A PRA Practioner looks at the Great East Japan Earthquake and Tsunami

A Ninokata Laboratory White Paper

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April 29th, 2011

INTRODUCTION

Background

The Fukushima Daiichi Nuclear Power Plant accident is an ongoing sequence of equipment, planning, and institutional failures resulting in releases of radioactive materials following the $9.0M_W$ Tōhoku earthquake and three tsunami, the largest of which was reported by TEPCO to be 14m tsunami, on March 11th, 2011, at 14:46 JST. The maximum PGA (peak ground acceleration) of the earthquake was measured at 2.99g in Miyagi prefecture at seismic site MYG004; the PGA in the vicinity of Fukushima Daiichi can be estimated as having been between 1.38g and 1.51g, the readings measured at FKS010 and FKS016, respectively, but perhaps greater.

Eleven reactors in Japan went into automatic shutdown.

The Fukushima Daiichi plant is connected to the rest of the power grid by three lines, the 500 kV Futaba Line and the two 275 kV Ookuma Lines to the Shin-Fukushima substation.

The Shin-Fukushima substation also connects to the Fukushima Daini plant by the Fukuoka Line. Its major connection to the north is the Iwaki Line, which is managed by another company. It has two connections to the south-west that connect it to the Shin-Iwaki substation.

At the time of the quake, reactor 4 had just been defueled while 5 and 6 were in cold shutdown for planned maintenance. The quake caused loss of offsite power, as the external power grid failed. The remaining reactors shut down automatically after the earthquake, with emergency diesel generators starting up to run the control electronics and water pumps needed to cool reactors.

The earthquake intensity has been estimated to be Shindo 6+ at the Fukushima sites. The Shindo scale is a measure of intensity, based to some extent on PGA (peak ground acceleration) and indicates a PGA of somewhere between 3.0m/s^2 to +4.0m/s^2. A Shindo scale table is included in the Appendix.

At this time, there seems to have been no substantial seismic damage to the safety systems of any of the three NPP sites, Onagawa, Fukushima Daini, and Tokai. Seismic damage to Fukushima Daiichi has not yet been ascertained. Until a detailed seismic walkdown can be done at all four NPP affected, it is impossible to make an informed judgement.

The plant was protected by a tsunami wall designed to withstand a 5.7m tsunami, but was not high enough to withstand the three tsunami waves which arrived during a 41 to 60 minute interval after the earthquake.

The entire plant was flooded, including the low lying diesel generators and electrical switchgear in reactor basements and external pumps for supplying cooling seawater. The connection to the electrical grid was totally lost and all emergency power was lost. All power for cooling was lost and the reactors started to overheat, due to natural decay of the fission products created before shutdown. The flooding and earthquake damage hindered external assistance, and subsequent releases of radioactivity to the air, soil, and sea have resulted.

As of the writing of this report, April 29, 2011, this accident has not yet reached a conclusion. The on-going situation is still a clear and present danger.

The Purpose of the Report

Why did this accident occur? Could it have been prevented or mitigated? What are the implications for the people of Japan? What are the implications for the nuclear industry?

From the PRA (Probabilistic Risk Assessment) point of view, the answers to these “whys” are the answers to the fundamental questions of risk assessment: What went wrong? How likely was it? What are the consequences?

It will be some time until definitive answers to these questions can be fully made. However, in an attempt to provide some guidance, even at this early stage, we will try to collect and analyze data and informed opinion concerning the Fukishima Daiichi accident as it was impacted by the earthquake and tsunami, focusing on the first two questions of PRA: What went wrong? How likely was it?

WHAT WENT WRONG?

> "From a PRA perspective: CDF = 1; release frequency = 1; and unfortunately, however we want to characterize the Level 3 parameter, it is >1." – Mark Reinhart, in a private communication after the Fukushima Daiichi accident, received on March 18th, 2011

From the PRA Point of View

The tsunami generated by the Great East Japan Earthquake caused the sequence of events and cascading accidents resulting in total station blackout at Fukushima Daiichi, loss of cooling, hydrogen explosions, and eventually radioactive dispersion into the air, deposition onto the land, and flow into the ocean. From preliminary seismic walkdowns at the Onagawa, the Fukushima Daini, and Tokai NPPs we can perhaps infer that no seismically caused safety system damages occurred. The author wants to emphasize the word "perhaps".

