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TECHNICAL ISSUES OF JAPANESE SEISMIC EVALUATIONS FROM THE POINT OF GLOBAL AND JAPANESE STANDARDS

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川内原発における耐震性評価の問題：国際基準と日本基準

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Technical Issues of Japanese Seismic Evaluations from the Point of Global and Japanese Standards

Greenpeace Summary

Greenpeace Japan commissioned independent consultant Satoshi Sato, former nuclear engineer at General Electric from 1984-2002, to assess the seismic standards as applied to the Kyushu Electric Sendai nuclear power plant and accepted by the Nuclear Regulation Authority (NRA). Some main points of the report are listed below.

The International Atomic Energy Agency (IAEA) recommends determining a safe design-basis-earthquake based on seismic events occurring with a probability of once every 10.000 to 100.000 years (annual exceedance probability 1E-4 and 1E-5).

However, the design-basis-earthquake, presented by Kyushu Electric, indicates the probability of a higher frequency, with seismic events happening partially once every 1.000 - 10.000 years (annual exceedance probability 1E-3 and 1E-4), which violates the IAEA's safety standards.

In the Construction Permit Application Kyushu Electric submitted to the NRA, only the continental crust was considered as a seismic source for the Sendai Nuclear Plants' non-seismic isolation buildings and not seismic sources at plate interface and within oceanic plate. As a result, the earthquake impacts from lower frequency (longer period) region of vibration spectrum, which has caused serious consequences in past nuclear accidents, are underestimated.

The lower frequency (longer period) region of vibration spectrum should not be underestimated, as it can lead to the destruction of tanks, pools and transformers in the reactor caused by swelling liquids (sloshing effects) as well as to great damage to machines, such as overhead polar cranes, lower pressure turbine rotors and underground pipes.

There have been examples both in the US and Japan of how seismic induced vibration from earthquakes has caused a sudden and excessive nuclear reaction (reactivity addition) of the fuels in the reactor, leading to an emergency shutdown of the reactors. This could also be effected by lower frequency (longer period) region of vibration spectrum; and it is a major problem that this point is not verified.

Based on the findings above, although each of the three newly developed design-basis-earthquakes (Ss-1, Ss-2, and Ss-L) developed by Kyushu Electric and approved by the NRA are significantly higher than previously, the methodology used by Kyushu Electric and accepted by the NRA is greatly different from the probabilistic seismic hazard analysis (PSHA) applied in the United States for the nuclear plant at Vogtle. It is difficult to determine if the methodology uniquely developed for Japanese nuclear plants is consistent with international practice. Nonetheless, the conclusion of the commissioned report is that the newly developed process to determine the design-basis-earthquake for the Sendai Nuclear Power Plant is less than adequate, simply because of the intentional separation of lower frequency (longer period) side of spectrum contributed from the long-distance earthquakes.

When comparing the process of determining the design-basis-earthquake in Japan to other examples in the U.S. and other countries, there are many unclear elements in the Japanese process, as it is not worked out comprehensively. It is unacceptable to promote this process as the highest standard in the world.

The author clearly states that the arguments delivered in this report do not only apply for the Sendai plant but also for all other remaining nuclear power plants in Japan.

Technical Issues of Japanese Seismic Evaluations from the Point of Global and Japanese Standards

Summary

This technical report reviews the methodology used by the Nuclear Regulation Authority (NRA) in assessing the seismic risks for nuclear power plants in Japan. It also assesses the approach used by Kyushu Electric Power Company in its seismic assessment for its two Pressurized Water Reactors (PWRs) at the Sendai power plant.

Some significant findings are briefly described in the list below. Detail of each finding and its technical basis are discussed in the main part of this report.

（1） The methodology and the process to determine the Hard Rock Response Spectra and the Free-Field Ground Surface Response Spectra are only roughly and conceptually explained and are largely left in a “black box”, making it impossible to objectively verify the adequacy. There is no evidence found in the Safety Evaluation Report supporting that the NRA has done it in a thorough manner.

（2） After all, a total of three different ground surface response spectra are proposed as the design-basis-earthquakes, consisting of Ss-1 and Ss-2 as mentioned above, and Ss-L separately and exclusively proposed for the Seismic Isolation Building. However, the author believes that there should ideally be just a single design-basis-earthquake bounding all three response spectra instead of three different spectra. The author also believes that the justification claimed by the Kyushu and accepted by the NRA to exclude the potential contribution from seismic sources at the plate-to-plate interface by simply implying that the earthquake of the seismic intensity V or greater generated at such a long distance is not anticipated based on the historical data is technically invalid. The author is concerned about the conclusion not to require to superpose the lower frequency (longer period) side of Ss-L spectrum contributed from the long-distance seismic source over either Ss-1 or Ss-2 because it is in fact the lower frequency (longer period) region of vibration spectrum that is mostly responsible for the earthquake impacts previously experienced in the Japanese nuclear power plants. The lower frequency (longer period) region of vibration spectrum of Ss-L should be integrated into design-basis-earthquake applied for the structures, systems, and components not only of those inside Seismic Isolation Building but also of those inside other plant facilities.

(3) Technical credibility of Uniform Hazard Spectra constructed by the Japan Nuclear Energy Safety Organization (JNES) in 2005 and in accordance with the methodology developed by the Atomic Energy Society of Japan (AESJ) in 2007 is questionable and possibly non-conservative. Nevertheless, there is no objective evidence in the safety evaluation report to support that the NRA has thoroughly assessed the adequacy of these hazard spectra which apparently are other examples of black-box in terms of development processes.

(4) The land territory of Japan is divided into eight regions in a very rough manner by the JNES (2005). Such a regional map suggests that all four sites of Fukushima Daiichi, Fukushima Daini, Tokai, and Kashiwazaki-Kariwa belong to the same region, and all sites of Hamaoka, Shika, and the sites along Wakasa-Bay belong to the other same region. It does not seem to be reasonable to apply a single set of uniform hazard spectra to each of such vast regions. Nevertheless, there is no objective evidence in the safety evaluation report to support that the NRA has thoroughly assessed the adequacy of this map.

(5) By comparison with those hazard spectra mentioned above, the Kyushu Electric Power Company has derived an overall conclusion that the annual exceedance probability of their design-basis-earthquake is somewhere between 1E-4 and 1E-6 or between 1E-4 and 1E-5. However, those figures referenced in the text actually do not fully support such a conclusion statement. For example, the Ss-2 (vertical) spectrum indicates the annual exceedance probability being between 1E-3 and 1E-4 with some portion even greater than 1E-3. The NRA obviously failed to point out this error.

Based on the findings above, although each of the three newly developed design-basis-earthquakes (Ss-1, Ss-2, and Ss-L) developed by Kyushu and approved by the NRA is significantly higher than previous PGA of 180Gals, the methodology used is greatly different from the probabilistic seismic hazard analysis (PSHA) applied for the Vogtle plant and it is difficult to determine if the one uniquely developed for the Japanese plants is consistent with the international practice. Nonetheless, it is author’s personal opinion that the newly developed process to determine the design-basis-earthquake for Sendai Nuclear Power Plant is less than adequate simply because of the intentional separation of lower frequency (longer period) side of spectrum contributed from the long-distance earthquakes.

(6) In the seismic response analysis of the containment, the soil-structure interaction (SSI) is considered to be one of the key factors. Although the analysis model

contained in the Construction Permit Application implies the consideration of this factor, no values are given to the spring constants of horizontal springs and rotational spring. Therefore, it is not clear if the effect of SSI is really included in the analysis. And if it is not properly considered, the expected output of the analysis could become non-conservative (under-estimation of the seismic behavior) especially in the lower frequency (longer period) side of response spectrum.

(7) By under-estimating the lower frequency (longer period) side of seismic behavior, the estimated impacts to the sloshing effects to the tanks, pools, and large transformers, and those steel structures of long span such as the fuel handling machine, overhead polar crane, and meteorological tower, as well as those components not tolerable for the large displacement such as the stainless steel liner of pools, lower pressure turbine rotors, underground pipes/trenches, become all non-conservative.

(8) By under-estimating the lower frequency (longer period) and larger displacement seismic motion, there are potential hidden risks that could result in various unfavorable consequences to the performances of severe accident mitigation guidelines, the physical protection systems, and the fire brigade activities. For instance, the damages to the roads assigned for the transportation of mobile equipment to mitigate the severe accident, the derailed physical protection gages, and broken emergency lights inside building could significantly hinder the critical actions under the emergency. If the ceiling of the building is heavily loaded with moistened volcanic ash or wet snow, and the natural frequency is lowered sufficiently, it may resonate with the lower frequency of earthquake, resulting in a collapse to the important equipment underneath.

(9) It has been learned from the previous events that the seismic vibration creates some perturbation to the coolant in proximity of fuel rods and adds extra positive reactivity. Fortunately, such previous events have not resulted in fuel failure. However, the possibility of exceeding the safety limit, leading to the gross fuel failure and damage to the reactor pressure boundary under unfavorable conditions and/or severer seismic events should be assessed.

It should be noted that the findings listed above are not unique to the Sendai Nuclear Power Plant alone and are generally applicable to all nuclear power plants in Japan including those of BWR designs.

