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Division V

SEISMIC RESPONSE ANALYSIS OF THE REACTOR BUILDING AT THE ONAGAWA NUCLEAR POWER PLANT UNIT 2 USING OBSERVATION RECORDS OF THE EARTHQUAKE OFFSHORE FUKUSHIMA PREFECTURE ON MARCH 16, 2022

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ABSTRACT

The seismic design after the 2011 Tohoku earthquake of the Onagawa Reactor Building UNIT No.2 is characterized by the use of a seismic response analysis model that takes into account the reduction in initial stiffness of the RC seismic walls, based on the effects of the 2011 Tohoku earthquake, etc.

In the earthquake off the coast of Fukushima Prefecture that occurred on March 16, 2022, the observed value on the mat slab of the reactor building exceeded 300Gal, which was the level at which the reactor automatically shut down. It was the largest seismic motion since the 2011 Tohoku earthquake and the April 7, 2011 earthquake off Miyagi Prefecture, which is the largest aftershock of the 2011 Tohoku earthquake.

Therefore, we analysed the seismic observation records installed in the Reactor Building UNIT No.2, and evaluate the change in the average stiffness of the entire building based on the analysis of the predominant frequency of the building before and after the 2022 Fukushima earthquake. We confirmed that the first natural frequency of the building calculated from the earthquake observation records were at the same level as those of the 2011 Tohoku earthquake.

Next, we conducted a simulation analysis using the observation records of the 2022 Fukushima earthquake and compare the analysis results with the earthquake observation records to verify the validity of using a seismic response analysis model that takes initial stiffness reduction into account for seismic design after the 2011 Tohoku earthquake. The analytical results generally reproduced the amplitude of the observation records and the period of the response spectrum, confirming the validity of the seismic design.

Finally, we confirmed that the shear stress of seismic share wall of the building to be lower than short-term allowable stress of a reinforcing bar, and that the integrity of the building against the 2022 Fukushima earthquake is sufficiently secured.

1. OUTLINE ABOUT THE 2022 FUKUSHIMA EARTHQUAKE

The following is the outline about the 2022 Fukushima earthquake. The earthquake specifications and maximum acceleration in each area are based on the Japan Meteorological Agency (JMA) (2023) and the National Research Institute for Earth Science and Disaster Resilience (NIED) (2023).

- Local date: 16 March 2022
- Local time: 23:36 JST
- Region name: Off Fukushima Prefecture
- Earthquake Characteristics
  M_{jma}: 7.4
  Epicenter: 37.6967°N, 141.6217°E
  Depth: 57km
- Type: intraplate earthquake
- Distance from Onagawa NPP
  Epicentral distance: 78km
  Hypocentral distance: 98km

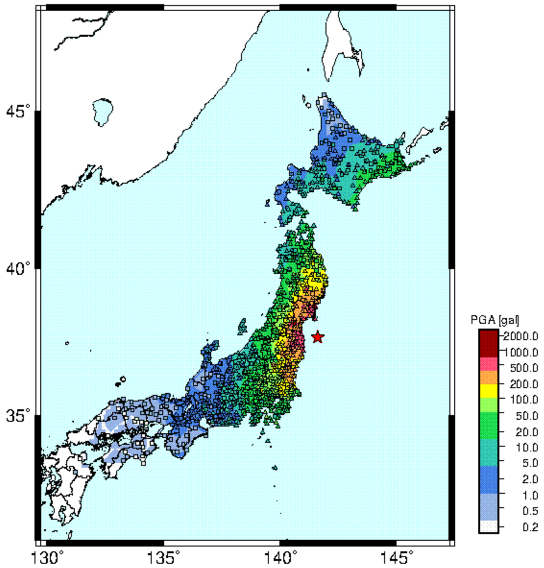


Figure 1. Maximum ground motion acceleration distribution

2. TREND ANALYSIS OF THE PREDOMINANT FREQUENCY DECREASE BASED ON EARTHQUAKE OBSERVATION RECORDS

At Onagawa NPP, seismic observations have been conducted on the ground and in the buildings, and we will analyse these seismic observation records.