The earthquake did cause the loss of offsite power initiating event as well as severely hampering recovery activities because of the damage to the local infrastructure. Seismic damage to the piping systems and concrete inside the Daiichi reactors may never be known, in some cases, because of the damage caused by the tsunami and hydrogen explosions. High radiation levels detected in Unit 1 on the evening of March11th could have been the result structural damage caused by the earthquake or the tsunami shock wave.

It should be noted that in Level 2 PRA, seismic-induced diesel generator failure, leading to total station blackout, leading to failure of cooling systems is the most likely cause of nuclear accidents from an external event.

The events at Fukushima Daiichi also point to omissions in many Level 2 PRAs which led to less than optimal emergency planning. While not directly contributing to "what went wrong", they certainly contributed to an attitude of complacency and subsequent belief that the events which did occur were "unforeseeable".

Section 1 answers the question of "what went wrong" by examining the earthquake, the tsunami, and the PRA omissions. Discussion of the adequacy of the frequency estimates for both an earthquake and tsunami of the size experienced is in Section 2, "How likely was it?"

The Earthquake

The Great East Japan Earthquake occurred at 14:46 JST, March 11, 2011. Its epicentre was located at 38.3 °N, 142.4 °E, which is off the Sendai coast 130km ESE of Oshika Peninsula, with a focal depth of 24km.

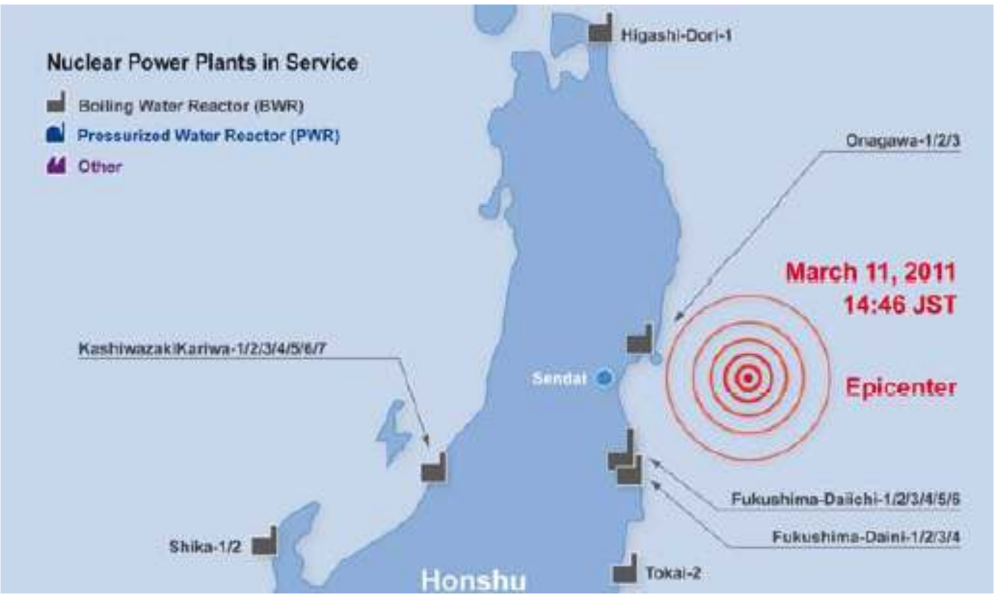
Two days before the main shock, an earthquake of 7.3M_W occurred off the Sendai coast at 11:45, March 9. It was accompanied by active aftershocks including a 6.8M_W event the next day. These events were located just north of the March 11th epicentre, implying that it was indeed a foreshock. Interestingly, Yoshimitsu Okada, the President of NIED (National Research Institute for Earth Science and Disaster Prevention), later stated that "… since an earthquake of 7.3 M_W is a sufficiently large one by itself, no one could ***imagine*** that this event could be linked to a coming huge earthquake" (the bold italics ours).

A seismic intensity of 7 on the JMA (Japan Meteorological Agency) scale was recorded at Kurihara City, Miyagi Prefecture, and intensities of 6+ or 6- were observed in a wide area along the Pacific region, ranging from Iwate Prefecture to Ibaraki Prefecture.