Contents

1. Background

Key Points

- Annual Exceedance Probability (AEP) being in the range between 1E-4 and 1E-3 in average or between 1E-5 and 1E-4 in median is an international expectation for the Design Basis Earthquake (DBE) explicitly stated in the IAEA Safety Standard, NS-G-1.6 "Seismic Design and Qualification for Nuclear Power Plants" (2003). This expectation is also in consistent with the Safety Goal for the full scale core damage being less than 1E-4 per reactor-year stated in INSAG-12, "Basic Safety Principle for Nuclear Power Plants" (1999).
- After Fukushima nuclear accident, the European Nuclear Safety Regulators Group (ENSREG) coordinated "Stress Test". Every member country as well as Switzerland and Ukraine submitted the report. The table below shows how DBE is set in terms of AEP in each country. Also included in the table is Design Basis Flood (DBF). AEP being 1E-4 is now considered as an international consensus.

Country	Reactor Model	DBE		AEP for DBF
		AEP	Acceleration	
France	PWR	1,000（MHPE）	0.1～0.3g	1,000
Germany	PWR/BWR	100,000（median）	42～210 gal	10,000
UK	AGR/PWR	10,000	0.13～0.25g	10,000
Netherland	PWR	30,000	75gal	1,000,000
Belgium	PWR	10,000	0.21g	10,000
Spain	PWR/BWR	220,000	0.20g	10,000
Sweden	PWR/BWR	100,000	0.15g	NA
Finland	PWR/BWR	100,000（median）	0.082g	NA
Czech	VVER	10,000	0.1g	10,000
Slovakia	VVER	10,000	0.344g	100
Hungary	VVER	10,000	0.25g	10,000
Romania	CANDU	1,000	0.2g	10,000
Bulgaria	VVER	10,000	0.2g	10,000
Slovenia	PWR	10,000	0.6g	10,000
Lithuania	RBMK（decomm.）	ー	60～100gal	ー
Ukraine	VVER/RBMK	10,000	0.1～0.12g	10,000
Switzerland	PWR/BWR	10,000	0.21g	10,000

（1g=980.665gal）

- Generally, there are two methodologies to determine the DBE, namely deterministic method and probabilistic method. Japan traditionally selected the deterministic method.
- The original DBE for Sendai Nuclear Power Plant was 180gal for most safety-related systems and 270gal for selected systems such as containment and shutdown system. On the other hand, Diablo Canyon Nuclear Power Plant in California was analyzed against various seismic conditions including the response spectra derived from an effective horizontal ground acceleration of 0.75g (735gal) based on the NRC recommendations discussed in Appendix C to Supplement No.5 of the Safety Evaluation Report dated September 1976. Both sites are located in the seismically active zones but were treated quite differently.
- Taiwan also conducted their own stress test and submitted the report to ENSREG for peer review. There are four NPPs in Taiwan. The DBE for the No.1 NPP is 0.3g, and 0.4g for all others. ENSREG concluded that Taiwan's DBE does not meet the international standard because it did not apply the probabilistic seismic hazard analysis (PSHA) to demonstrate that AEP is less than 1E-4.
- Kyushu Electric Power Company based on the probabilistic method and determined 540gal as the new DBE. This is called Ss-1. They then demonstrated that this level of DBE is in the range between 1E-6 and 1E-4 of AEP. However, they followed NRC's instruction and added a new DBE. This is called Ss-2 and 620gal.

2． Description of Technical Approach Taken by Kyushu Electric Power Company

Key Points

- Four locations of seismic sources are considered for Sendai NPP. They are 1) continental crust, 2) plate interface, 3) oceanic plate, and 4) others. For each location, both pre-identified sources and un-identified sources are considered.
- However, seismic sources at plate interface and within oceanic plate are excluded because their intensity is considered less than V and insignificant.
- However, only for the seismic isolation building where the emergency operation facility is located, seismic sources only from large active faults and from the Ryukyu Trench are considered.

	Continental Crust	Plate Interface	Oceanic Plate	Others (Volcanic)
Pre-identified Seismic Sources	Yes (Faults within 200km)	Excluded (expected max. intensity < V)	Excluded (expected max. intensity < V)	Yes
Un-identified Seismic Sources	Yes (max.)	Excluded (expected max. intensity < V)	Excluded (expected max. intensity < V)	Excluded
DBE for Seismic Isolation Bldg.	Yes (Large active faults)	Yes Ryukyu Trench (Mw9.1)	Excluded	Excluded

- The results of the evaluation are summarized in the table below. The previous DBE of 180/270gal has been greatly raised upward.

			DBE（Gal）	Elastic Design Basis（Gal）
Facilities other than Isolation Bldg.	Design Response Spectrum	Hor.	540 (Ss-1H)	324
		Vert.	324 (Ss-1V)	195
	Un-identified Seismic Sources	Hor.	620 (Ss-2H)	372
		Vert.	320 (Ss-2V)	192
Only Isolation Building		Hor.	400 (Ss-LH)	
		Vert.	240 (Ss-LV)	

- The last step is to evaluate the adequacies of Ss-1 and Ss-2 from AEP aspect. The uniform response spectra constructed by JNES and AECJ for 1E-3, 1E-4, 1E-5, and 1E-6 are used for comparison. JNES' method (2005) divides the entire Japan Islands into 8 regions including 3 within Kyushu Island. JNES' uniform response spectra are given for the hard rock whereas AESJ's uniform response spectra are for the free-field ground surface.
- Both Ss-1 and Ss-2 response spectra constructed for Sendai lays in between 1E-6

and 1E-4, meeting the international expectation.

Sendai DBE		Uniform Hazard Spectra to be compared	
		JNES	AESJ
Hard Rock (Vs > 3000m/s)	Ss-1	10^{-4}～10^{-6}	10^{-4}～10^{-6}
	Ss-2	NA	
Free-Field Gnd. Surf. (Vs > 700m/s)	Ss-1	NA	10^{-4}～10^{-5}
	Ss-2	NA	

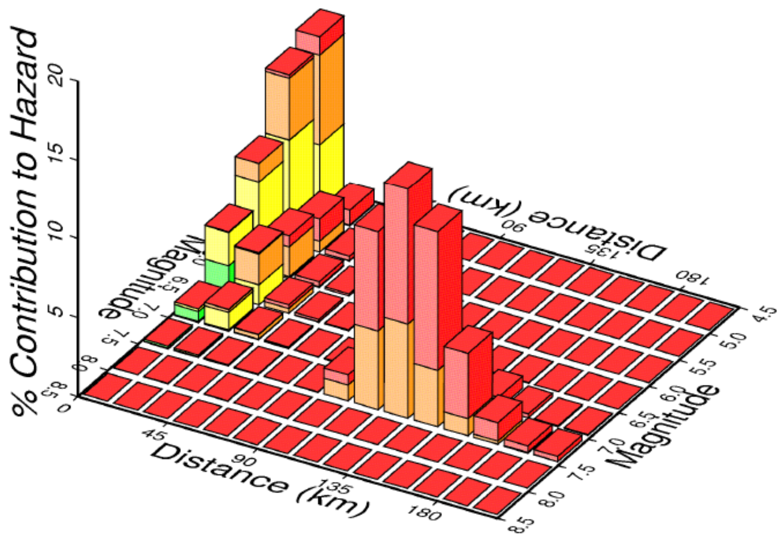
- DBEs (Ss-1 and Ss-2) on the free-field ground surface have been determined above. The reactor containment facility is constructed on the top of 8-meter thick 87,500 metric tons man-made rock which sits on the free-field ground surface. Both containment vessel and outer shield building are on the man-made rock.
- The ground level is EL 13m. The bottom elevations of each structure or building is as follows: Containment Vessel EL -18.5m. Aux. Bldg. EL -9m. Fuel Handling Bldg. EL -0.10m. Diesel Generator Bldg. EL 9.3m. Main Steam Line Bldg. EL 9.2m.
- The response spectrum of each floor of each building is determined based on DBE. This is analyzed by injecting a synthesized time history wave into the building model. Naturally, the upper floors receive greater amplification, resulting in higher acceleration.

3. Description of Technical Approach Taken by Author

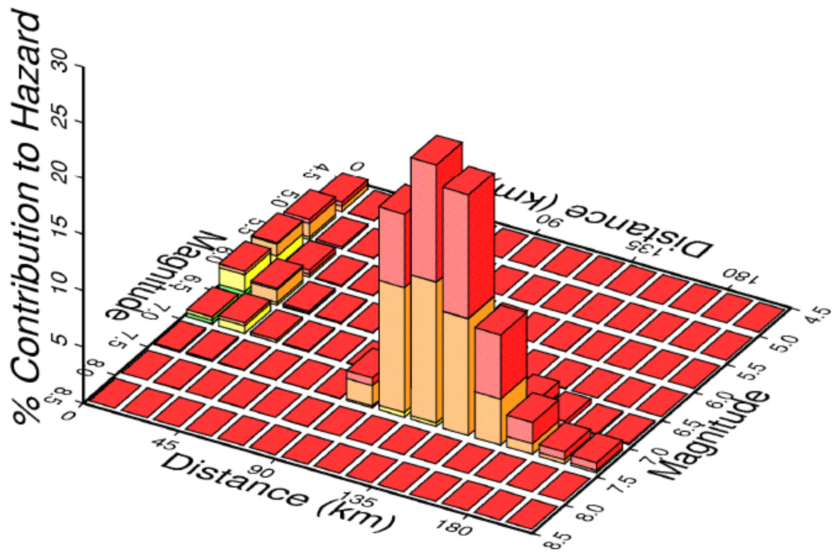
3.1 Technical Approach applied for Vogtle Nuclear Power Station

Key Points

- On August 31, 1886, a magnitude 7.3 earthquake hit Charleston, South Carolina. 60 People died and over 2,000 buildings were collapsed. This historical event affects the determination of DBE for Vogtle.
- The PSHA methodology specified in NRC Regulatory Guide 1.165 "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion", Rev.0 March 1997 has been used. This methodology is composed of the following steps:
  - De-aggregation: If the net contribution from seismic sources located farther than 100km to the total hazard is greater than 5%, they should be considered in the process to construct the DBE response spectrum. This criterion is met in case of Vogtle. The earthquake of M7.2, 130km from epicenter represents the low frequency region, whereas the earthquake of M5.6, 12km from epicenter represents the high frequency region.

