1 = (h_1/h_2)^{1/4}$.
- The initial value of tsunami amplitude H_1 was set at 4.5 m from the wave height meter recording of the second wave (first step).
- The initial value of sea depth h_1 was about 13 m at the wave height meter location.
- The propagation time was obtained in the same approach as in a, using the total water depth instead of the still water depth.
- As the Table on the next page shows, the tsunami propagation time from the wave height meter location to the southern breakwater bend was obtained as about 57 s.

Based on the examination above, the propagation time from the wave height meter to the harbor area is estimated as 57 to 70 s.

Distance from wave height meter [m]	a. Examination using still water depth			b. Examination using total water depth			
	Average water depth in each section [m]	Wave velocity obtained from approximate formula with still water depth [m/s]	Propagation time in each section [s]	Wave height by Green's Rule [m]	Average water depth in each section [m]	Wave velocity obtained from approximate formula with total water depth [m/s]	Propagation time in each section [s]
0～50	12.8	11.2	4.5	4.5	17.3	13.0	3.8
50～100	12.5	11.1	4.5	4.5	17.0	12.9	3.9
100～150	12.1	10.9	4.6	4.6	16.7	12.8	3.9
150～200	11.8	10.7	4.7	4.6	16.4	12.7	3.9
200～250	11.4	10.6	4.7	4.7	16.0	12.5	4.0
250～300	11.0	10.4	4.8	4.7	15.7	12.4	4.0
300～350	10.7	10.2	4.9	4.7	15.4	12.3	4.1
350～400	10.3	10.1	5.0	4.8	15.1	12.2	4.1
400～450	10.0	9.9	5.1	4.8	14.8	12.0	4.2
450～500	9.6	9.7	5.2	4.9	14.5	11.9	4.2
500～550	9.2	9.5	5.3	4.9	14.1	11.8	4.2
550～600	8.9	9.3	5.4	4.9	13.8	11.6	4.3
600～650	8.5	9.1	5.5	5.0	13.5	11.5	4.3
650～700	8.2	9.0	5.6	5.1	13.2	11.4	4.4
	Total propagation time [s]		69.8		Total propagation time [s]		57.3

[Appendix 5] Reproducibility of the tsunami source model N04-3 in a wide area

Tsunami source model N04-3 reproduces well the observed data in a wide area. Example comparisons between observed data and calculated results are shown below.



Comparison of observed and calculated tsunami waveforms (excerpt from Annaka et al. (2020) [2)]

[Appendix 6]　Details of numerical simulation of tsunami

- Basic equations and computational conditions
  - ✓ The nonlinear long wave theory (shallow water theory) was used for the basic equations.
  - ✓ The calculation conditions for each calculation item are shown in the table.

- Basic equations

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} - K_h\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right) + {\gamma_b}^2 \frac{M\sqrt{M^2+N^2}}{D^2} = 0$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} - K_h\left(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2}\right) + {\gamma_b}^2 \frac{N\sqrt{M^2+N^2}}{D^2} = 0$$

t : Time　　　　　　x, y : Plane coordinates

η : Water level variation taken vertically upward from the still water surface

M : Linear flow in x-direction　　　N : Linear flow in y direction

h : Still water depth　　　D : Total water depth ($D = h + \eta$)

g : Gravitational acceleration

K_h : Horizontal eddy kinematic viscosity coefficient

${\gamma_b}^2$: Coefficient of friction (=$gn\ 2 / D^{1/3}$),　n: Manning's roughness coefficient

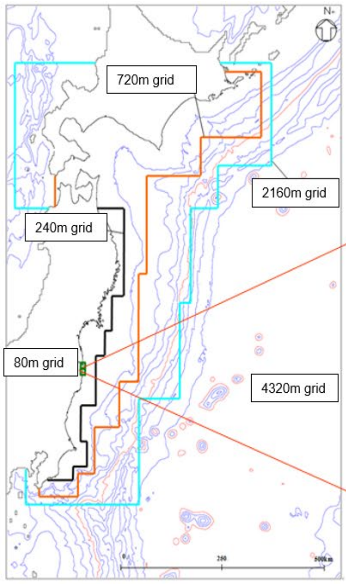
- Main calculation conditions

Item	Calculation condition
Computation time interval	Set as 0.1 second to satisfy C.F.L. condition
Basic equations and scheme of numerical calculations	Goto and Ogawa (1982) method based on nonlinear long wave theory (shallow water theory)
Off-coast boundary condition	Goto and Ogawa (1982) conditions for free transmission
Land side boundary condition	• The area around the site: (calculation grid spacing 80-5 m) is the onshore runup boundary condition of Kotani et al. (1998) • Otherwise, perfect reflection condition
Overflow boundary condition	Overflow is considered by Honma formula (1940) and Aida formula (1977)
Sea bottom friction coefficient	Manning's roughness coefficient (n=0.03m $^{-1/3}$s)
Initial conditions	Vertical displacement distribution of the seabed is obtained by the method of Mansinha and Smylie (1971) and given as the initial water level.
Calculation time	6 hours

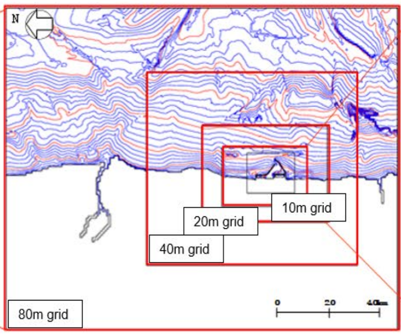
- Analysis model

  The numerical simulation model reflects the latest topographic data from the Japan Hydrographic Association, the Geospatial Information Authority of Japan, and other organizations, as well as the results of the latest deep and shallow surveys in the vicinity of power plant sites and harbors.