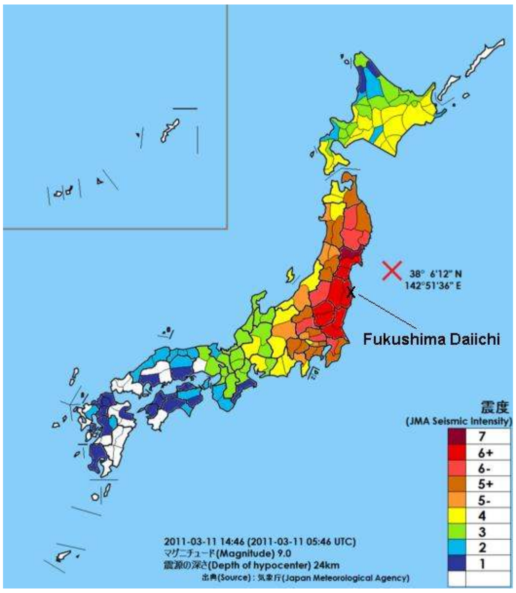
A PGA of 2,933gal (a composite of the three vector components) was observed at Tsukidate, Kurihara City, one of the NIED K-NET station.

It was the third time that an intensity of 7 was recorded in Japan following the 1995 Kobe Earthquake (7.3M_W) and 2004 mid-Niigata Earthquake (6.8M_W).

The magnitude of the earthquake was initially announced as 7.9M_W by JMA and was then revised to 8.4M_W at 16:00 and again revised to 8.8M_W at 17:30. It was finally determined to be 9.0M_W on March 13,



The measure of an earthquake in Japan is given by the JMA (Japan Meteorological Agency) Shindo scale of 1 to 7, which is an intensity scale. Many Sanriku and Sendai coast accelerations were estimated because some of the K-Net stations, K-Net is the electronic seismic network of NIED, were inoperable. The estimated intensity for Fukushima Daiichi was 6+.

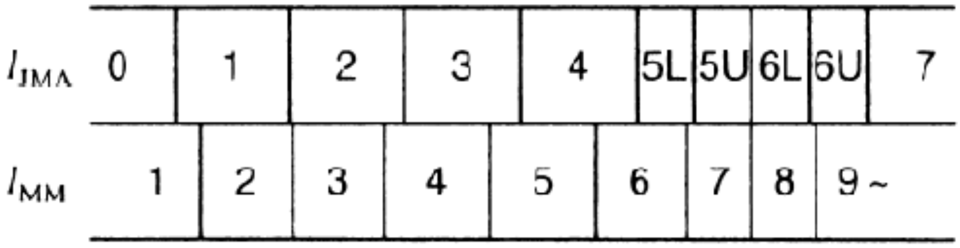


Shindo Scale

Number (Shindo Number in Japanese) / *Meter reading*	**People**	**Indoor situations**	**Outdoor situations**	**Wooden houses**	**Reinforced-concrete buildings**	**Lifelines**	**Ground and slopes**	**PGA**
0 (0) / *0–0.4*	Imperceptible to people.							Less than 0.008 m/s²
1 (1) / *0.5–1.4*	Felt by only some people indoors.							0.008–0.025 m/s²
2 (2) / *1.5–2.4*	Felt by most people indoors. Some people awake.	Hanging objects such as lamps swing slightly.						0.025–0.08 m/s²
3 (3) / *2.5–3.4*	Felt by most people indoors. Some people are frightened.	Dishes in a cupboard rattle occasionally.	Electric wires swing slightly.					0.08–0.25 m/s²
4 (4) / *3.5-4.4*	Many people are frightened. Some people try to escape from danger. Most sleeping people awake.	Hanging objects swing considerably and dishes in a cupboard rattle. Unstable ornaments fall occasionally.	Electric wires swing considerably. People walking on a street and some people driving automobiles notice the tremor.					0.25–0.80 m/s²
5-lower (5 弱) / *4.5-4.9*	Most people try to escape from a danger. Some people find it difficult to move.	Hanging objects swing violently. Most unstable ornaments fall. Occasionally, dishes in a cupboard and books on a bookshelf fall and furniture moves.	People notice electric-light poles swing. Occasionally, windowpanes are broken and fall, unreinforced concrete-block walls collapse, and roads suffer damage.	Occasionally, less earthquake-resistant houses suffer damage to walls and pillars.	Occasionally, cracks are formed in walls of less earthquake-resistant buildings.	A safety device cuts off the gas service at some houses. On rare occasions water pipes are damaged and water service is interrupted. (Electrical service is interrupted at some houses)	Occasionally, cracks appear in soft ground, and rockfalls and small slope failures take place in mountainous districts.	0.80–1.40 m/s²
5-upper (5 強) / *5.0–5.4*	Many people are considerably frightened and find it difficult to move.	Most dishes in a cupboard and most books on a bookshelf fall. Occasionally, a TV set on a rack falls, heavy furniture such as a chest of drawers fall, sliding doors slip out of their groove and the deformation of door frames makes it impossible to open doors.	In many cases, unreinforced concrete-block walls collapse and tombstones overturn. Many automobiles stop because it becomes difficult to drive. Occasionally, poorly-installed vending machines fall.	Occasionally, less earthquake-resistant houses suffer heavy damage to walls and pillars and lean.	Occasionally, large cracks are formed in walls, crossbeams and pillars of less earthquake-resistant buildings and even highly earthquake-resistant buildings have cracks in walls.	Occasionally, gas pipes and / or water mains are damaged.(Occasionally, gas service and / or water service are interrupted in some regions)	Occasionally, cracks appear in soft ground. and rockfalls and small slope failures take place in mountainous districts.	1.40–2.50 m/s²