2.1 Earthquake Observation Records at the Site

Seismic observation points at Onagawa Nuclear Power Plant are shown in Figure 2. Figure 3 shows the acceleration waveform and response spectrum of the subsurface record at the seismic observation points above the free bedrock (O.P.[*2]-8.6m: G.L.-27.3m), which represent the vibration characteristics of the free surface of base stratum[*1]. The response spectrum diagram also shows the 2011 Tohoku earthquake and the 2011 off Miyagi Prefecture earthquake, which is largest aftershock of the 2011 Tohoku earthquake.

*1: Shear wave velocity at the free surface of base stratum: Vs = 1,500m / s

*2: O.P.: Onagawa Peil, the Onagawa NPP datum plane for construction, -0.74m below standard mean sea level of Tokyo Bay

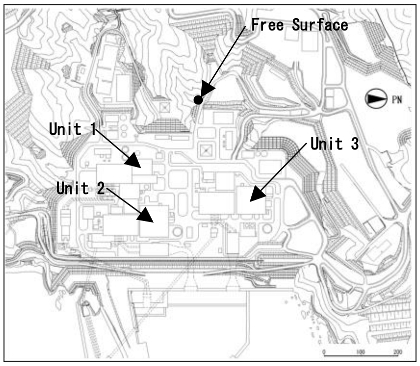


Figure 2. Seismic observation points at the site

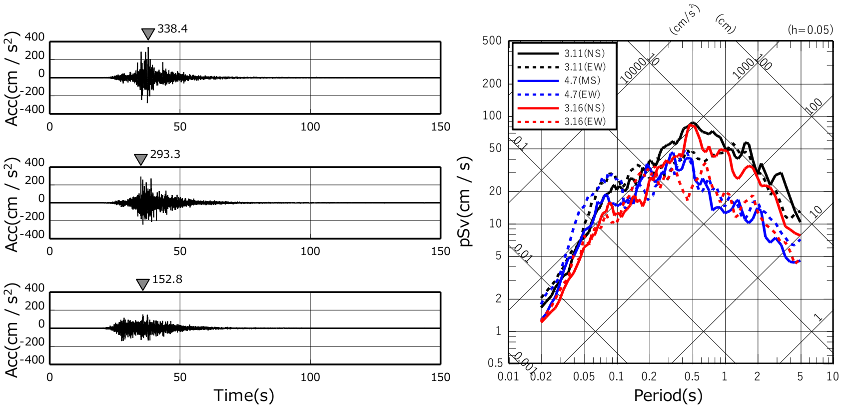


Figure 3: Acceleration waveform and response spectrum of the ground motions, which were recorded at seismic stations above the free surface of base stratum

The 2022 Fukushima earthquake was the third largest acceleration ever observed at Onagawa NPP, following the two major earthquakes in 2011, but the response spectrum was smaller than that of past major earthquakes and no damage to safety-critical equipment was confirmed during inspections immediately after the earthquake.

2.2 Trend Analysis of the Predominant Natural Frequency Decrease Based on Seismic Observation Records in the Reactor Building

The structural drawing of the Reactor Building UNIT No.2 and seismic observation points in the building are shown in Figure 4. The Reactor Building UNIT No.2 is a reinforced concrete structure (partially steel-framed reinforced concrete and steel frame) with three underground floors and three above-ground floors.