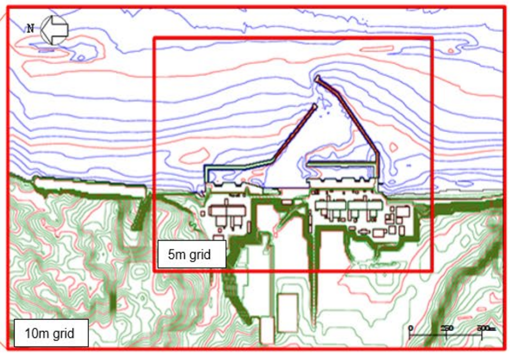
Item	Data
Wide-area undersea topography	• JTOPO30 30 second grid bathymetry data for the seas around Japan : Japan Hydrographic Association • Digital data of basic chart of coastal seas : Japan Hydrographic Association • Japan Coastline Data : Japan Hydrographic Association
Land area, near the power station, in the harbor	• Numerical map 50m mesh : Geospatial Information Authority of Japan • Overall plane map (CAD) (June 2007) • Survey of the surrounding sea area (CAD, including open culverts for water intake) (August 2007) • Survey of depth and shallow water in the harbor (CAD) (surveyed on October 15 and 19, 2007)



(Depth contour interval 500m)



Around the power plant
(sea contour interval: 2m, land contour interval: 2m)



Near power plant
(sea contour interval: 1m, land contour interval: 1m)

■ Analysis conditions

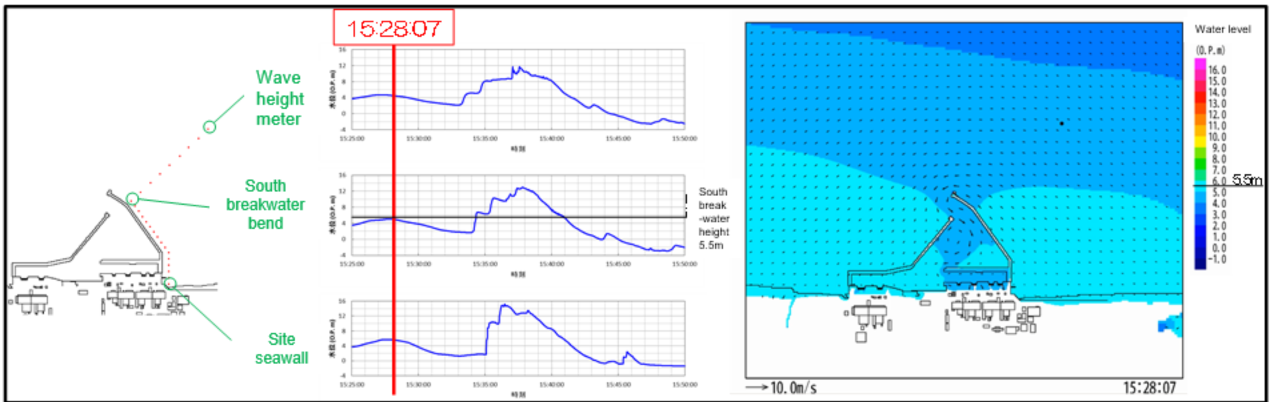
Item	Content
Calculation area	Pacific Ocean from Hokkaido to near Boso, Chiba
Calculation grid spacing	Offshore 4320m→2160m→720m→Coastal area240m →Around the site80m → 40m → 20m → 10m → 5m sequentially subdivided
Calculation time interval	Δt=0.025 seconds
Calculation time	6 hours after earthquake
Basic equation	Goto-Ogawa (1982) method based on nonlinear long wave theory
Calculation scheme	Staggered grids, leap-frog method
Boundary conditions	Off-coast side: free transmission, Land side: consider runup (below 80m grid),
Overflow condition	Breakwater (upper structure, etc.): Homma formula, Seawall: Aida formula
Sea bottom friction coefficient	Manning's roughness coefficient (n=0.03m -1/3s)
Horizontal eddy viscosity coefficient	Not considered
Amount of crustal movement	Method of Mansinha and Smylie (1971) (Wave generation by horizontal displacement is considered. Tanioka and Satake(1996))
Tsunami wave source model	Reproduce wave height meter records and GPS continuous observation records. Tsunami wave source model N04-3 is used.
Initial tidal level	Estimate the tide level of the power station at the time of the tsunami using the tide level records of the power station tide station before the missing measurements* and Onahama tide station tide level records, and consider the difference between the numerical simulation of tsunami and the actual amount of crustal deformation (O.P. +0.6m).
Sand movement by tsunami	Sand movement was considered because of the change in seafloor topography before and after the tsunami.
The overturning of the upper structure of the north breakwater	Because it was observed that the overturning of the north breakwater was observed, two cases with and without overturning were conducted.
Roughness coefficient of runup area	Two cases were conducted: a case set up in the same way as the sea area (0.03) and a case adjusted to the actual topography (mostly pavement/concrete plate) (0.015).