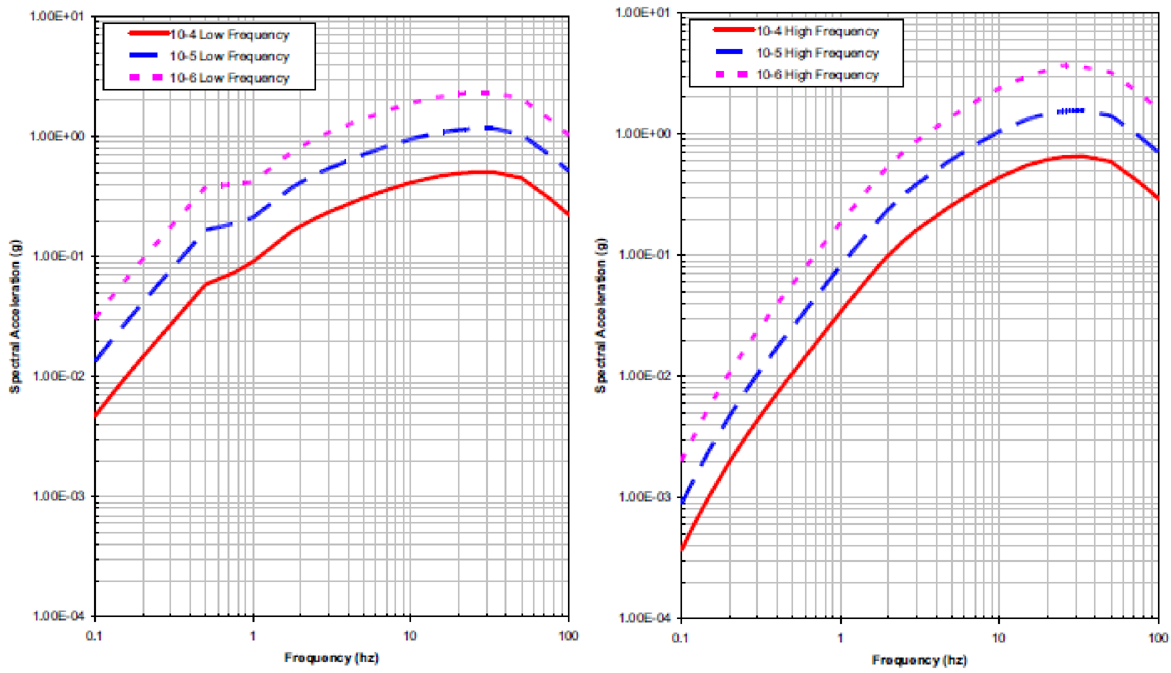


High Frequency Region



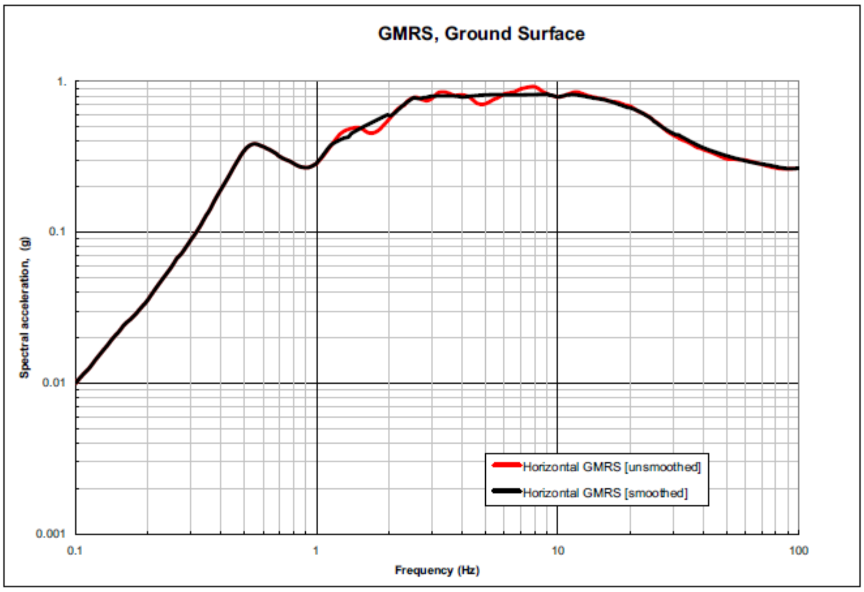
Low Frequency Region

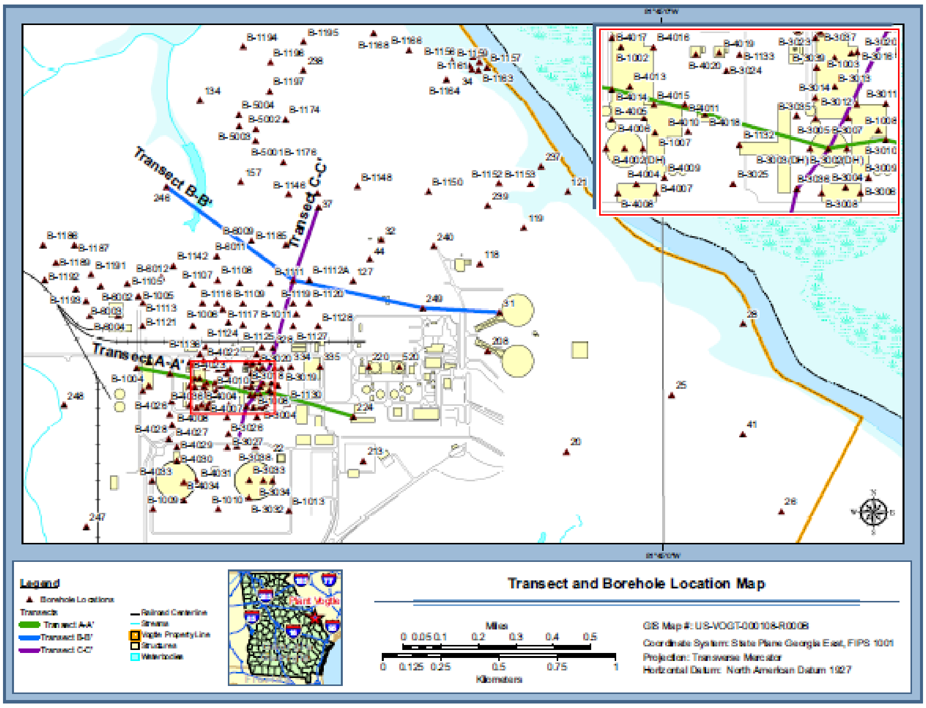
- Hard Rock Target Spectra: The spectrum at the hard rock (approximately 300 meters below surface) is determined for each representative earthquake.

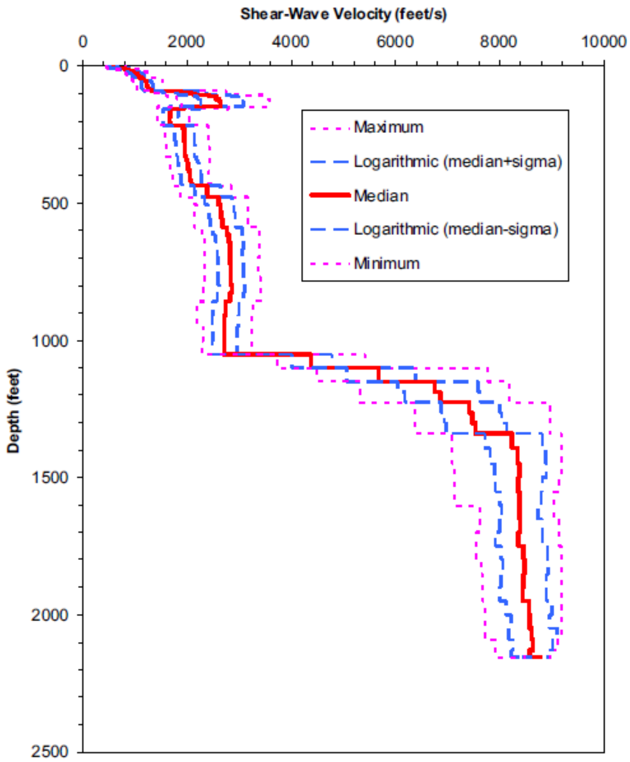


Hard Rock Target Spectra: 130km/M7.2 (Left), 12km/M5.6 (Right)

