# Tsunami evaluation and countermeasures at Onagawa Nuclear Power Plant

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**SUMMARY:**
On March 11 in 2011, all reactors of Onagawa Nuclear Power Plant stopped automatically by the 2011 off the Pacific coast of Tohoku Earthquake (hereinafter referred to as 3.11 Earthquake). A tsunami generated by this earthquake attacked the Power Plant afterwards. By this earthquake and the tsunami, some facilities were damaged, but all reactors are keeping cold shutdown state safely, because important facilities functioned soundly. We have been carrying out the safety measures for the tsunami of the nuclear power plant while reflecting the latest knowledge. As the first, the history of evaluation and the measures for the tsunami about Onagawa Nuclear Power Plant that was able to endure the maximum tsunami in history of Japan is outlined. As the second, findings such as the reproduction analysis of the tsunami caused by 3.11 Earthquake are explained.

*Keywords: nuclear power plant, the 2011 off the Pacific coast of Tohoku Earthquake, tsunami measures, reproduction analysis*

## 1. TSUNAMI EVALUATION AND COUNTERMEASURES AT ONAGAWA NPP

### 1.1. Process of the Tsunami Evaluation and Countermeasures at Onagawa NPP

We have been carrying out the safety evaluation and measures for the tsunami of the nuclear power plant while reflecting the latest knowledge in us. The process of tsunami evaluations and measures are summarized in Table 1. Onagawa unit 1 (BWR, 524MW) is our first nuclear power plant (location; see Fig. 1). Then we performed the evaluation by documents investigation (numerical computation technology of the tsunami was not established in those days). On the other hand, we established an internal committee and took into account experts' opinions about the tsunami. While we planned Onagawa unit 2 (BWR, 825MW), we carried out a trace investigation of the AD869 Jogan tsunami that a quantitative evaluation had not been done formerly, and we carried out numerical simulation of tsunami. In planning Onagawa unit 3 (BWR, 825MW), we carried out numerical simulation like the unit 2. In 2002, we performed an in-house study on the virtual tsunami according to the method proposed by the Japan Society of Civil Engineers (JSCE). At that time, we estimated it as 13.6m, and in March 2011, the maximum tsunami height of approximately 13.0m was recorded at the site.

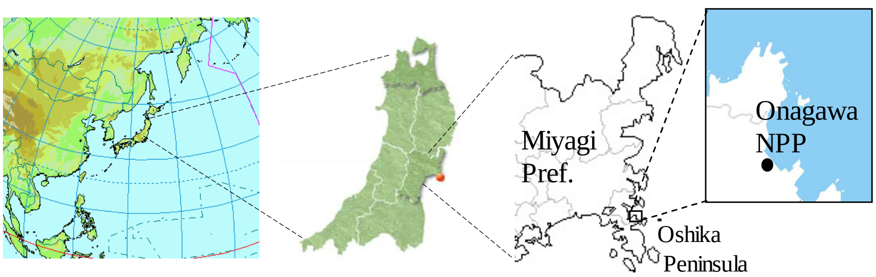



**Figure 1.**Location of the Onagawa NPP

**Table 1.**Outlines of Tsunami Evaluation and Countermeasures at Onagawa NPP

| | Contents | Outlines | Tsunami height*1 | Measures | Notes |
|---|---|---|---|---|---|
| 1970.5<br><br>(1984.6) | Unit1<br>Installation License Application<br><br>(Commercial Operation started) | 1. Literature search & Interview survey<br>2. Tsunami measures were argued by a internal committee by specialists. (1968～1980) | About 3m<br>— | -The site height (O.P.+14.8m)<br>-Layout of structures(O.P.+15.0m)<br>-Tide gauge | Literature search & Interview survey |
| 1987.4<br><br>(1995.7) | Unit2 I.L.A.<br><br>(C. O. started) | 1. Vestigial investigation of Jogan Tsunami(A.D.869) in Sendai Plain<br>2. Numerical simulation of tsunamis | O.P.+9.1m | -Slope protection (O.P.+9.7m) | Evaluation by the reproduction calculation of the biggest historical tsunami |
| 1994.5<br>(2002.1) | Unit3 I.L.A.<br>(C. O. started) | 1. Numerical simulation of tsunamis | O.P.+9.1m | | |
| 2002.2 | Tsunami evaluation technique (JSCE) | 1. Numerical simulation based on evaluation technique by Japan Society of Civil Engineers. | O.P.+13.6m | - Tsunami height is below the site height. | Estimation by the virtual tsunami considering indeterminacy |
| 2006.9 | Revision of the Regulatory Guide *2 | 1. Tsunami evaluation compared with a new guideline is being carried out based on directions from the government (Sep. 20th , 2006). | Now under evaluation | — | |
| 2010.3 | Tide gauge for backup | 1. A tide gauge was added for prevention of data missing. | — | -Tide gauge for backup | — |
| 2011.3 | The 2011 off the Pacific coast of Tohoku Earthquake | 1. Reproduction analysis of the tsunami which attacked Onagawa N.P.S. | O.P.+13m (Tide gauge) | Relocation of devices to a high place (Underway) | — |