＊Tide meter was damaged by the earthquake

[Appendix 7] Comparison of continuous photographs and numerical simulation of tsunami (time history of water level and water level distribution)

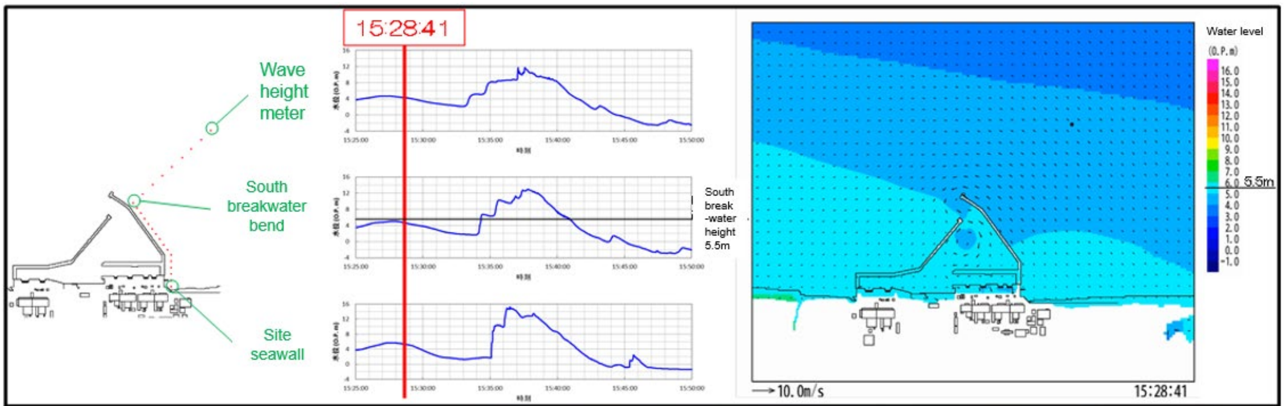
Legend at upper left of photo

Photo No. (Time elapsed since Photo No. 1) Time after correction (time after correction) Time before correction (camera internal time* before correction) *Built-in camera clock time



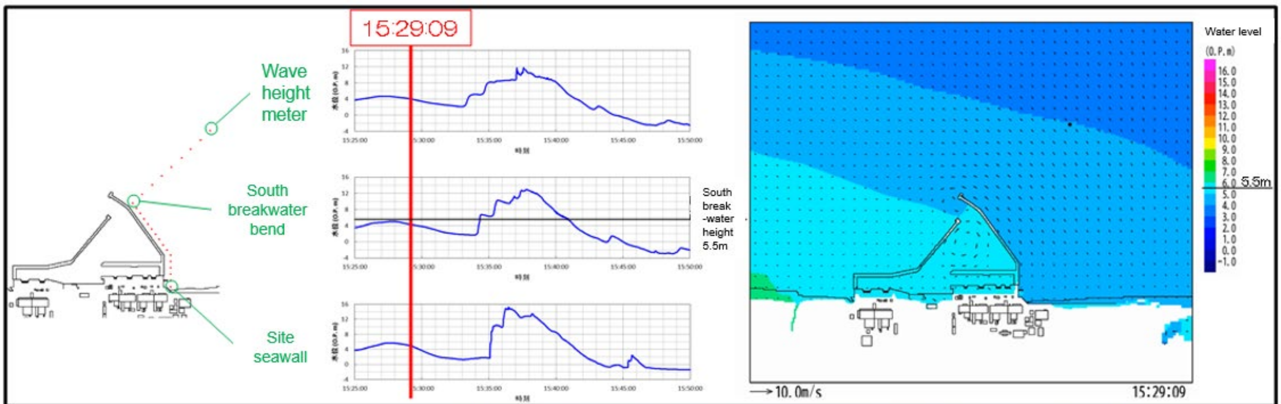
1 (after 00 minutes and 00 seconds)
About 15:28:07 (time after correction)
15:35:16 (camera internal time before correction)

＊Corrected by numerical simulation results



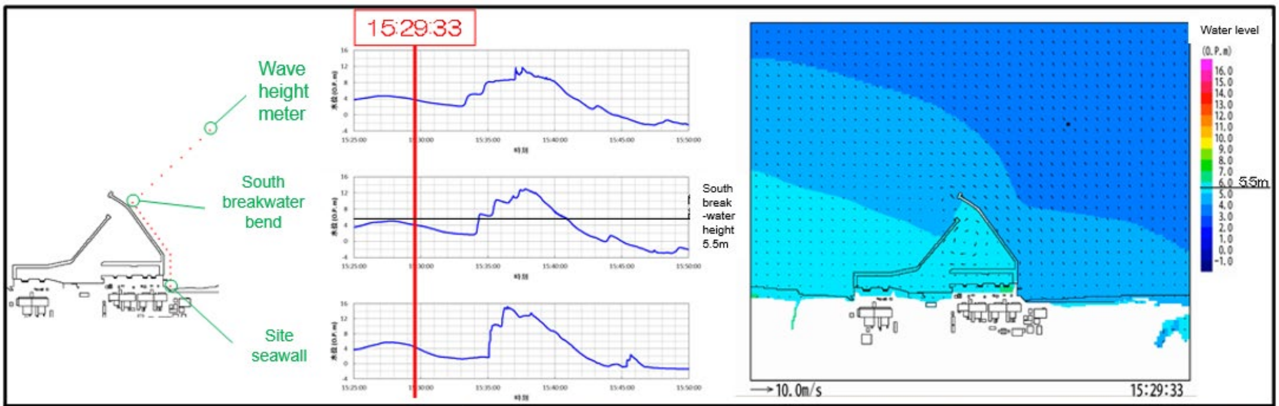
2 (after 00 minutes and 34 seconds)
About 15:28:41 (time after correction)
15:35:50 (camera internal time before correction)