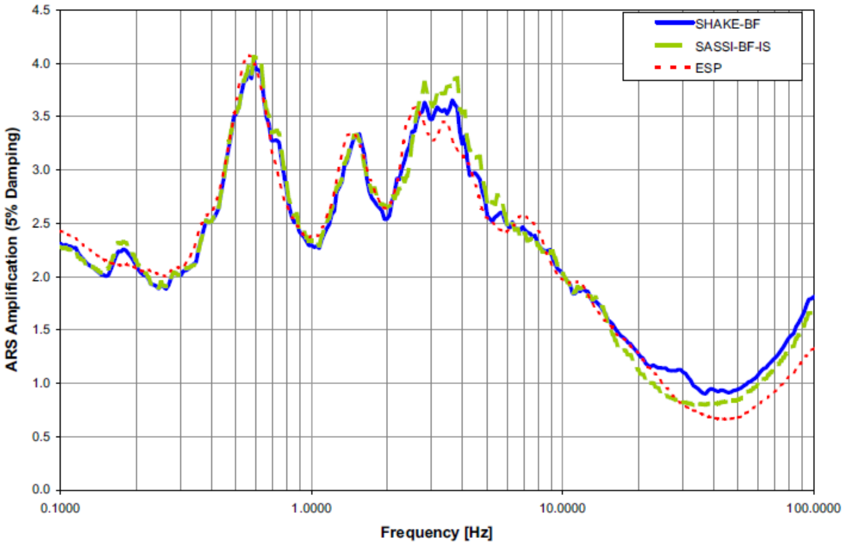
- Ground Motion Response Spectra (GMRS): The hard rock spectra are either amplified or attenuated through the soil between the hard rock and the ground surface to be the GMRS. Such amplification/attenuation factors vary depending on the property of soil and depending on the frequency of interest. The GMRS is obtained as shown below. To determine the properties of soil between the hard rock and the ground surface, boring as deep as 400 meters at a total of 186 locations within and in the vicinity of the site has been done. The share wave velocity is one of the important parameters. Although the share wave velocity tends to increase as a function of depth, it is accompanied by large variations.



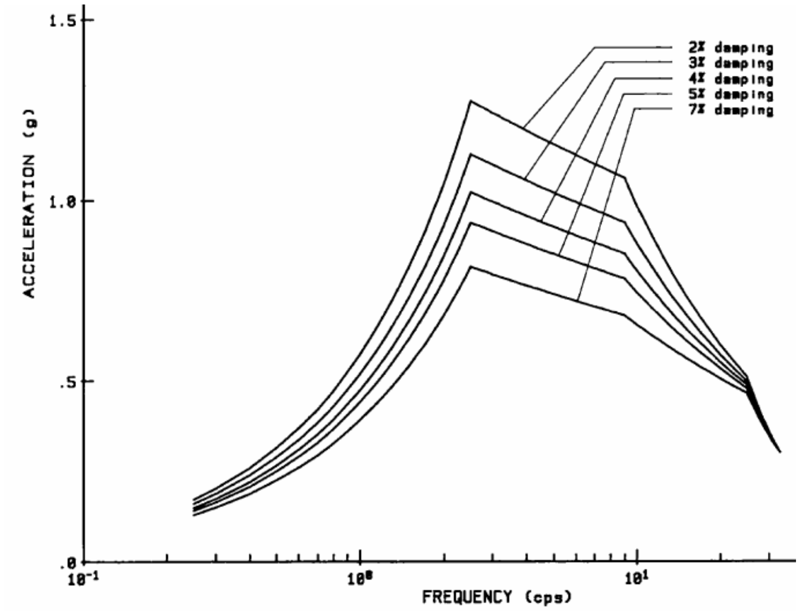




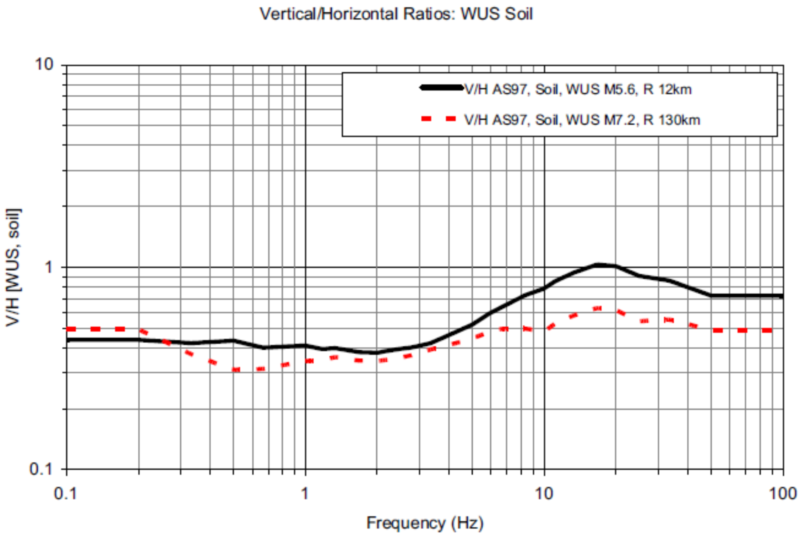
The amplification spectrum as a function of frequency is determined as shown below. To gain the free-field ground surface response spectra, the target spectrum is multiplied by this amplification spectrum at every frequency point. A damping factor of 5% is used for this amplification spectrum.



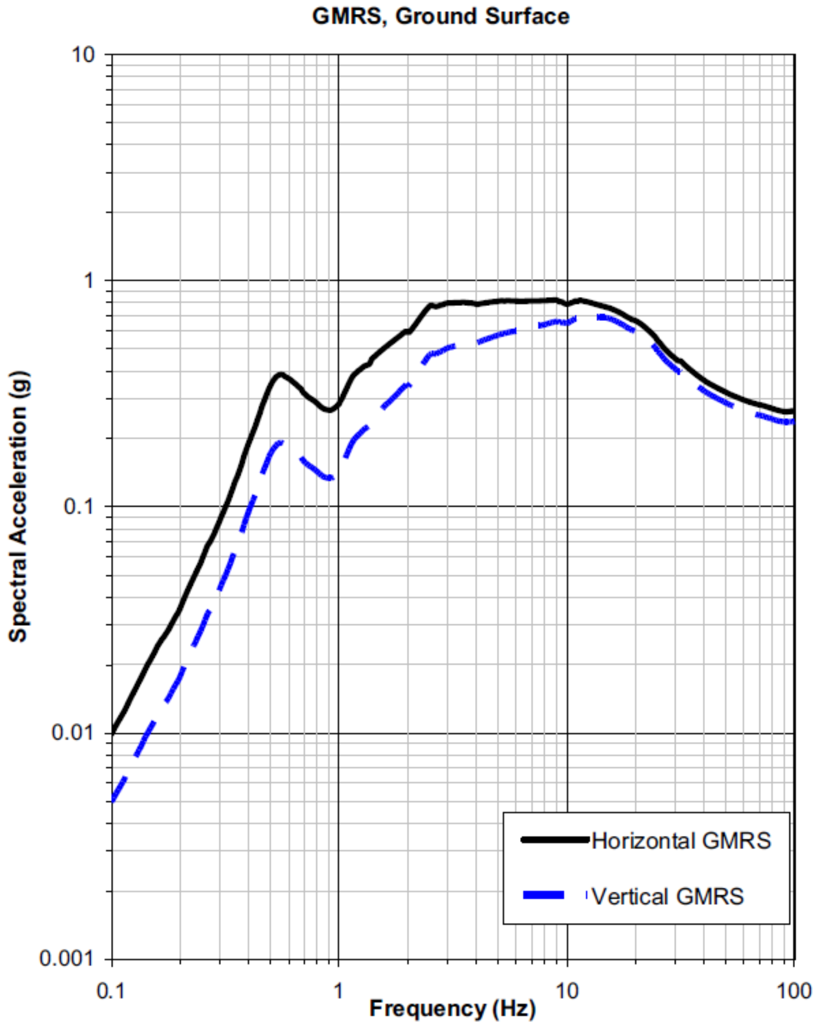
The assumption of 5% for the damping factor has been traditionally used. However, a sensitivity study for the damping factor indicated that the acceleration in high frequency (near 3Hz) region is greatly increased when the damping factor is reduced only slightly. Incidentally, there is a peak in the amplification spectrum near the same frequency. Another big peak is seen in the amplification spectrum in the lower frequency (0.4 to 0.9Hz) region. These peaks in the amplification spectrum as well as the large sensitivity of damping factor play important roles in determining the response spectrum on the free-field ground surface or GMRS.



The discussion to this point is concerning the GMRS in horizontal direction. To determine the GMRS in vertical direction, a V/H spectrum is used for the conversion. As indicated below, the acceleration of long distance strong earthquake attenuates much more in vertical direction than in horizontal direction in higher frequency region.