*1 : O.P. is Onagawa N.P.S. datum plane for construction, and is the height of the−0.74m from standard mean sea level of Tokyo Bay (T.P.)
*2 : Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities (The Nuclear Safety Commission of Japan (NSC))

## 1.2. Tsunami Evaluation for the Onagawa Unit 1

### *1.2.1. Documents investigation and inquiry investigation*

To obtain the information about tsunami for the Onagawa unit 1, we extracted the big tsunami of the scale in the Sanriku coast around the site by documents investigation. In addition, we carried out an inquiry investigation at Koyadori beach. From these results, we estimated the tsunami height at the site as "around 3m".

### *1.2.2. Argument by the committee in the company*

The Onagawa unit 1 was the first among us as construction of the exclusive harbours as nuclear power plant. In addition, about the site level, we had thought around 15m to be most suitable by the comparative study, but we thought that expertise was necessary about the safety for the tsunami, and we installed "Research Committee of seashore facilities". Nine experts on civil engineering, geophysics, etc. participated in the committee. Masashi Honma, the professor emeritus at Tokyo University and the professor at Toyo University became a chairperson. The period was from July, 1968 to August, 1980. The experts argued about the past tsunami records and the latest thesis on tsunami. They said, "The tsunami height may become higher, if an earthquake occurs in southern area, such as AD 869 Jogan earthquake tsunami or AD 1611 Keicho earthquake tsunami, rather than AD 1896 Meiji Sanriku tsunami or AD 1933 Showa Sanriku tsunami." After the arguments, finally, they gathered the opinion "As a countermeasure to the tsunami, making the ground level higher will be effective, and as for the Onagawa NPP, around 15m is enough." Considering the above experts' opinions, we decided the site level (14.8m), and the level of the first floor of main buildings and the outdoor important structures (15.0m).

## 1.3. Tsunami Evaluation after the Onagawa Unit 1

By the 1980s when we planned the Onagawa unit 2, a numerical simulation method of the tsunami was already established by Aida (1977), and the tsunami wave source model of Keicho tsunami (AD 1611) and Showa Sanriku tsunami (AD 1933) etc. On the other hand, about the technique of the tsunami trace investigation, it was the time when new method was developed. To plan the Onagawa unit 2, reflecting new knowledge, we carried out a tsunami trace investigation and numerical simulation.

*1.3.1. Trace investigation into tsunami of AD869 Jogan tsunami*

About the tsunami took place in AD 869 (11th year of the Jogan Era), only one ancient document contains a record, and it was said to be very difficult to grasp the tsunami height quantitatively. However, late Ito honorary professor of Tohoku University suggested a method to confirm the trace of the tsunami by views of the remains investigation. On the other hand, Professor Minoura of Tohoku University had proposed a method to investigate tsunami trace by analysis of the sediment. To plan the Onagawa unit 2, our employees carried out the trace investigation into Jogan tsunami.

As a result of the investigation in the Sendai Plain, trace of Jogan tsunami (in general plains apart from the river) was estimated as 2.5 to 3m high, and the inundated area was around 3km from the shoreline. And the Jogan tsunami flooded across the bank lines of the beach widely and was estimated that it had a long period (Abe et al. (1990)). By comparison of the tsunami trace of Jogan tsunami and Keicho tsunami (6-8m at Iwanuma in Sendai plains according to Hatori (1975)), it was estimated that Keicho tsunami was bigger than Jogan tsunami at the Onagawa site.

*1.3.2. Application of the numerical value simulation technology*

We carried out numerical simulation of Keicho tsunami for the Onagawa unit 2, and evaluated the tsunami height as 9.1m. In order to check the validity of simulation, we carried out the simulation of Showa Sanriku tsunami (AD 1933), too. For the unit 3, we carried out tsunami simulation similar to the unit 2, and evaluated the tsunami height as 9.1m.

### 1.4. Tsunami Evaluation by the JSCE Method

In 2002, "Tsunami Assessment Method for Nuclear Power Plants in Japan" was published by Japan Society of Civil Engineers (JSCE). The evaluation flow of JSCE’s method is shown in Fig. 2. The left half shows the flow of reproducibility confirmation of the tsunami in the past, the right half shows the examination of the design tsunami caused by the assumption tsunami, and parameter study to consider a calculation error and uncertainness was introduced newly. We set standard fault model of Mw8.3 and Mw8.6 along the Japan Trench, and carried out parametric study by this method, we evaluated the tsunami height as 13.6m.