＊Corrected by numerical simulation results



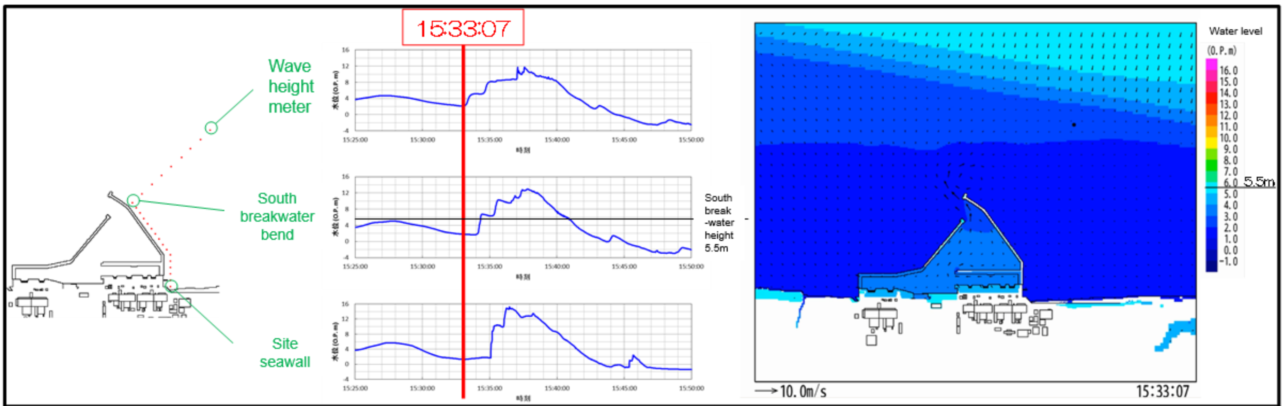
3 (after 01 minutes and 02 seconds)
About 15:29:09 (time after correction)
15:36:18 (camera internal time before correction)

＊Corrected by numerical simulation results



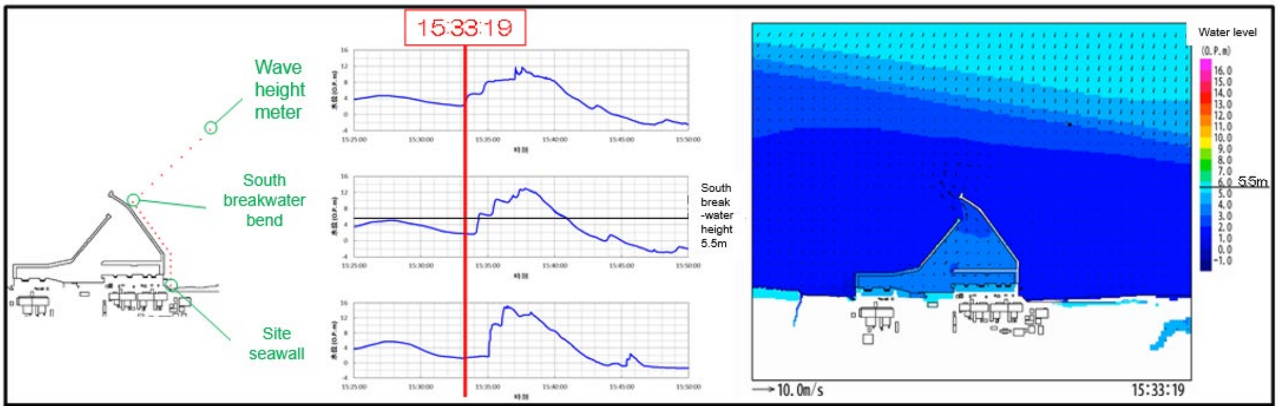
4 (after 01 minutes and 26 seconds)
About 15:29:33 (time after correction)
15:36:42 (camera internal time before correction)

＊Corrected by numerical simulation results



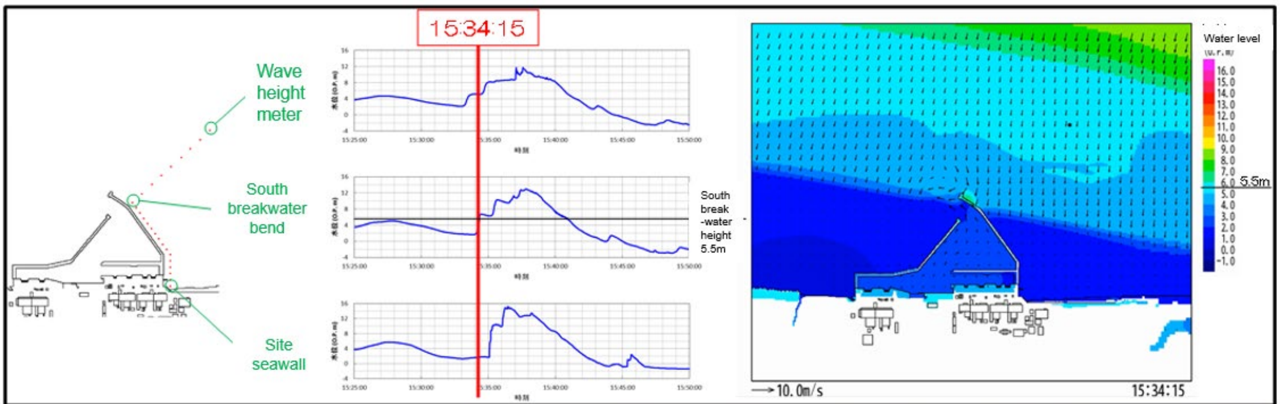
5 (after 05 minutes and 00 seconds)
About 15:33:07 (time after correction)
15:40:16 (camera internal time before correction)