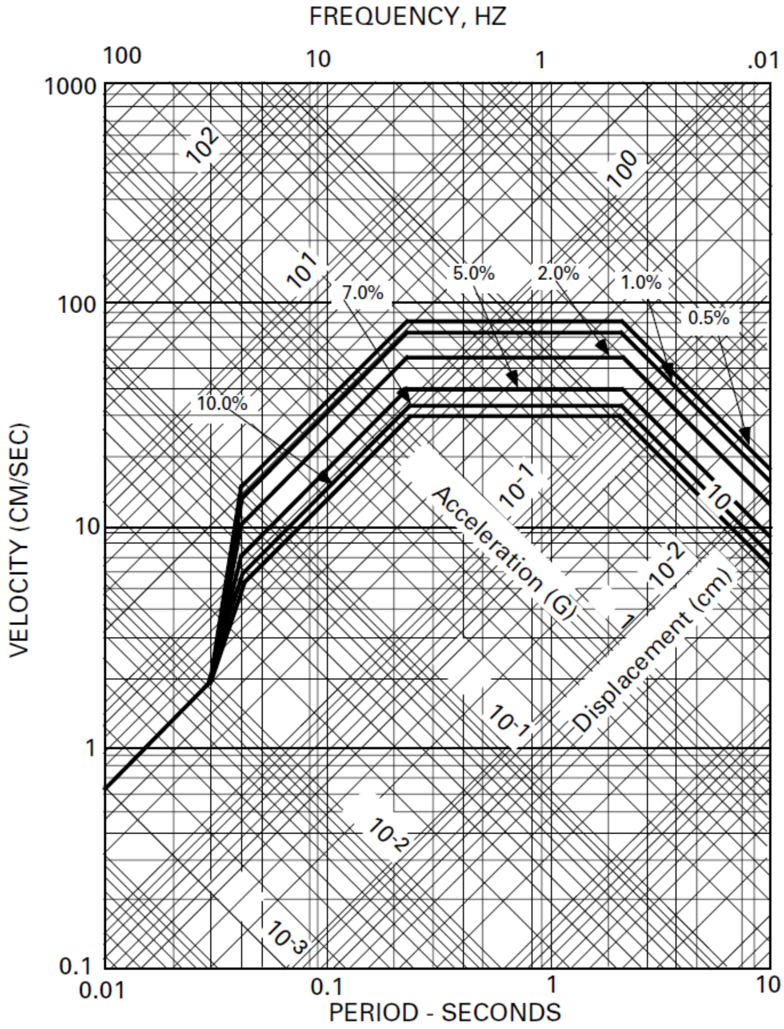
GMRS' in horizontal direction and in vertical direction are finally completed. Looking back the entire process, one can understand there are many factors involved and each factor has some degree of uncertainty.



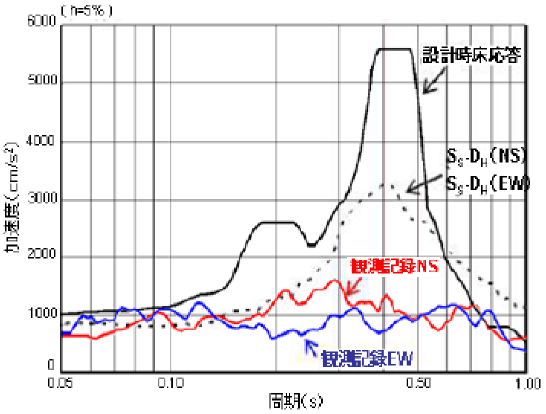
3.2 Niigata Chuetsu Earthquake (2007) and Great Tohoku Earthquake (2011)

Key Points

- The previous section (2.1) emphasized the important contribution of long distance strong earthquake in low frequency region.
- As illustrated in the diagram below (extracted from the PSAR of Lungmen NPP in Taiwan), the vibratory motion in low frequency region generally produces low acceleration but high velocity and large displacement. Therefore, the mechanism to cause earthquake damage in low frequency may be by means of large displacement, instead of high acceleration.



- Potential resonance with low natural frequency of equipment, structure, and sloshing must be evaluated.
- The floor spectra of Tokai Unit 2 exceeded the design response spectra in the low frequency region during Great Tohoku Earthquake in 2011. The diagram is cut off at 1Hz. However, if it is expanded down to 0.1Hz, more significant exceedance might have been seen and potential resonance with sloshing might have been predicted. It was reported that a 25 cubic meters of sloshing flood occurred during the 2011 earthquake.



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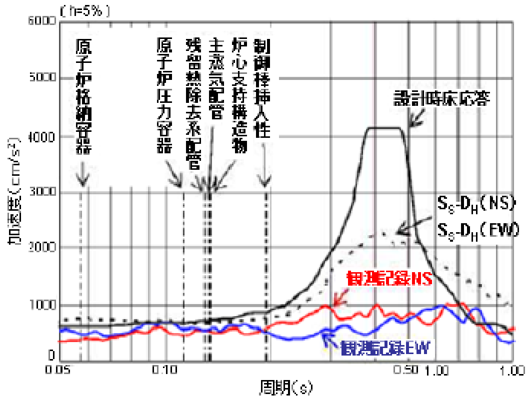

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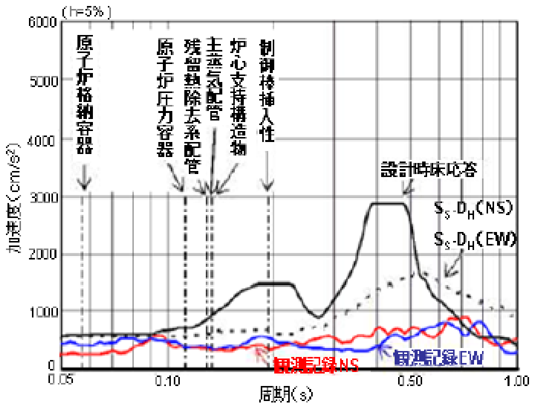

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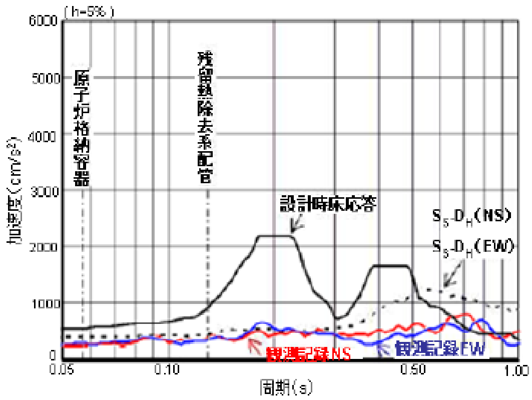


地下 2 階

Observed Floor Spectra (Blue and Red) versus Design Floor Spectra

Tokai Unit 2

- Unexpected large amount of seismically induced sloshing flood was reported not only from Tokai but also from Fukushima Daiichi during 2011 earthquake. Other types of sloshing reportedly occurred in the large transformers and suppression pool.
- Low pressure turbine blades were badly damaged at Onagawa and Tokai. Tokai reactor tripped due to turbine trip caused by high vibration, not by the high vibration signal directly.
- Due to the unfavorable orientation of turbine in Japan, the occurrence of turbine missile must be limited to once per 100,000 turbine-year. However, the turbine is

more sensitive to the seismic motion and it undergoes severe damage before the reactor SCRAM, suggesting that the earthquake may contribute to the turbine missile frequency.

- Overhead crane was damage during 2007 Chuetsu Earthquake. Also a fire protection piping was severed at the penetration to the reactor building and flooded the reactor building.
- All of these impacts above may occur in any domestic plant including Sendai.

3.3 Unanalyzed Reactivity Addition due to Seismic Vibration and Potentially Resultant Fuel Damage and other impacts

Key Points

- On August 23, 2011, an M5.8 earthquake occurred in Virginia State, 11 miles away from North Anna Power Station when both units 1 and 2 are operating at rated power. Both units were automatically shut down, however, it was reported that the cause of their shutdown were due to “High Flux Rate”.
- A similar event was observed in Japan on April 23, 1987 when an M6.5 earthquake occurred at 38km away from Fukushima Daiichi. Units 1, 3, and 5 were shut down due to rapid increase of neutron flux. It is believed that the vibration of fuel assembly momentarily accelerated the separation of voids from the surface of fuel rods, causing an insertion of positive reactivity.
- The event at North Anna in 2011 accidentally proved that this phenomenon could occur on both BWRs and PWRs.
- Fortunately, the power excursion was safely arrested by the reactor SCRAM and neither of these two instances resulted in a gross fuel failure or any damage to the components of reactor pressure boundary. Nevertheless, it is necessary to confirm that the safety limits for the Minimum Critical Power Ratio (MCPR) for the BWR fuels and the Departure from Nucleate Boiling Ratio (DNBR) for the PWR fuels are never violated during any postulated earthquake throughout any operation cycle.

4. Discussions

(1) The methodology and the process to determine the Hard Rock Response Spectra and the Free-Field Ground Surface Response Spectra are only roughly and conceptually explained and are largely left in a “black box”, making it impossible to objectively verify the adequacy. There is no evidence found in the Safety Evaluation Report indicating that the NRA has done it in a thorough manner.

The processes are unclear specifically in the following steps:

- How were the Hard Rock Response Spectra determined?
- What amplification spectra were used to convert the Hard Rock Response Spectra to the Free-Field Ground Surface Response Spectra, and how they were determined?
- What vertical to horizontal (V/H) ratio spectra were used to determine the response spectra in vertical direction based on those in horizontal direction, and how they were determined?
- Due to uncertainties involved in each process above, how much error in total is ultimately included in the Free-Field Ground Surface Spectra?