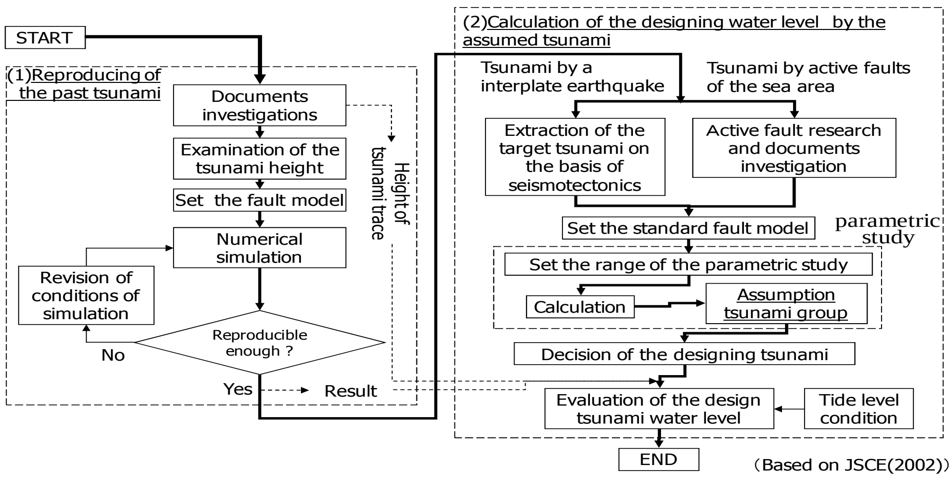
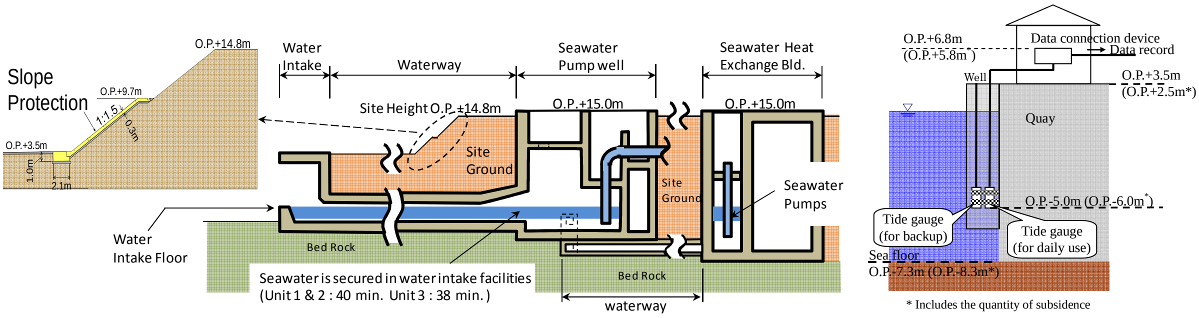



**Figure 2.**Tsunami evaluation flow proposed by JSCE

### 1.5. Tsunami Countermeasures

Since the planning of the unit 1, we designed the site height to be safe from a rise in water level due to a tsunami (O.P. +14.8m) (cf. *1.2.2.*). Besides, we installed the important seawater pumps in Seawater Pump Well (unit 1 & 2) or Seawater Heat Exchange Building (unit 3) built in the ground level of +14.8m. On the other hand, as measures against the dilatational waves caused by a tsunami, enough seawater is secured in waterways. In addition, we installed a slope protection (see Fig. 3(a))). A tide gauge for daily use had been installed during the construction of unit 1, but we installed a back-up tide gauge in March, 2010 (see Fig. 3(b)), and fortunately, it was possible to utilize the observation record of the new tide gauge for reproduction analysis (cf. 2.3) of the tsunami caused by 3.11 Earthquake.




(a) Site height, placement of the structure (example of unit 3) (b) Tide gauges

**Figure 3.**Tsunami measures at Onagawa NPP

## 2. FINDINGS OF THE TSUNAMI CAUSED BY THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

About the situation that the tsunami caused by 3.11 Earthquake attacked in Onagawa NPP, our investigation flow is shown in Fig. 4.