＊Corrected by numerical simulation results



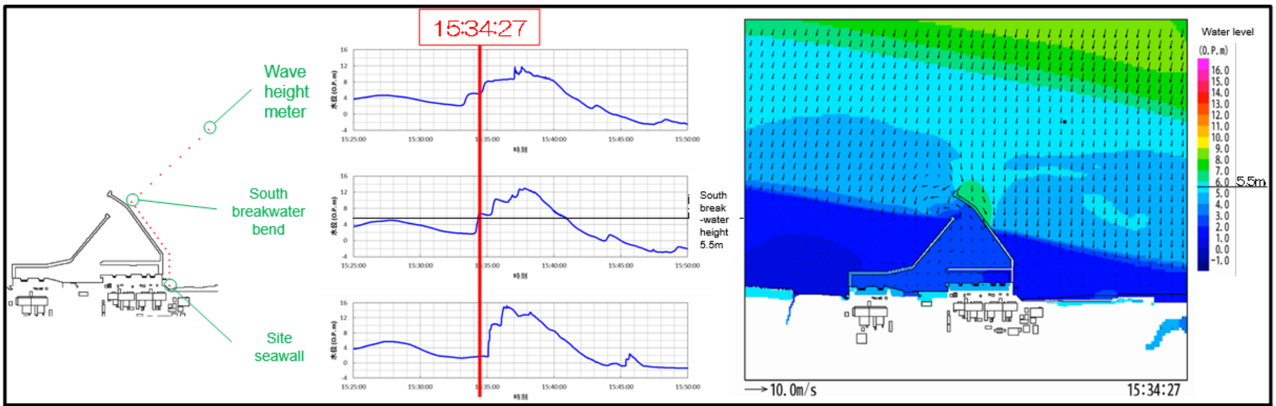
6 (after 05 minutes and 12 seconds)
About 15:33:19 (time after correction)
15:40:28 (camera internal time before correction)

＊Corrected by numerical simulation results



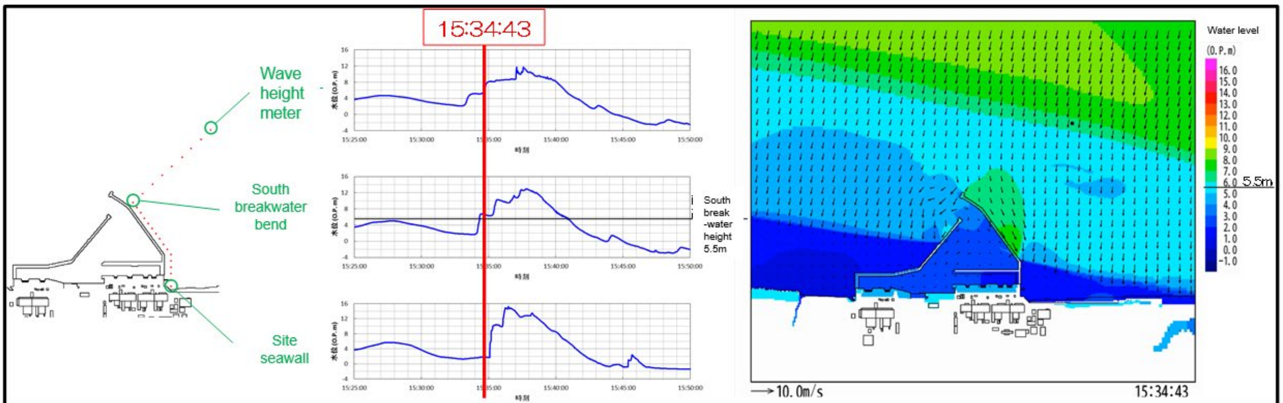
7 (after 06 minutes and 08 seconds)
About 15:34:15 (time after correction)
15:41:24 (camera internal time before correction)

＊Corrected by numerical simulation results



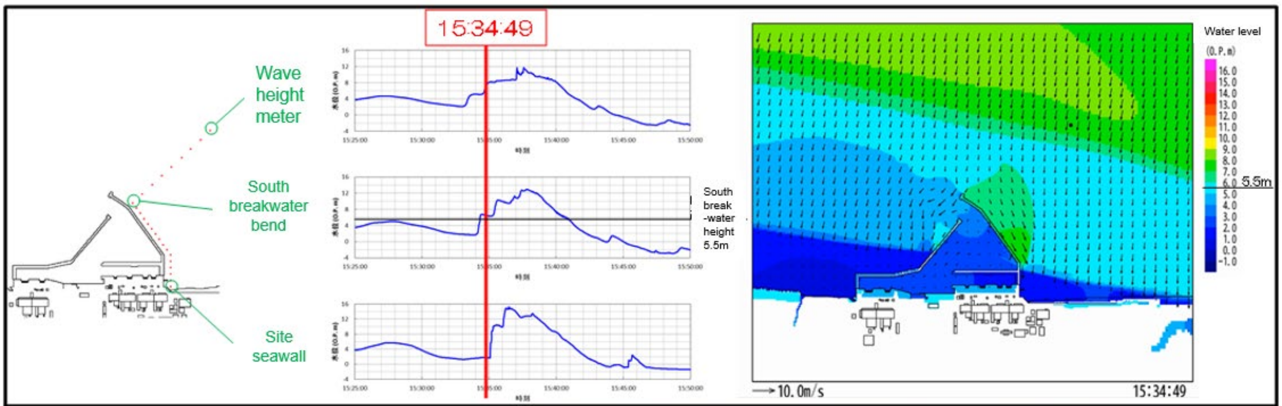
8 (after 06 minutes and 20 seconds)
About 15:34:27 (time after correction)
15:41:36 (camera internal time before correction)