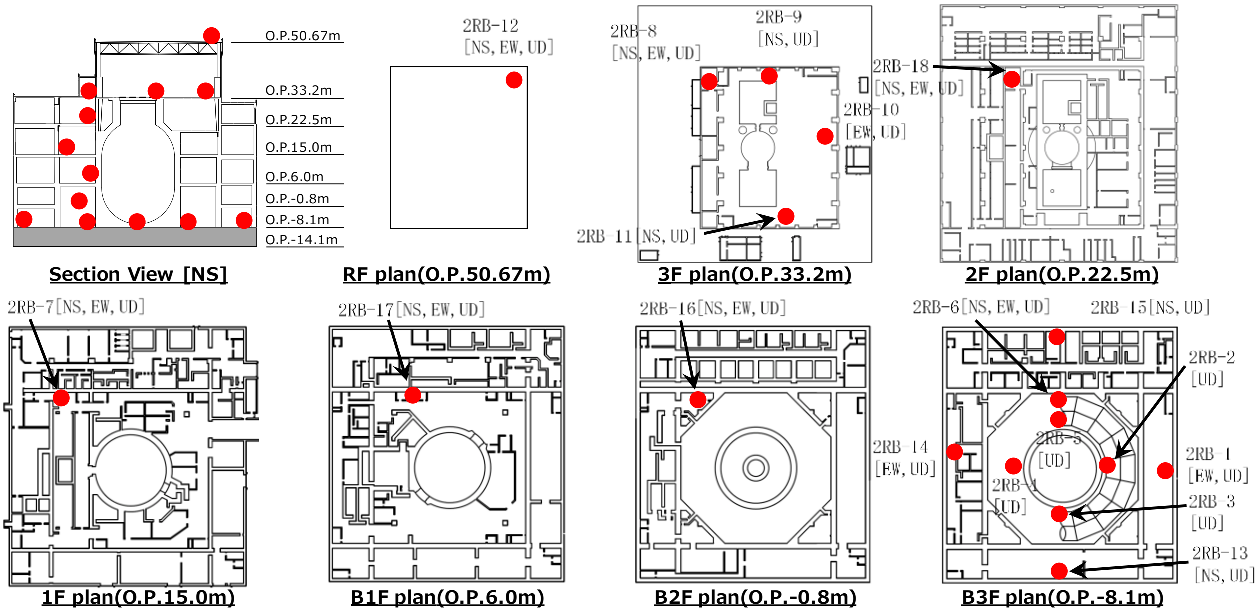
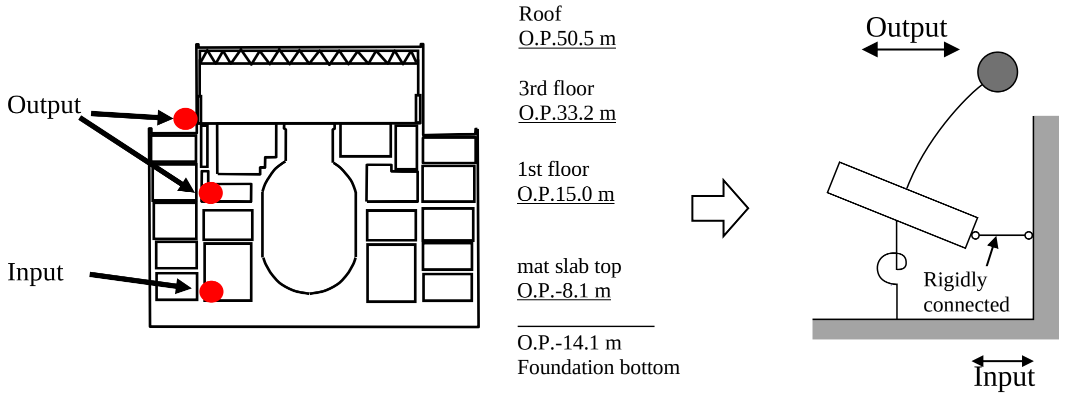


Figure 4. The structural drawing of the reactor building and seismic observation points in the building

A lot of seismic records have been obtained at the building shown in Figure 4, including the two major earthquakes in 2011 and the 2022 Fukushima earthquake.

We analysed the fluctuation in the predominant frequency of the reactor building from the beginning of seismic observation when the building was replaced with an equivalent single mass system model using observation records on the mat slab, first floor, and operation floor of the reactor building. From the fluctuation in the predominant frequency, we can evaluate the change in the average stiffness of the entire building. If we have observational records of the vertical motion at both ends of the mat slab, we can evaluate the transfer function for the foundation fixed condition by treating the mat slab as a rigid body and evaluating the rotational motion of the mat slab.

Figure 5 shows a conceptual diagram of the predominant frequency evaluation.