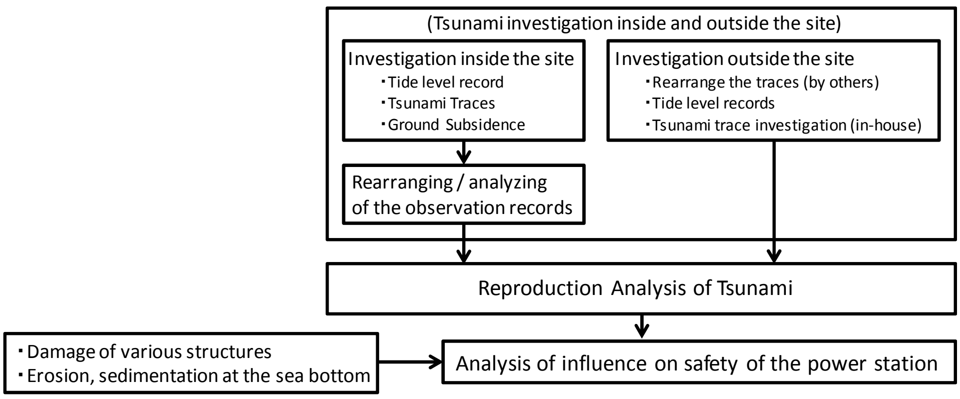



**Figure 4.**Investigation flow of the tsunami caused by 3.11 Earthquake

### 2.1. Collection of Data about the Tsunami Caused by 3.11 Earthquake

We collected ground change data, tsunami traces, tide level observation records, inundation area (see Table 2). Of these, tsunami traces and the inundation area at the site are shown in Fig. 5, and the observation record by the tide gauge at the site is shown in Fig. 6.

**Table 2.**The list of collected data

| Items | | Tohoku-EPCO's data | Others' data |
|---|---|---|---|
| 1 | Ground changing | ･Land area : GPS control point surveying | ･Land area : Data of Ministry of Land, Infrastructure and Transport (MLIT)<br>･Sea area : Data of Japan Coast Guard |
| 2 | Tsunami traces | ･Onagawa NPP site (11 points)<br>･Onagawa Town ～ Ishinomaki City (22 points) | ･Data of The 2011 Tohoku Earthquake Tsunami Joint Survey Group (2,635 points) |
| 3 | Tide level records | ･A tide level record by the back-up tide gauge in the exclusive harbor | ･Data of The Meteorological Agency, Geographical Survey Institute, Ports and Harbours Bureau etc.<br>･Data of Fukushima Daiichi, Tokai Daini (45records) |
| 4 | Inundation area | ･Inundation area data of the Onagawa NPP site | ･Data of Geographical Survey Institute<br>･Data of Fukushima Pref. (by TEPCO), Ibaraki Pref. (by JAPC) |

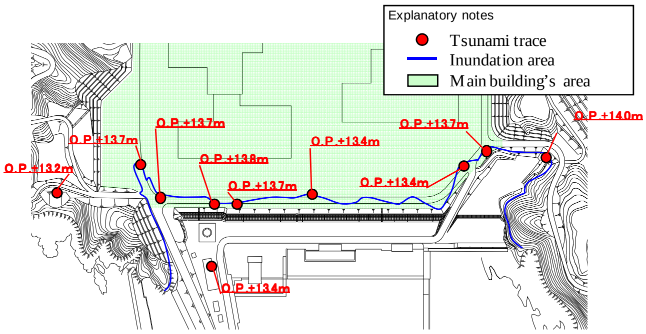



**Figure 5.**Tsunami traces & Inundation area (at Onagawa NPP)

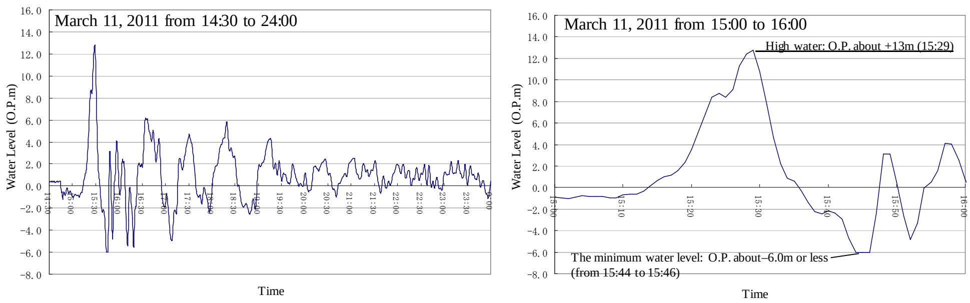



**Figure 6.**Observation record by the tide gauge (at Onagawa NPP)

## 2.2. Reproduction Analysis Model

*2.2.1. Setting and numerical simulation of the reproduction analysis model*

We used a heterogeneous model (96-piece, 40-piece models) by Fujii and Satake (2011) to make our reproduction analysis model. We carried out numerical simulation for each model and examined consistency with the observation record and ground change at the site (see Fig. 7). The calculation conditions are shown in Table 3.

Comparison between calculated wave patterns (96-piece, 40-piece model) and observed wave pattern at the position of the tide gauge of the power station are shown in Fig. 8. As for the Onagawa NPP site, we considered that 40-piece model is more consistent with the observation wave pattern than 96-piece model, mainly from the viewpoint of the phase. Based on 40-piece models of Fujii and Satake (2011), we devised the tsunami wave source model which could reproduce the observed wave, quantity of ground change, and the tsunami traces by adjusting quantity of sliding (see Fig. 9).