＊Corrected by numerical simulation results



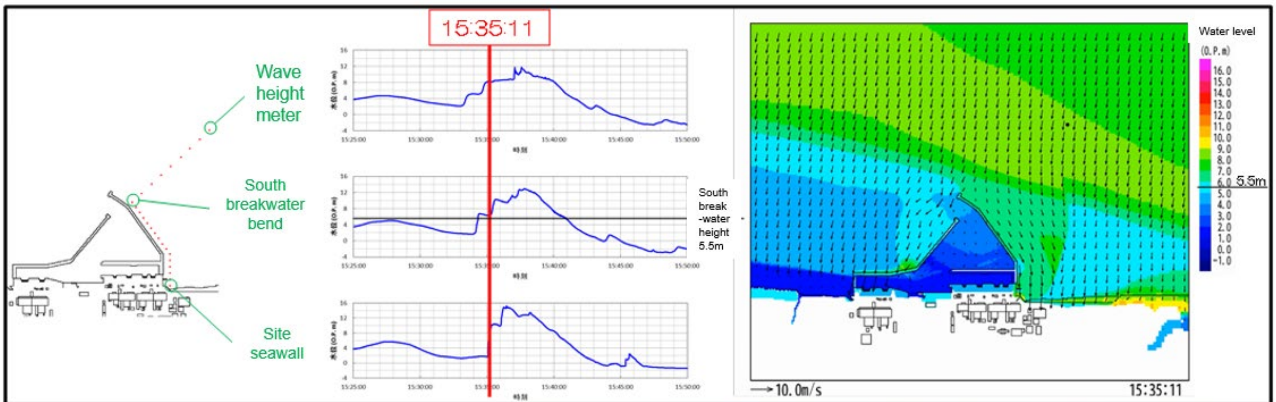
9 (after 06 minutes and 36 seconds)
About 15:34:43 (time after correction)
15:41:52 (camera internal time before correction)

＊Corrected by numerical simulation results



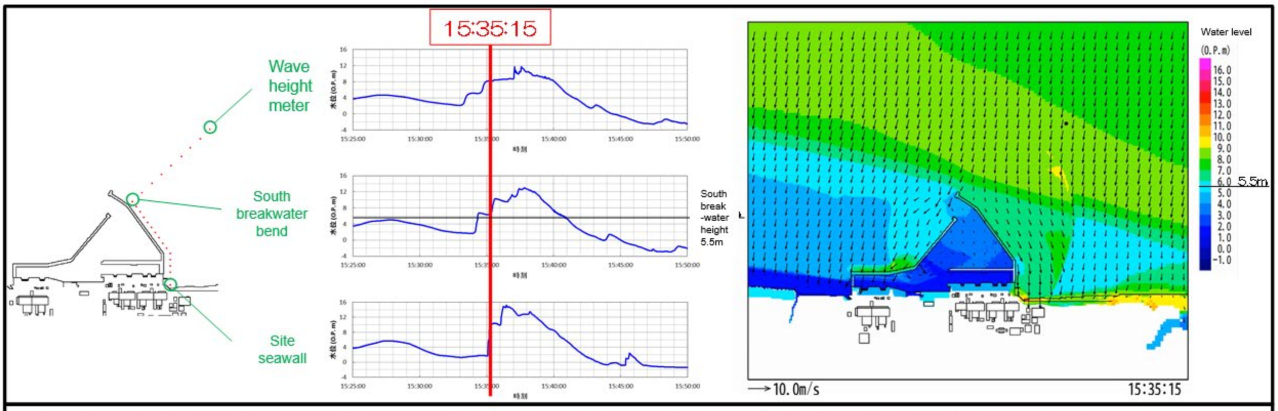
10 (after 06 minutes and 42 seconds)
About 15:34:49 (time after correction)
15:41:58 (camera internal time before correction)

＊Corrected by numerical simulation results



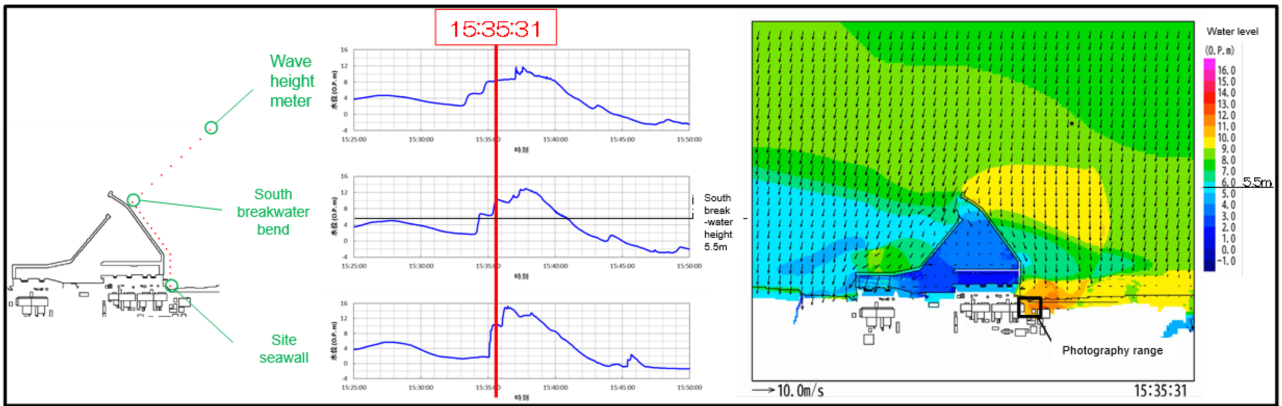
11 (after 07 minutes and 04 seconds)
About 15:35:11 (time after correction)
15:42:20 (camera internal time before correction)