(2) After all, a total of three different ground surface response spectra are proposed as the design-basis-earthquakes, consisting of Ss-1 and Ss-2 as mentioned above, and Ss-L separately and exclusively proposed for the Seismic Isolation Building. However, the author believes that there should ideally be just a single design-basis-earthquake bounding all three response spectra instead of three different spectra. The author also believes that the justification claimed by the Kyushu and accepted by the NRA to exclude the potential contribution from seismic sources at the plate-to-plate interface by simply implying that the earthquake of the seismic intensity V or greater generated at such a long distance is not anticipated based on the historical data is technically invalid. The author is concerned about the conclusion not to require to superpose the lower frequency (longer period) side of Ss-L spectrum contributed from the long-distance seismic source over either Ss-1 or Ss-2 because it is in fact the lower frequency (longer period) region of vibration spectrum that is mostly responsible for the earthquake impacts previously experienced in the Japanese nuclear power plants. The lower frequency (longer period) region of vibration spectrum of Ss-L should be integrated into design-basis-earthquake applied for the structures, systems, and components not only of those inside Seismic Isolation Building but also of those inside

other plant facilities.

- The Ss-L spectra should not be separated from Ss-1 or Ss-2. Instead, Ss-1 and Ss-2 should contain Ss-L as a part of their low frequency component. Furthermore, a single Ss spectrum should be determined to encompass both Ss-1 and Ss-2 spectra with the modification above. In fact, the US-NRC Regulatory Guide (RG 1.165) does specify this intent as illustrated below.
- The reason that the expected intensity of earthquake from inter-plate is not greater than V does not seem to be appropriate to exclude.
- Frequent occasions exceeding under-estimated low frequency spectra were previously experienced and massive sloshing flood events observed at the spent fuel pools of some BWR units may be attributable to this reasoning.

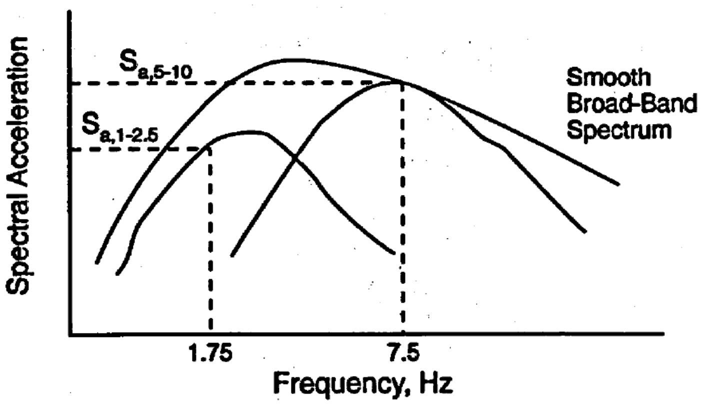
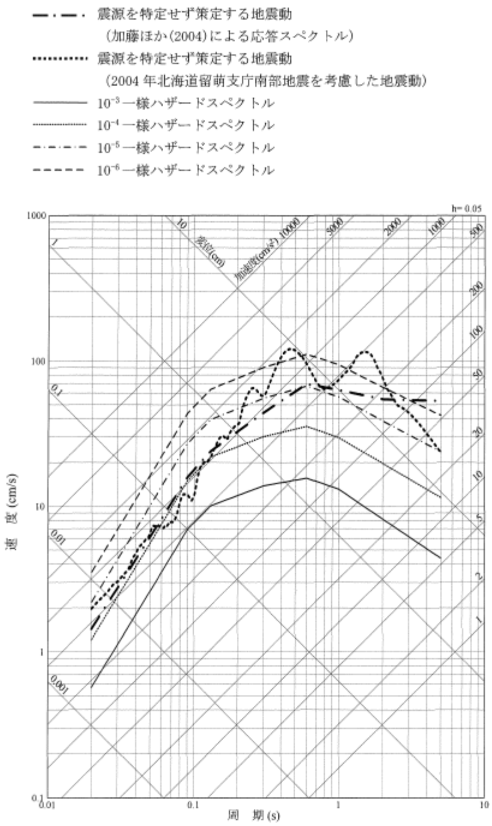


Figure F.3 Development of a Site-Specific SSE Spectrum

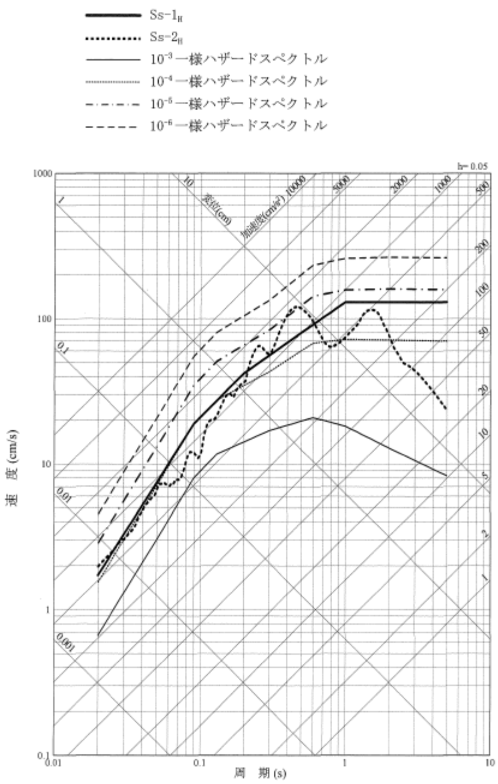
(3) Technical credibility of Uniform Hazard Spectra constructed by the Japan Nuclear Energy Safety Organization (JNES) in 2005 and in accordance with the methodology developed by the Atomic Energy Society of Japan (AESJ) in 2007 is questionable and possibly non-conservative. Nevertheless, there is no objective evidence in the safety evaluation report to support that the NRA has thoroughly assessed the adequacy of these hazard spectra which apparently are other examples of black-box in terms of development processes.

- How were these Uniform Hazard Spectra developed? What data and methodologies were used? How valid are they considering the fact that many large earthquakes occurred especially in the eastern region of the country since they were developed? Should they have been updated by now?
- If these Uniform Hazard Spectra are non-conservative, the conclusion that the AEP being in the range between 1E-6 and 1E-4 is no longer valid.

- The US-NRC and its co-sponsors Department of Energy (DOE) and Electric Power Research Institute (EPRI) studied the seismic hazards in the center and eastern United States and the results were compiled in the report, NUREG-2115. This report is publicly available. No similar document is publicly available to support the Uniform Hazard Spectra constructed by JNES and AESJ.
- Although the JNES spectra and AESJ spectra are significantly different each other, NRA does not comment. Both are developed for the same hard rock, there should not be an excessive difference.
- The JNES spectra is lower than the one for the center and eastern United States for the same AEP. The credibility of JNES spectra is questionable.
- The Uniform Hazard Spectra for the hard rock and for the free-field ground surface are presented below on the left and right respectively. However, the same Ss-2 response spectrum is apparently used for both for comparison. Because of their technical implication, this is to be treated as more than a simple editorial error.



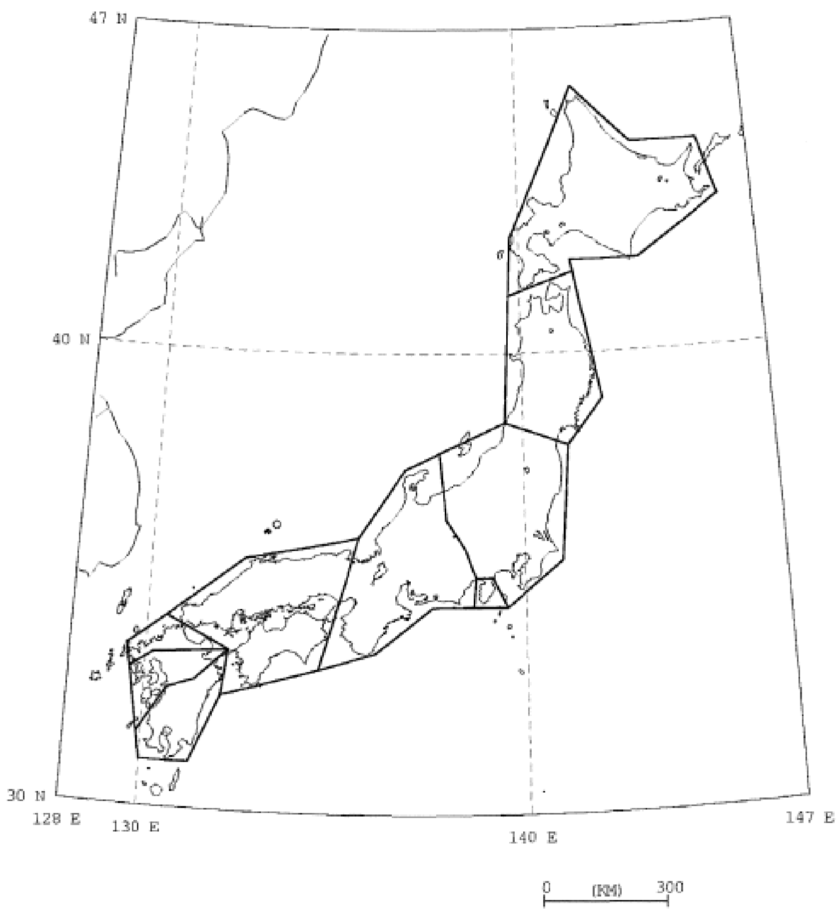
第 7.5.6.42 図　震源を特定せず策定する地震動の応答スペクトル及び
領域震源による地震動の一様ハザードスペクトル（水平方向）