Arrengement of seismographs

Fixed sway condition

Figure 5. Conceptual image of the predominant frequency evaluation

We selected records with large maximum accelerations and magnitudes and long durations for our study. The variation of the predominant frequencies of each observed records over the time series is shown in Figure 6.

The predominant frequency tends to decrease slowly over time, but it decreased significantly during the 2011 Tohoku earthquake and has not shown any tendency to recover to the frequency before the 2011 Tohoku earthquake in subsequent earthquakes. In addition to the 2022 Fukushima earthquake, three earthquakes with acceleration exceeding 100Gal were observed on the mat slab in 2021, but the decrease in the predominant frequency was less than 0.1Hz, confirming that we have not seen a progressive decrease in frequencies.

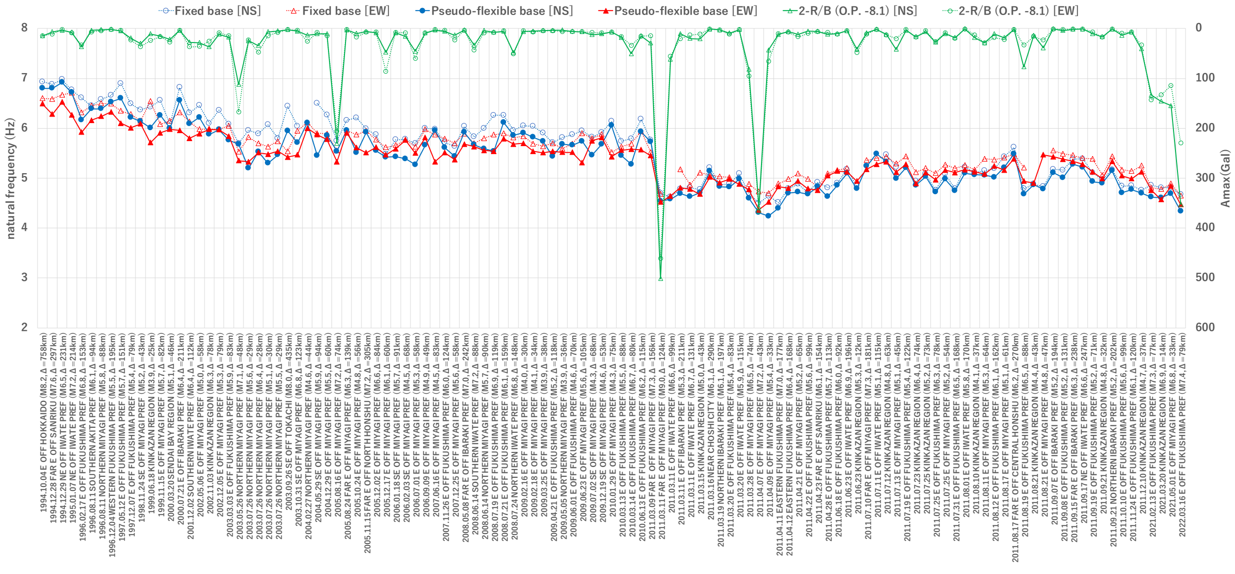


Figure 6. Peak frequency evaluation results (1994 to 2022)