＊Corrected by numerical simulation results



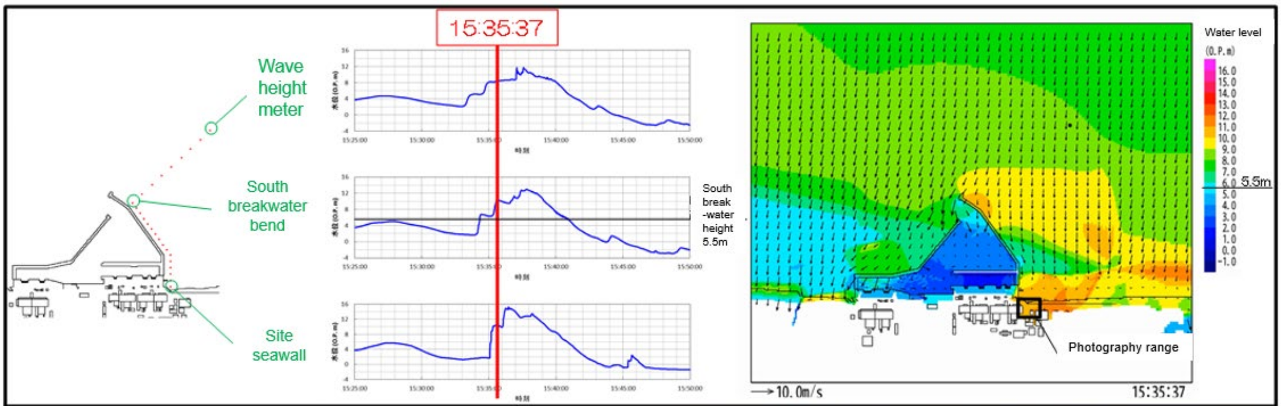
12 (after 07 minutes and 08 seconds)
About 15:35:15 (time after correction)
15:42:24 (camera internal time before correction)

＊Corrected by numerical simulation results



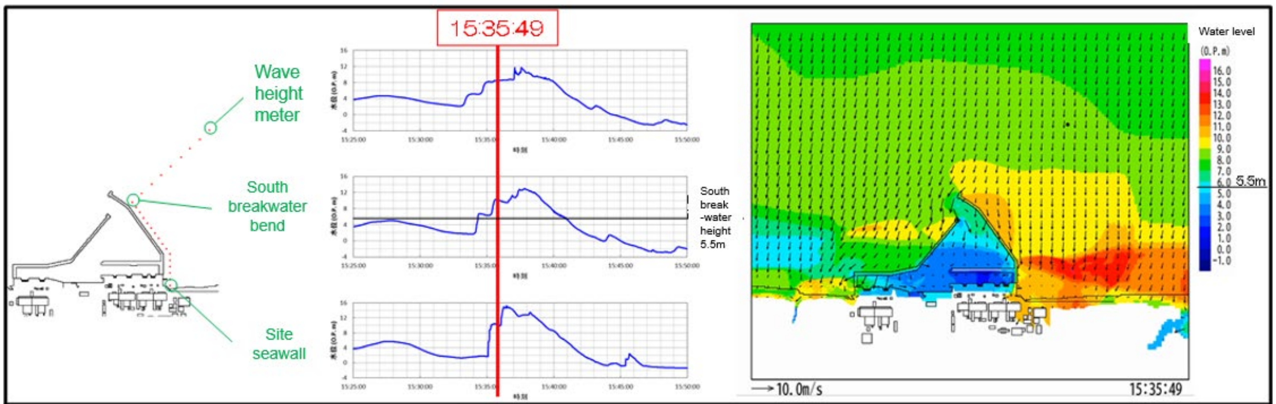
13 (07 minutes and 24 seconds later)
About 15:35:31 (time after correction)
15:42:40 (camera internal time before correction)

＊Corrected by numerical simulation results



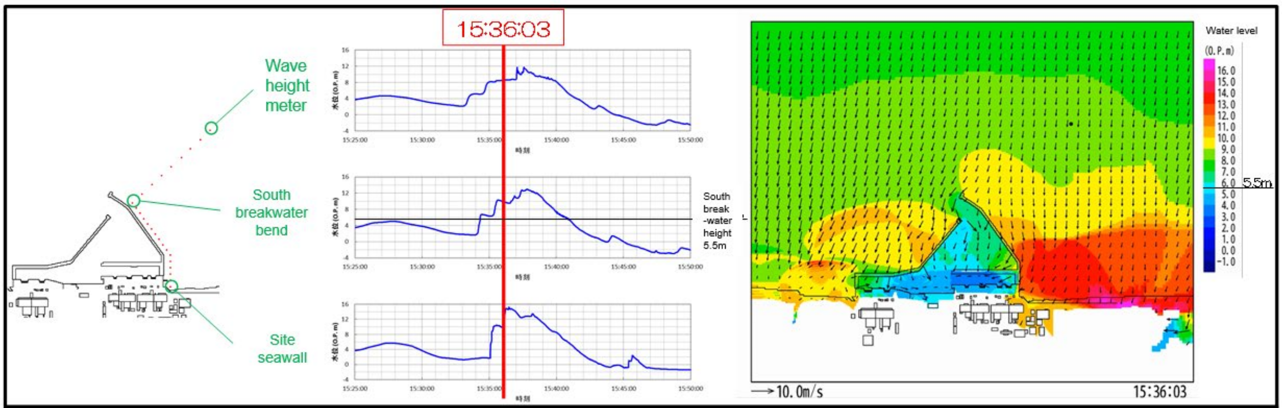
14 (07 minutes and 30 seconds later)
About 15:35:37 (time after correction)
15:42:46 (camera internal time before correction)