第 7.5.6.60 図　基準地震動の応答スペクトル及び解放基盤表面における地震動の
一様ハザードスペクトル（水平方向）

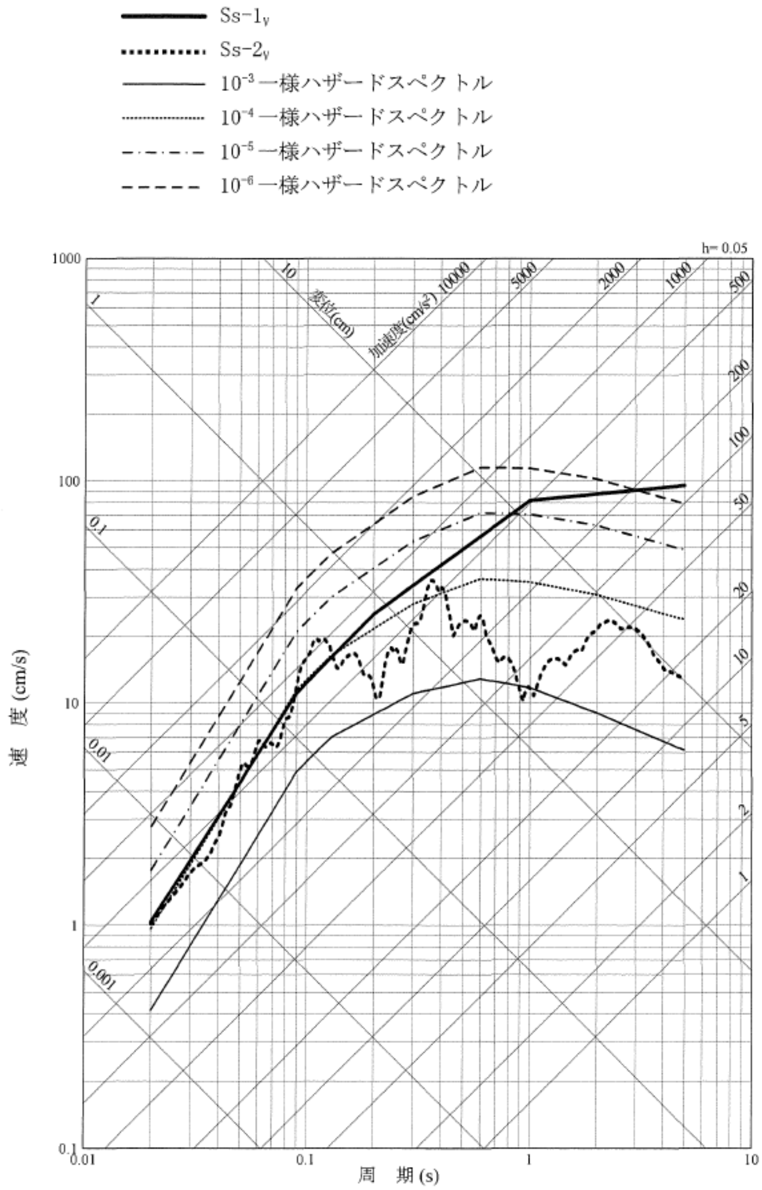
（4） The land territory of Japan is divided into eight regions in a very rough manner by the JNES (2005). Such a region map suggests that all four sites of Fukushima Daiichi, Fukushima Daini, Tokai, and Kashiwazaki-Kariwa belong to the same region, and all sites of Hamaoka, Shika, and the sites along Wakasa-Bay belong to the other same region. It does not seem to be reasonable to apply a single set of uniform hazard spectra to each of such vast regions. Nevertheless, there is no objective evidence in the safety evaluation report to support that the NRA has thoroughly assessed the adequacy of this map.

- JNES divided the entire land territory of Japan into 8 regions. The Seismic Study Commission in 2009 did it quite differently. This brings up a question. What sectioning was used by AESJ when they developed the methodology for the Uniform Hazard Spectra? Are they the same or different each other?
- The NUREG-2115 includes maps of the seismotectonics zones. Detail technical discussions are also presented in the report. No similar information is publicly available to understand the technical basis for JNES' sectioning. It is not clear even whether it represents the seismotectonics zones.



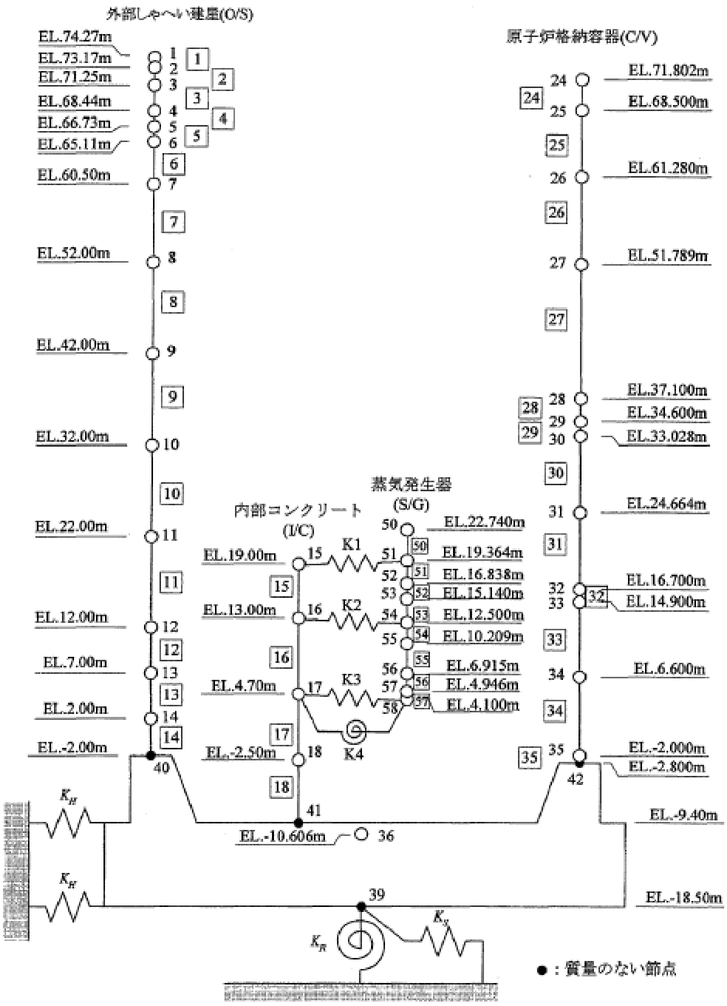
（5） By comparison with those hazard spectra mentioned above, the Kyushu Electric Power Company has derived an overall conclusion that the annual exceedance probability of their design-basis-earthquake is somewhere between 1E-4 and 1E-6 or between 1E-4 and 1E-5. However, those figures referenced in the text actually do not fully support such a conclusion statement. For example, the Ss-2 (vertical) spectrum indicates the annual exceedance probability being between 1E-3 and 1E-4 with some portion even greater than 1E-3. The NRA obviously failed to point out this error.

- The attached figure does not support the statement in text in that one of the free-field ground surface response spectra (Ss-2 vertical) is completely out of the range between 1E-6 and 1E-4. The Ss-2 spectrum was determined without smoothening.



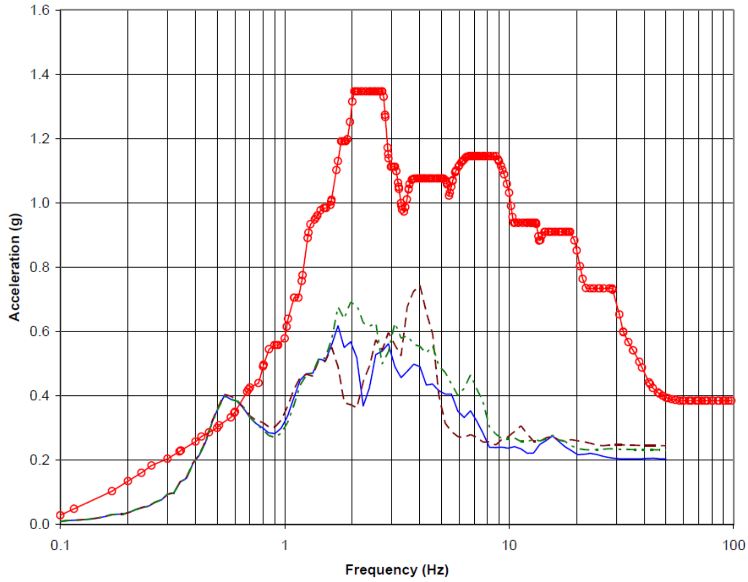
(6) In the seismic response analysis of the containment, the soil-structure interaction (SSI) is considered to be one of the key factors. Although the analysis model contained in the Construction Permit Application implies the consideration of this factor, no values are given to the spring constants of horizontal springs and rotational spring. Therefore, it is not clear if the effect of SSI is really included in the analysis. And if it is not properly considered, the expected output of the analysis could become non-conservative (under-estimation of the seismic behavior) especially in the lower frequency (longer period) side of response spectrum.

- In the sketch below, K_H and K_y represent the horizontal springs and K_R represents the rotational spring. However, no value is given to these parameters. How was NRA able to review the adequacy of Soil-Structure Interface (SSI) evaluation done by Kyushu Electric Power Company?