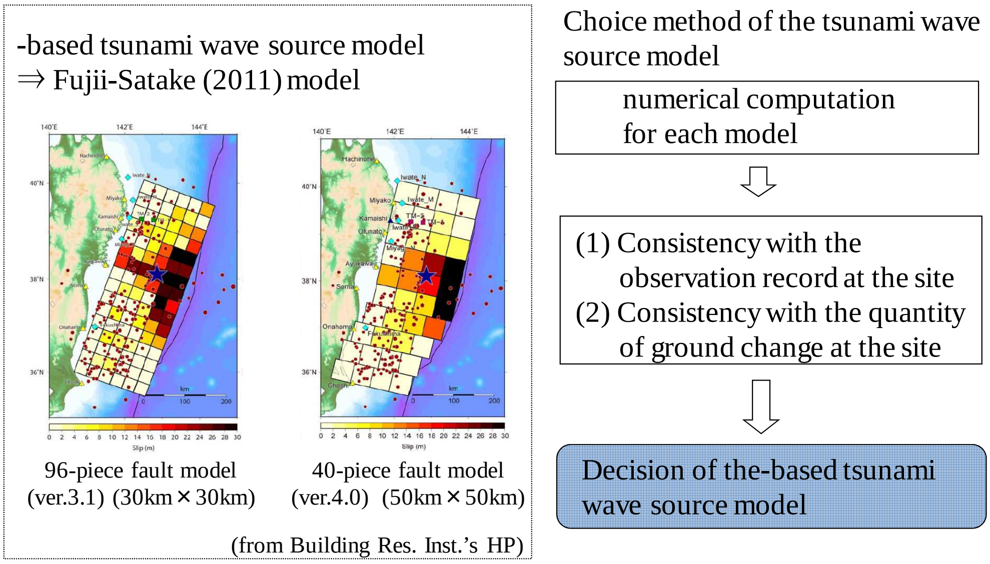



**Figure 7.**Examination flow of the tsunami wave source model for reproduction analysis

**Table 3.**Calculation Condition for the Numerical Simulation

| Item \ Area | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|
| Space Lattice Interval ($\Delta s$) | 2.5 km | 833 m (2500/3) | 278 m (2500/9) | 93 m (2500/27) | 31 m (2500/81) | 10.3 m (2500/243) | 5.1 m (2500/486) |
| Time Lattice Interval ($\Delta t$) | 0.1 sec. (by calculation stability criteria) | | | | | | |
| Basic Equation | Linear long wave | Non-Linear long wave | | | | | |
| Offing side boundary condition | Free transmission | Connect water level, flow quantity to outside larger lattice domain | | | | | |
| Landside boundary condition | Complete reflection | Complete reflection (Consider sea ground exposure) | Run-up boundary condition by Kotani et al. (1998) | | | | |
| Initial fluctuations of sea level | Apply calculated vertical displacement by a method of Mansinha and Smylie(1971) on the sea surface in 1 min. in a rise time | | | | | | |
| Sea Bottom friction | not considered | Roughness coefficient by Manning ($n = 0.03 m^{-1/3}/s$) | | | | | |
| Initial tide level condition | T.P.−0.4 m | | | | | | |
| Calculation time | 3 hours after the earthquake occurrence | | | | | | |

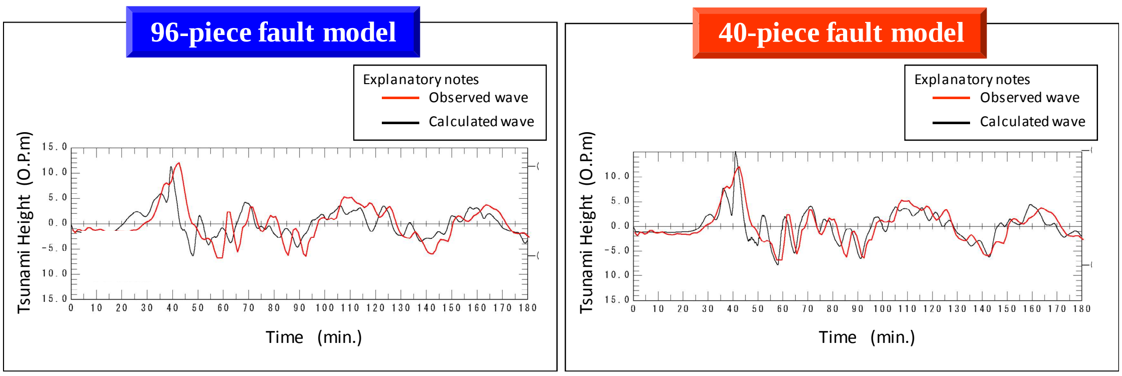
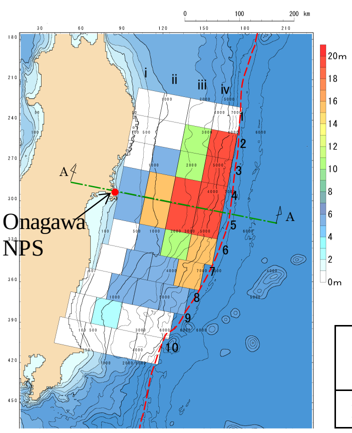
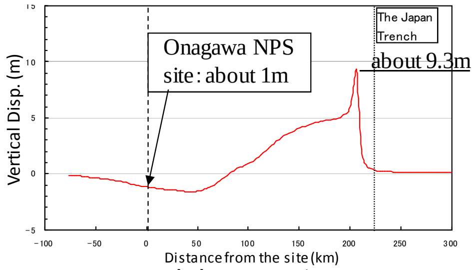