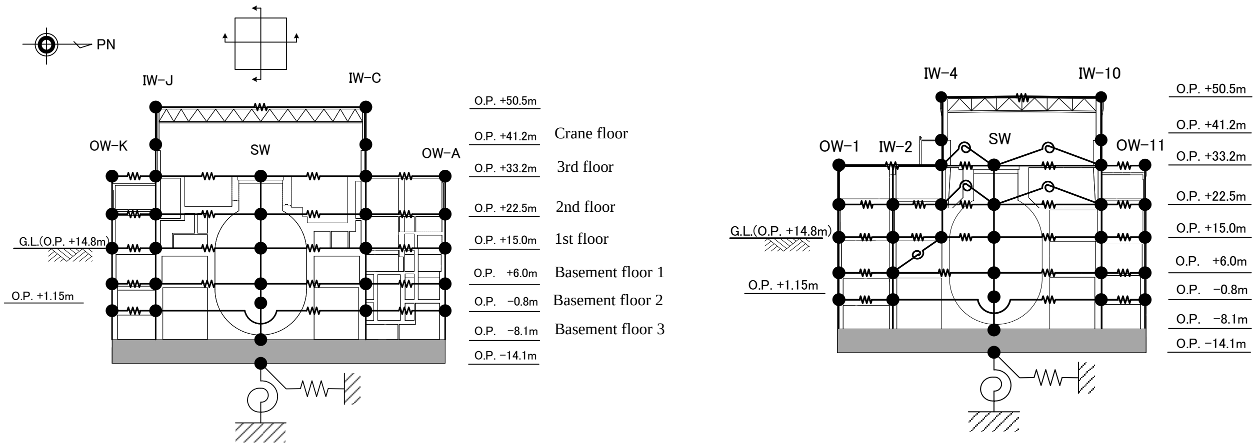
3. SIMULATION ANALYSIS USING THE OBSERVATION RECORDS ON THE MAT SLAB

3.1 Characteristics of the Seismic Response Analysis Model of the Reactor Building UNIT No.2 Based on the Effects of the 2011 Tohoku Earthquake, Etc.

We will conduct a simulation analysis using the observation records of the Onagawa Reactor Building UNIT No.2 by the following method.

1. The horizontal seismic response analysis model is a nonlinear lumped mass model consisting of shell walls, seismic share walls, steel braces, and floor slabs that deform in bending and shear. For the ground, a soil structure interaction model is used in which the soil is evaluated as equivalent spring model.
2. The input ground motion outside the soil spring is calculated with the record observed on the basemat by a linear analysis model in frequency domain.
3. The earthquake response analysis is performed by a non-linear analysis model in time domain.

The seismic response analysis model of the Reactor Building UNIT No.2 is shown in Figure 7.



[NS direction] [EW direction]

Figure7. Simulation model of the Reactor Building

A part of the comparison of the acceleration response spectra of the simulation analysis of the Onagawa Reactor Building UNIT No.2 for the 2011 Tohoku earthquake is shown in Figure 9, and the material properties used for earthquake response analysis are listed in Table 1.

As a result of the simulation analysis of the 2011 Tohoku earthquake, we confirm the following tendencies (Hirotani et al. (2012), Kusaka et al. (2019)).

1. To evaluate the shear stiffness of the reinforced concrete, that of the seismic shear walls was set as equivalent stiffness to agree with the observation records and the first stiffness for hysteresis characteristics was modified from the design value (Figure 8).
   The initial stiffness of the reinforced concrete section (seismic share wall) below the operating floor (O.P. +33.2 m) was set approximately 20% from the design value, and above the operating floor was set approximately 50% to 70%, which considered in the design, for better consistency with the observation records (Figure 9).
2. The damping ratio of the building was reset to be represented entirely by the damping of the reinforced concrete parts, so that the analysis results would consistent with the observation records. Results in good agreement with the records were obtained by adopting an RC damping ratio of 7% (Figure 9).
   In the seismic design of the Reactor Building UNIT No.2, the damping of the reinforced concrete is set at 5% so that the result of the evaluation is on the safe side.