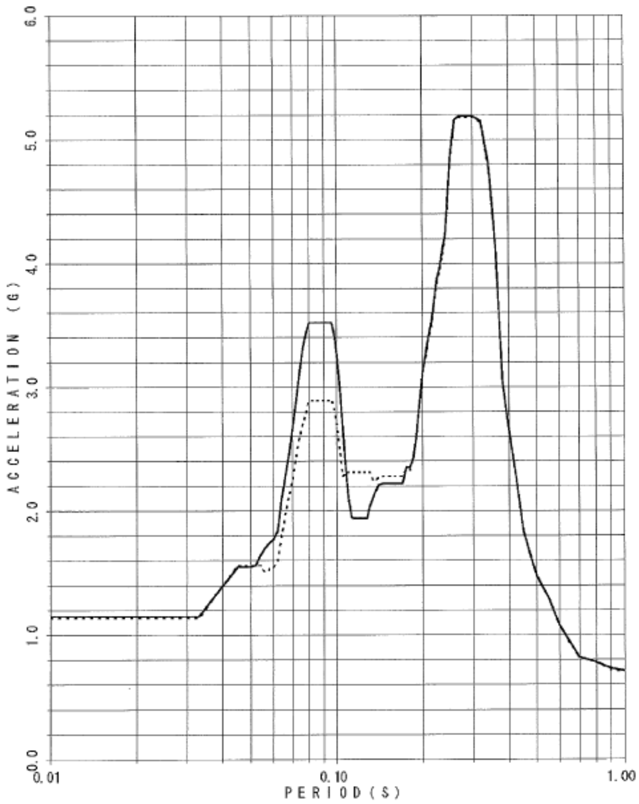


第 2－1 図　原子炉格納施設の地震応答解析モデル（水平方向）

- If the effect of SSI has not been properly incorporated in the analysis, there is a possibility that any significant response in the lower frequency (<1Hz) portion of spectrum has been overlooked. In fact, a sensitivity analysis for the SSI effect for Vogtle revealed the presence of a significant peak below 1 Hz.



- In case of Sendai, the frequency range for analysis is cut off at 1 Hz, disabling to find the potential peaks below 1 Hz.



- The phenomenon potentially overlooked due to this practice is the resonance between building frequency and sloshing frequency. As indicated in the table below, sloshing frequency is significantly below 1Hz.
- To determine whether or not a massive sloshing flood is possible in case of Sendai,

a sensitivity analysis for the SSI effect should be performed for the frequency range including below 1 Hz.

Tank and Seismic Response Direction	Frequency Hertz
Fuel Area	
Fuel Pool, EW	0.39
Fuel Pool, NS	0.26
Fuel Transfer Canal, EW	0.68
Fuel Transfer Canal, NS	0.26
Cask Loading Pit, EW	0.39
Cask Loading Pit, NS	0.37
Cask Washdown Pit, EW	0.39
Cask Washdown Pit, NS	0.36

(7) By under-estimating the lower frequency (longer period) side of seismic behavior, the estimated impacts to the sloshing effects to the tanks, pools, and large transformers, and those steel structures of long span such as the fuel handling machine, overhead polar crane, and meteorological tower, as well as those components not tolerable for the large displacement such as the stainless steel liner of pools, lower pressure turbine rotors, underground pipes/trenches, become all non-conservative.

- Seismic motions in lower frequency region yields relatively lower acceleration but larger displacement, potentially resulting in excessive deformation, rupture of stainless steel liner of spent fuel pool, and additional risk of turbine missile. The tall structures such as meteorological towers and ventilation stacks may resonate with seismic motion especially when it receives strong and stead wind load and its natural frequency is lowered significantly.
- Normal power operation is not the only timing the earthquake may hit. It may hit during and soon after the refueling operation. Sloshing load will be added in the horizontal direction to the telescope mast of refueling bridge if an earthquake occurs while it carries the irradiated fuel assembly for refueling or shuffling. If an earthquake occurs while the spent fuel cask is in being transported by the overhead crane, a significantly more vertical load is added to the crane cable.
- All of the potential impacts above associated with seismic events may have some risk significance.

(8) By under-estimating the lower frequency (longer period) and larger displacement

seismic motion, there are potential hidden risks that could result in various unfavorable consequences to the performances of severe accident mitigation guidelines, the physical protection systems, and the fire brigade activities. For instance, the damages to the roads assigned for the transportation of mobile equipment to mitigate the severe accident, the derailed physical protection gages, and broken emergency lights inside building could significantly hinder the critical actions under the emergency. If the ceiling of the building is heavily loaded with moistened volcanic ash or wet snow, and the natural frequency is lowered sufficiently, it may resonate with the lower frequency of earthquake, resulting in a collapse to the important equipment underneath.

(9) It has been learned from the previous events that the seismic vibration creates some perturbation to the coolant in proximity of fuel rods and adds extra positive reactivity. Fortunately, such previous events have not resulted in fuel failure. However, the possibility of exceeding the safety limit, leading to the gross fuel failure and damage to the reactor pressure boundary under unfavorable conditions and/or severer seismic events should be assessed.

The fact that the reactor core behaves so sensitively relative to the seismically induced vibratory motion even below the SCRAM set point poses a significant concern. Although various bounding reactivity additions are postulated as a part of Design Basis Accident analysis, this type of reactivity abnormity has never been evaluated in a comprehensive manner in the past.

5. Conclusions

The following conclusions are commonly applicable not only for Sendai but also all other nuclear power plants in Japan.

- Unlike US-NRC's Regulatory Guide (RG 1.165), the procedure to construct DBE spectrum for Sendai does not require the integration of low frequency components contributed from the high magnitude long distance seismic sources. This results in a non-conservative DBE spectrum. The DBE spectrum is typically constructed with a set of several straight lines to encompass all expected response spectra. However, the Ss-2 spectrum for Sendai is a raw response spectrum and not smoothened.
- Because a time history wave is synthesized based on a DBE response spectrum, the non-conservatism with the DBE response spectrum in the low frequency regrion is carried over to the time history wave.
- It is questionable if the concept of uniform hazard spectrum is adequately employed in the probabilistic analysis. There is a significant difference between the one constructed by JNES (2005) and the one constructed in accordance with the procedure proposed by AESJ (2007). It should be noted that the one constructed by JNES (2005) is lower than the one for the central and eastern United States for the same AEP. The same response spectrum (Ss-2) is (possibly erroneously) compared with the two different uniform hazard spectra, one for the hard rock and the other for the free-field ground surface.
- The AEP of DBE response spectra relative to the uniform hazard spectra for the free-field ground surface being in the range between 1E-6 and 1E-4 is apparently a wrong conclusion. One of the DBE response spectra (Ss-2V) shows a significant exceedance beyond 1E-4 over a wide range and even 1E-3 locally. This indicates that such a DBE response spectrum does not meet the international requirement.
- There is basically no explanation provided about the process to construct the uniform hazard spectra. The basis for the seimotectonic zones is not discussed either. There should be publicly available references equivalent to NUREG-2115 and NRA should review the technical adequacy of such references.
- The Structure-Soil Interaction (SSI) may not have been adequately evaluated. This may contribute to the non-conservative estimate especially for the low frequency region of floor response spectra.
- Knowledge gained from the previous events including Niigata-Chuetsu-Earthquake, Great-Tohoku-Earthquake, and the ones in the US, have not been sufficiently used. Evaluation of impacts due to the earthquake (not simply by acceleration) should not be limited to the structural analysis. It should be applied for other potential impacts

such as sloshing of water pools and transformer oil, turbine missile, and positive reactivity addition. To enhance the evaluation for these potential impacts, the floor response spectra should be expanded to cover the range from 0.1 to 100Hz instead of 1 to 100Hz as currently done.

6. References

This report discussed some significant findings along technical basis for each, as a result of reviewing the following documents:

- "Amendment Request for Site Permit for Power Generating Reactor at Sendai Nuclear Power Station" submitted to the Nuclear Regulatory Authority (NRA) by the Kyushu Electric Power Company on July 8, 2013 along with two supplemental revisions submitted on June 14, 2014 and September 4, 2014, and the associated Safety Evaluation Report prepared by the NRA, "Compliance of Standards under the Law Regulating Nuclear Resources, Nuclear Fuel Materials, and Nuclear Power Reactors in the matter of Amendment Request for Site Permit for Power Generating Reactors for the Kyushu Electric Power Company Sendai Nuclear Power Station Units 1 and 2".
- "Construction Permit Application for the Sendai Nuclear Power Station Units 1 in the matter of Facility Modification" submitted to the NRA by the Kyushu Electric Power Company on July 8, 2013 along with two supplemental revisions submitted on September 30, 2014 and October 8, 2014.

In reviewing the contents and conclusions contained in the documents above, the author has collectively based on the following as a guide and reference.

1) US. Nuclear Regulatory Commission (NRC) Regulatory Guide (RG) 1.165 "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion", Rev.0 March 1997.
2) NUREG-2115 (DOE/NE-0140, EPRI 1021097) "Central and Eastern United States Seismic Source Characterization for Nuclear Facilities" (2012)
3) Early Site Permit, Part-2 (Site Safety Analysis Report) submitted by the Southern Nuclear Power Company for Vogtle Units 3 and 4.
4) International Atomic Energy Agency (IAEA) Safety Standard, NS-G-1.6 "Seismic Design and Qualification for Nuclear Power Plants"(2003).
5) General perspectives from the 2007 Niigata-Chuetsu Offshore Earthquake and the 2011 Great Tohoku Earthquake.
6) Licensee Event Report (LER) 2011-003-00 "Dual Unit Reactor Trip and ESF Actuation During Seismic Event With a Loss of Offsite Power" submitted by Virginia Electric Power Company North Anna Power Station (October 20, 2011)