**Figure 8.**Comparison of the observation wave and the calculation wave




Sliding Quantity (m)

| | i | ii | iii | iv |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 10 | 20 |
| 3 | 0 | 5 | 10 | 20 |
| 4 | 5 | 15 | 20 | 20 |
| 5 | 5 | 15 | 20 | 20 |
| 6 | 0 | 5 | 10 | 15 |
| 7 | 0 | 5 | 5 | 15 |
| 8 | 0 | 5 | 5 | 5 |
| 9 | 0 | 2 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 |



A-A cross section

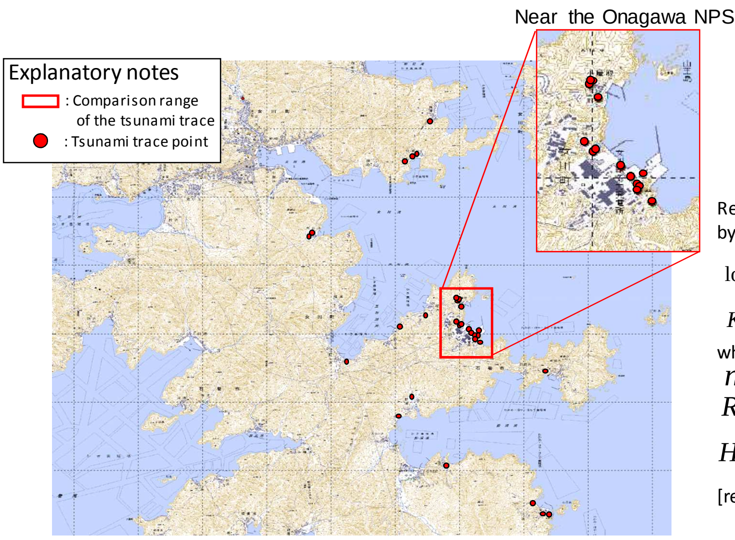
Specifications of the wave source model

| Strike | Angle of inclination | superior border depth | Quantity of sliding (Max.) | Moment magnitude Mw |
|---|---|---|---|---|
| 193° | 14 ° | 3km | 20m | 8.94 |

**Figure 9.**Devised tsunami wave source model

*2.2.2. Validity confirmation of the reproduction analysis model*

We confirmed the validity of the reproduction analysis model comparing to the observed data (tsunami traces, the inundation area, tide level records, quantity of ground change). About the tsunami trace, good plasticity was provided in the power station neighbourhood (see Fig. 10 and Fig. 11). About the plasticity of the inundation area in the site and outside around the site, we could reproduce almost well. About the plasticity of the observation record of the tide gauge, we could reproduce phase and high water almost well (see Fig. 12). About the quantity of ground change, we confirmed that simulation result was congruent with the observed data.




Comparison range of the tsunami trace (power station neighborhood)

Reproducibility confirmation result

| K | κ | n |
|---|---|---|
| 1.00 | 1.04 | 14 |

Reproducibility evaluation index (K,κ) by Aida (1977)

$$\log K = \frac{1}{n}\sum_{i=1}^{n}\log K_i \ , \quad \log\kappa = \left[\frac{1}{n}\left\{\sum_{i=1}^{n}(\log K_i)^2 - n(\log K)^2\right\}\right]^{1/2}$$