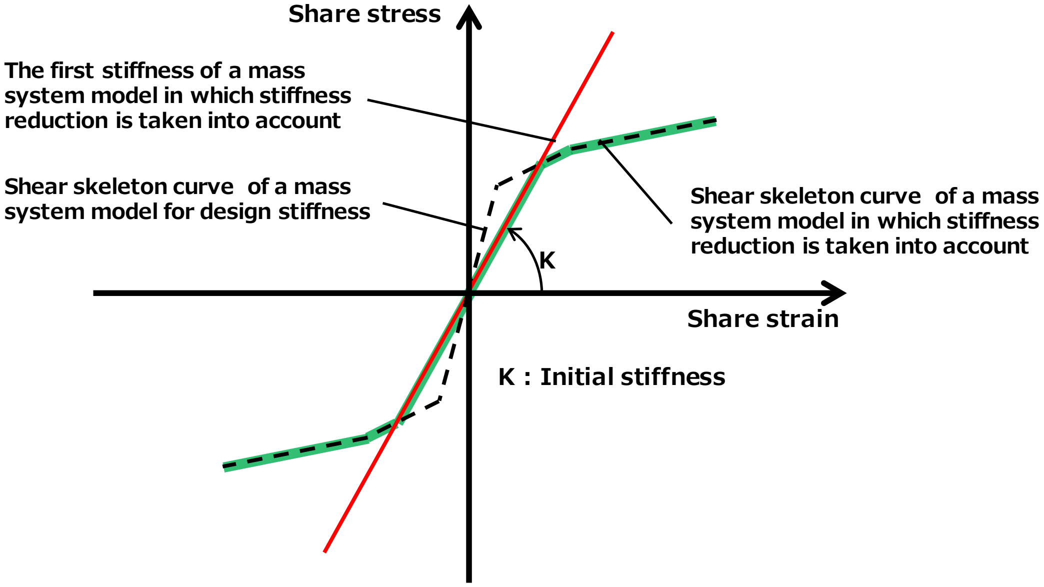


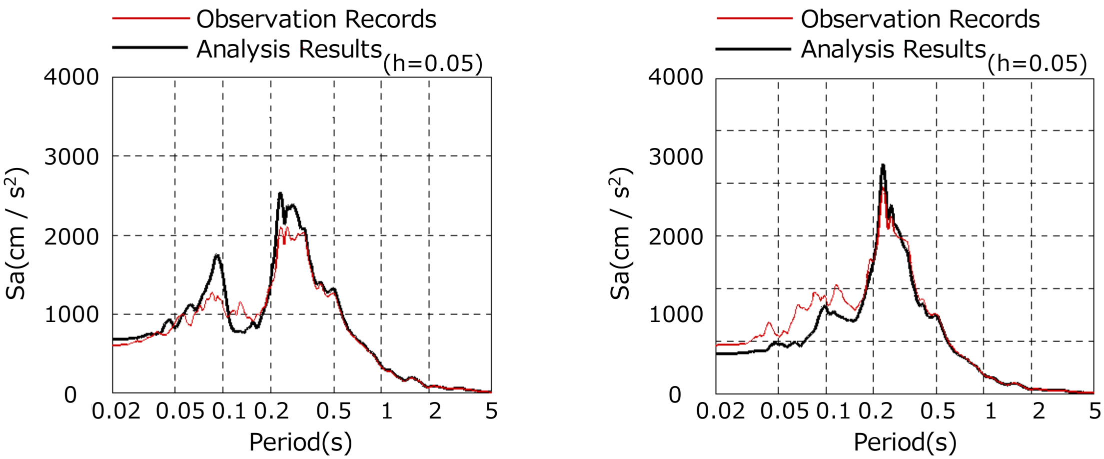
Figure 8. Conceptual diagram of the skeleton curve for the seismic share wall, in which initial stiffness reduction is taken into account

Table 1. Material properties used for earthquake response analysis

Material		Direction	Initial stiffness correction factor*	Young's modulus E (N/mm^2)	Shear modulus G (N/mm^2)	Damping ratio h (%)	
						Simulation analysis of the 2011 Tohoku Earthquake	Seismic design of the Reactor Building Unit No. 2
Concrete	O.P.+50.5 m to O.P.+33.2 m	NS	0.3	7.94×10^3	3.41×10^3	7	5
		EW	0.5	13.24×10^3	5.69×10^3	7	5
	O.P.+33.2 m to O.P.-8.1 m	NS	0.75	19.86×10^3	8.53×10^3	7	5
		EW	0.80	21.18×10^3	9.10×10^3	7	5

* These initial stiffness correction factors are for the design initial stiffness values of the concrete walls set to agree with the observation records.