＊Corrected by numerical simulation results



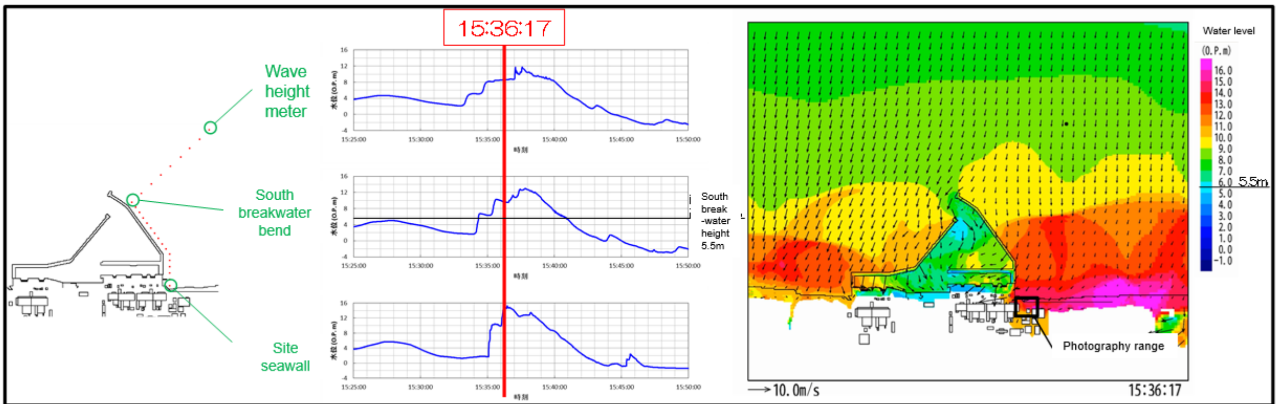
15 (07 minutes and 42 seconds later)
About 15:35:49 (time after correction)
15:42:58 (camera internal time before correction)

＊Corrected by numerical simulation results



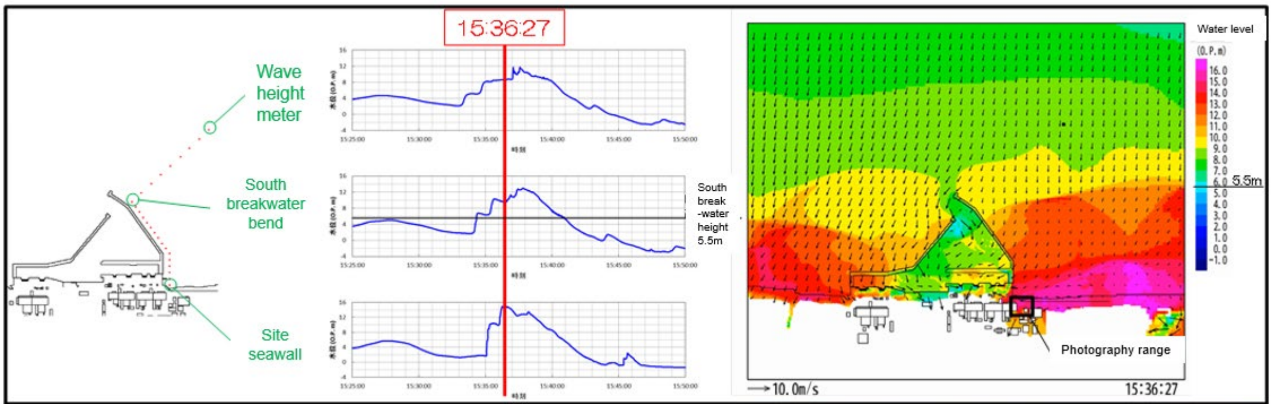
16 (07 minutes and 56 seconds later)
About 15:36:03 (time after correction)
15:43:12 (camera internal time before correction)

＊Corrected by numerical simulation results



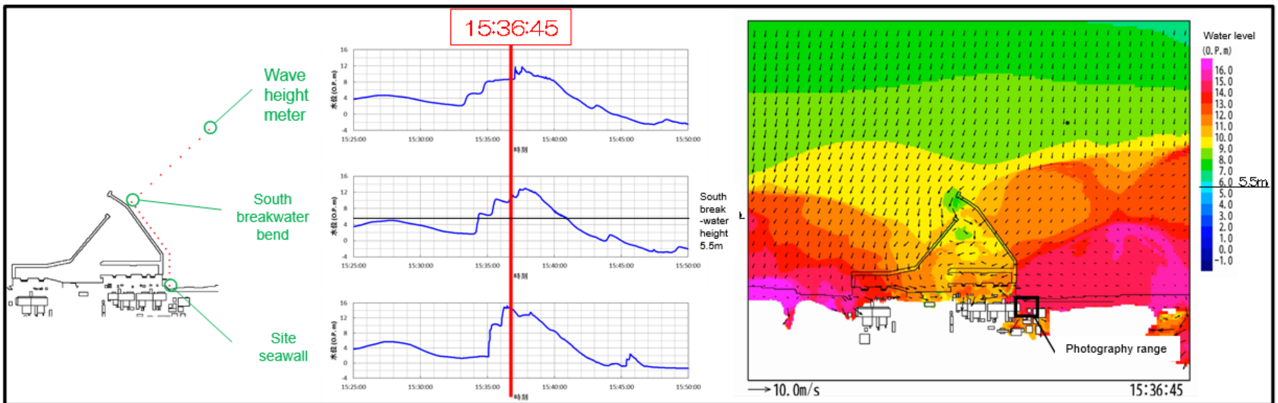
17 (08 minutes and 10 seconds later)
About 15:36:17 (time after correction)
15:43:26 (camera internal time before correction)

＊Corrected by numerical simulation results



18 (08 minutes and 20 seconds later)
About 15:36:27 (time after correction)
15:43:36 (camera internal time before correction)

＊Corrected by numerical simulation results



19 (08 minutes and 38 seconds later)
About 15:36:45 (time after correction)
15:43:54 (camera internal time before correction)

＊Corrected by numerical simulation results

References

1) TEPCO Holding : Regarding the error of the information on the installation location of the wave height meter at Fukushima Daiichi Nuclear Power Station, August 20, 2019, http://www.tepco.co.jp/press/release/2019/1516534_8709.html.

2) T. Annaka, A. Nishi, and T. Kanedo: Tsunami model of the Tohoku region off-coast earthquake reproduced from Fukushima Daiichi Nuclear Power Plant wave height meter records, Proceedings of the Japan Society of Earthquake Engineering, Vol. 20, No. 4, pp. 4_1-4_17, 2020.