$$K_i = R_i / H_i$$

where,

$n$ : Number of tsunami trace points,

$R_i$ : Observation level at the number $i$ point (the level of trace),

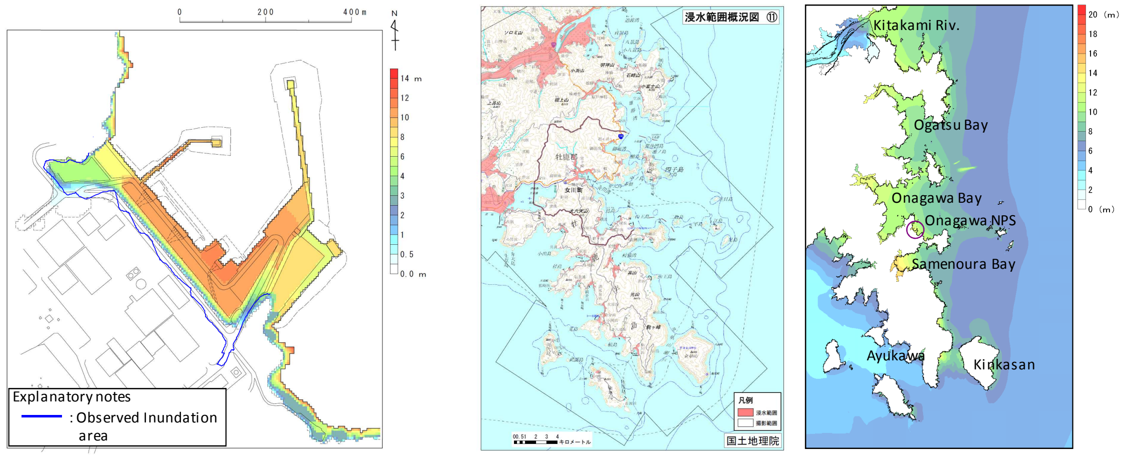
$H_i$ : Numerical simulation result at the number $i$ point

[reproducibility aim by JSCE(2002)*]

0.95<K<1.05 , κ<1.45

* Tsunami Assessment Method for Nuclear Power Plants in Japan (Japan Society of Civil Engineers)

**Figure 10.**Reproducibility of the tsunami traces




Comparison of inundation area between observed data and calculation result

Inundation area by Geographical Survey Institute

High water distribution map by the reproduction analysis

**Figure 11.**Reproducibility of the inundation area

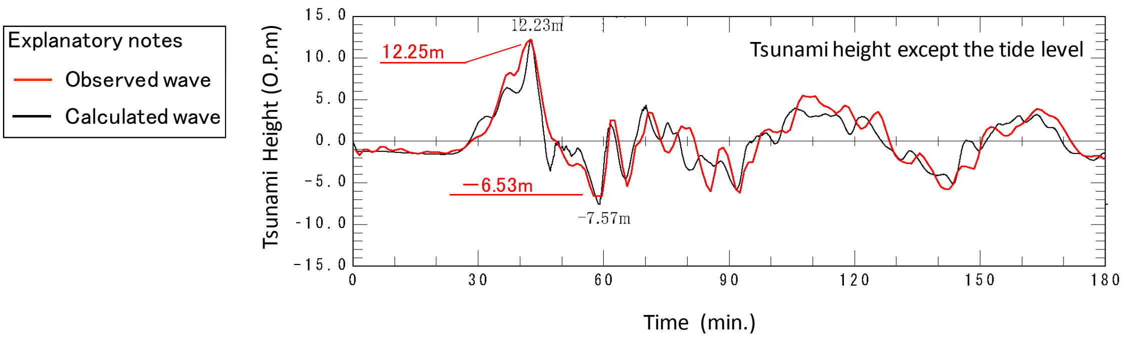



**Figure 12.**Reproducibility of the tide gauge record

## 2.3. Influence on Safety of the Power Plant

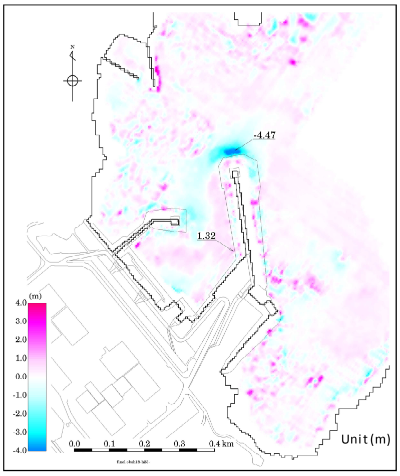
### *2.3.1. Influence on power plant by the tsunami*

The tsunami did not arrive at the safety-related facilities as shown in Fig. 5. In addition, as a result of reproduction analysis, it was estimated that water level decreased below intakes for several minutes by the dilatational wave of the tsunami, but enough quantity of seawater was secured in the water intake facilities (cf. 1.5), and there was no influence on important seawater pumps. On the other hand, via the waterway of the unit 2, the third floor under the ground of R/B (non-controlled area) was partially inundated, but we could avoid severe damage. In addition, some slight damages caused by the tsunami were observed.

### *2.3.2. Sand Movement Situation*

Sedimentation and the erosion situation of the sand in the site front sea area before and after the tsunami by the bathymetric survey are shown in Fig. 13. Erosion of up to around 5.5m and sedimentation of 0.5m - 0.6m were observed, but seawater intakes were not blocked up by the sand, and we confirmed that that there was no influence on water intake facilities.