Design values Young's modulus 2.65×10^4 N/mm^2
Shear modulus 1.14×10^4 N/mm^2



O.P.15.0m
(1st floor above ground level)

O.P.33.2m
(3rd floor above ground level)

Figure 9. Comparison of acceleration response spectra (h = 5%)
(The 2011 Tohoku earthquake, NS direction, RC damping ratio :7%)

3.2 Validation of Seismic Design After the 2011 Tohoku Earthquake Through Simulation Analysis

In the seismic design after the 2011 Tohoku earthquake of the Reactor Building UNIT No.2, from the viewpoint of confirming the validity of using a seismic response analysis model that takes into account the reduction in initial stiffness based on the effects of the 2011 Tohoku earthquake, etc, we will conduct a simulation analysis using the observation records on the mat slab of the Reactor Building UNIT No.2 and compare the results with the observation records. In addition, from the viewpoint of confirming the integrity of the building, the maximum response shear force will be confirmed. The method of the simulation analysis is described in 4.1.

Comparison of the maximum acceleration of the analysis results with the observation records is shown in Figure 10, and comparison of the acceleration response spectrum of the analysis results with the observation records is shown in Figure 11. We confirmed that the analytical results of the seismic design model, in which initial stiffness reduction taken into account generally reproduce the magnitude of the maximum response acceleration and the peak period of the response spectrum in the observation records.

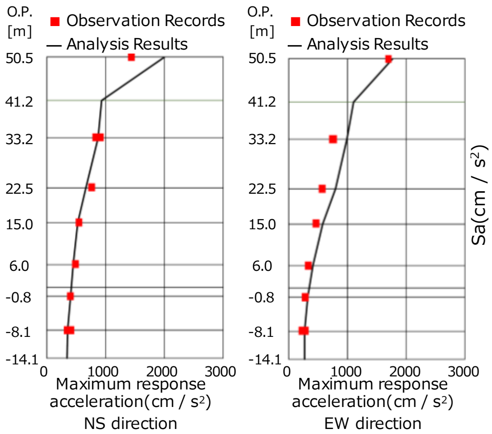


Figure 10. Comparison of maximum response acceleration

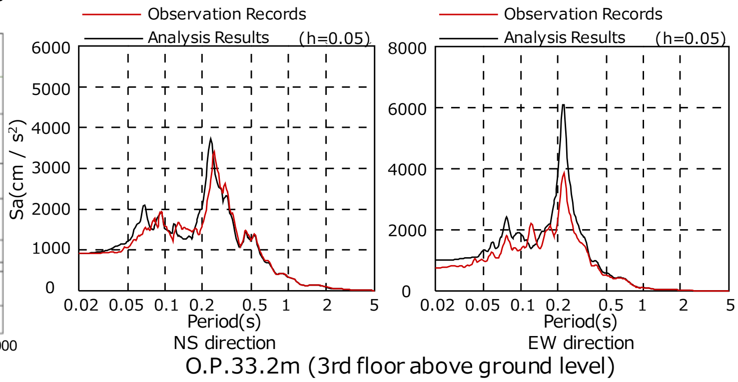


Figure 11. Comparison of acceleration response spectra (h = 5%)

3.3 Confirmation of Building Integrity by Shear Stress

The shear stresses at each floor obtained from the simulation analysis are shown in Figure 12 for each axis of the analytical model. Figure 12 also shows the short-term allowable stress intensity that can be bear only by the reinforcing bar of seismic share wall*.

The ratio of the shear stress at each floor to the yield value that can be borne only by the reinforcing bar is 0.57 in the NS direction and 0.70 in the EW direction at maximum, which is well below the yield value that can be bear only by the design reinforcing bar.

*: p_w: The amount of design reinforcing bar (This is the smaller of the amount of reinforcing bar in the vertical and horizontal directions, with an upper limit of 1.2%).