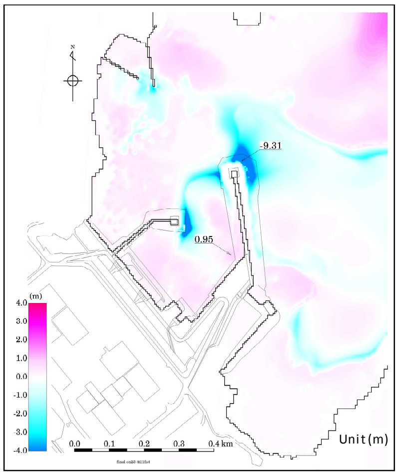
About the sand movement, using analysis model (Takahashi et al. (1999)), we carried out numerical simulation. We calculated under the condition of 1%, and 5% of upper limit floating sand density. As a result, the case of 1% density was almost equivalent to the actual survey result. In the analysis, erosion of up to 9.3m near the end of the east breakwater, and it is much more than the observed data. However, we considered that the shape of the erosion domain that affected from the east breakwater tip north breakwater was expressed well.




As for the seafloor topography after the tsunami , approx. 1m of the subsidence caused by the earthquake is included.

| | Surveying date | Surveying interval |
|---|---|---|
| Before 3.11 | Oct. 26-28, 2010 | 10～20m |
| After 3.11 | Apr. 27–May.10, 2011 | 10～20m |

Comparison of sedimentation & erosion, before & after the 2011.3.11 tsunami



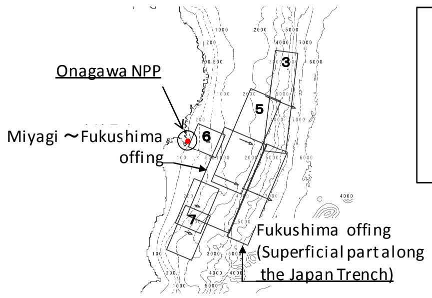

(Calculation model : Takahashi et al. (1999))

Numerical simulation result of the sand movement

**Figure 13.**Bathymetric survey result and the sand movement analysis result

## 3. STUDY ON THE QUANTITY OF SLIDING OF THE TSUNAMI CAUSED BY 3.11 EARTHQUAKE

In reference to distribution of the quantity of sliding of the out reproduction analysis model (see Fig. 9), we built up a model consist with existing tsunami source models (rectangular and uniform sliding fault models, see Fig. 14). In this study, we regulated quantity of sliding of the tsunami source models in consideration of increase of the quantity of sliding with the interlocking movement of the earthquake segments in 3.11 Earthquake. We confirmed that the wave pattern observed at the site and tsunami traces observed around the site could be reproduced well when we made the quantity of sliding 1.5 times as big as the original value uniformly. This may show that quantity of sliding became big with each tsunami linking. Therefore, we think when we examine an interlocking movement by existing tsunami models (rectangular and uniform sliding fault model), it is appropriate to increase quantity of the sliding to 1.5 times uniformly.

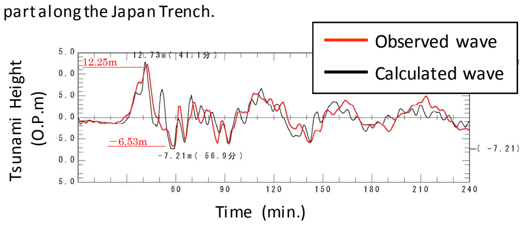



・Domain 3 : Revised AD 1896 Meiji Sanriku Tsunami JSCE(2002) model
・Domain 5 : AD1793 Tsunami JSCE(2002) model
・Domain 6 : Expanded AD1978 Tsunami JSCE(2002) model
・Domain 7 : AD1938 Tsunami (Sato et al.(1989) Shioyazaki-Oki Ⅱ, Ⅲ)
・Miyagi～Fukushima offing : AD869 Jogan Tsunami (Satake et al.(2008) model 10)
・Fukushima offing : AD 1896 Meiji Sanriku Tsunami *

*Any tsunami had not been confirmed in this area before 3.11, we assumed AD1896 Meiji Sanriku Tsunami in superficial part along the Japan Trench.

Reproducibility confirmation of tsunami traces

| | Near the site (n=14) | | Around the site (n=123) | |
|---|---|---|---|---|
| | K | κ | K | κ |
| Calculation result by the model mentioned above | 0.97 | 1.03 | 0.97 | 1.21 |
| (reference) reproduction analysis model | 1.00 | 1.04 | 1.15 | 1.24 |




Reproducibility confirmation of the observation wave

**Figure 14.**Comparison between existing tsunami models and the reproduction analysis model

## 4. CONCLUDING REMARKS

Since the Onagawa unit 1, reflecting the latest knowledge about tsunami, we have been evaluating the tsunami effects on the power plant. And we have been taking safety measures against the tsunami in various ways. By such past actions, we were able to evade heavy damage by the tsunami on March 11 in 2011. By our investigation into the tsunami caused by 3.11 Earthquake including the reproduction analysis, we acquired the knowledge about situation of the tsunami.
We consider that we have to improve the safety of the nuclear power plant continually, reflecting the lessons and the knowledge obtained from the 3.11 Earthquake.

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