σ_y: The yield value of reinforcing bar (SD345: 345N / mm^2)

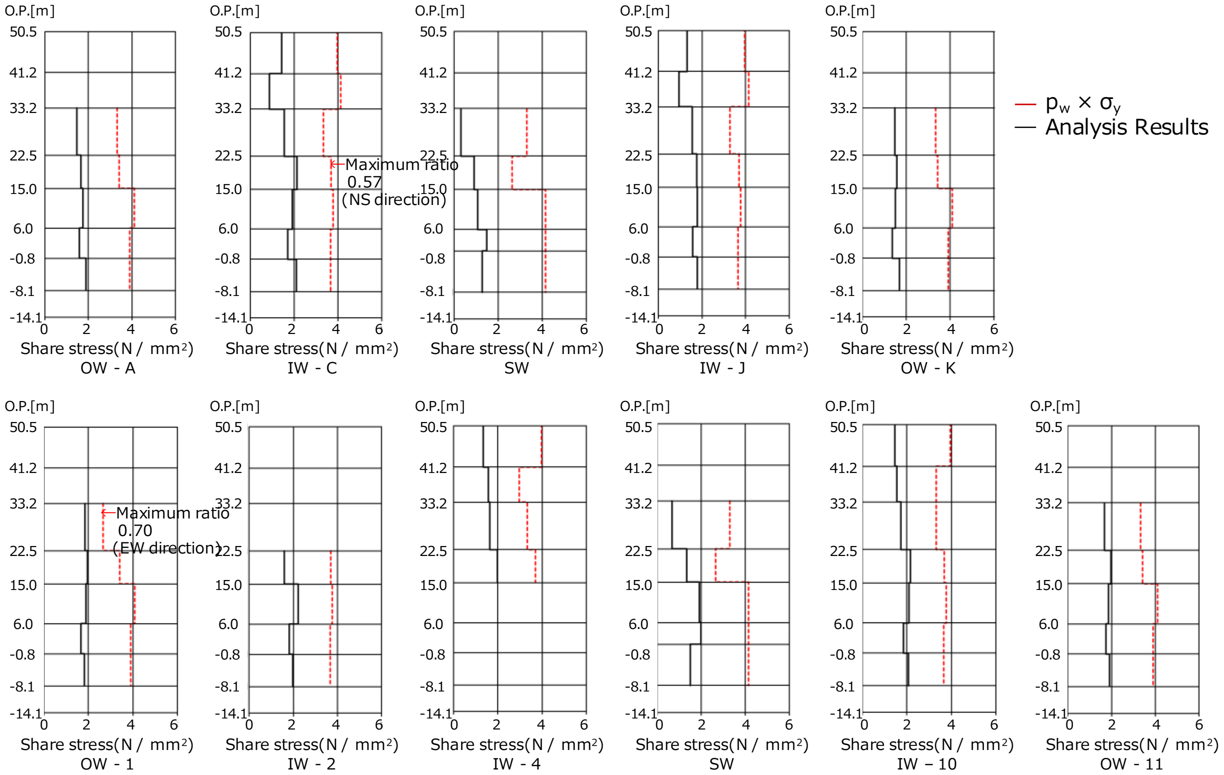


Figure 12: Comparison of shear stresses of seismic share walls at each floor
(Upper row shows NS direction, Lower row shows EW direction)

4. CONCLUSION

- In light of the fact that acceleration exceeding the level of automatic reactor shutdown was observed in the 2022 Fukushima earthquake, we analysed the items taken into the seismic design (e.g., consideration of initial stiffness reduction) based on the effects of the 2011 Tohoku earthquake, etc, from the viewpoints of confirming the validity of the seismic design, and we also studied the Reactor Building Unit No.2 using seismic observation records.
- In addition to the 2022 Fukushima earthquake, three earthquakes with acceleration exceeding 100Gal were observed on the mat slab in 2021. However, we analyse the records observed by seismometers installed at various locations in the Reactor Building, we confirmed that the decline in the natural frequency has not progressed.
- The results of the simulation analysis of the 2022 Fukushima earthquake using the seismic design model considering initial stiffness reduction generally reproduced the amplitude of the observation records and the period of the response spectrum, and we confirmed the validity of our seismic design after the 2011 Tohoku earthquake.
- The shear stress of each floor of the building has a sufficient margin against the yield value that can be borne only by the amount of design reinforcing bar, and we confirmed that the integrity of the Reactor Building UNIT No.2 against the 2022 Fukushima earthquake is sufficiently secured.

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