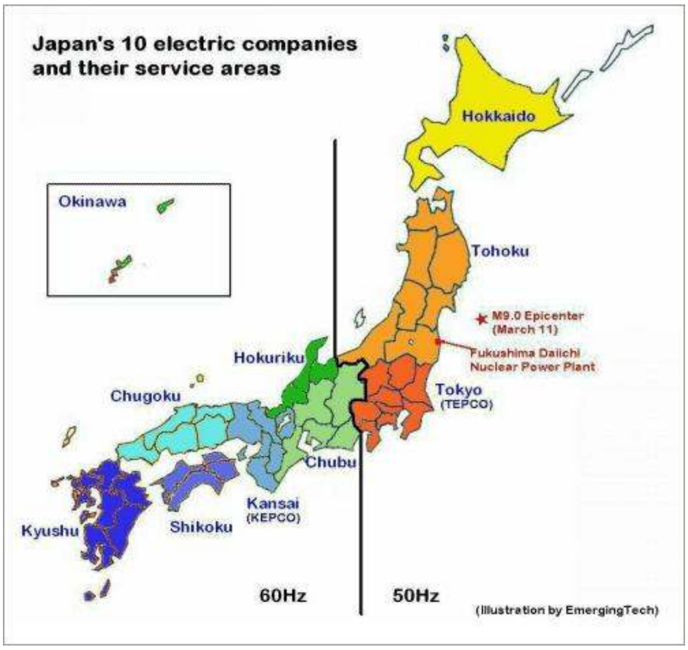
6-lower (6 弱) / *5.5–5.9*	Difficult to keep standing.	A lot of heavy and unfixed furniture moves and falls. It is impossible to open the door in many cases.	In some buildings, wall tiles and windowpanes are damaged and fall.	Occasionally, less earthquake-resistant houses collapse and even walls and pillars of highly earthquake-resistant houses are damaged.	Occasionally, walls and pillars of less earthquake-resistant buildings are destroyed and even highly earthquake-resistant buildings have large cracks in walls, crossbeams and pillars.	Gas pipes and/or water mains are damaged. (In some regions, gas service and water service are interrupted and electrical service is interrupted occasionally.)	Occasionally, cracks appear in the ground, and landslides take place.	2.50–3.15 m/s²
6-upper (6 強) / *6.0–6.4*	Impossible to keep standing and to move without crawling.	Most heavy and unfixed furniture moves and falls. Occasionally, sliding doors are thrown from their groove.	In many buildings, wall tiles and windowpanes are damaged and fall. Most unreinforced concrete-block walls collapse.	Many, less earthquake-resistant houses collapse. In some cases, even walls and pillars of highly earthquake-resistant houses are heavily damaged.	Occasionally, less earthquake-resistant buildings collapse. In some cases, even highly earthquake-resistant buildings suffer damage to walls and pillars.	Occasionally, gas mains and / or water mains are damaged.(Electrical service is interrupted in some regions. Occasionally, gas service and / or water service are interrupted over a large area.)	Occasionally, cracks appear in the ground, and landslides take place.	3.15–4.00 m/s²
7 (7) / *6.5 and up*	Thrown by the shaking and impossible to move at will.	Most furniture moves to a large extent and some jumps up.	In most buildings, wall tiles and windowpanes are damaged and fall. In some cases, reinforced concrete-block walls collapse.	Occasionally, even highly earthquake-resistant buildings are severely damaged and lean.	Occasionally, even highly earthquake-resistant buildings are severely damaged and lean.	Electrical service gas service and water service are interrupted over a large area.	The ground is considerably distorted by large cracks and fissures, and slope failures and landslides take place, which occasionally change topographic features.	Greater than 4 m/s²

The empirically obtained relationship between Shindo instrumental intensity, I_{JMA}, and instrumental modified Mercalli intensity, I_{MM}, is clearly given below:



The four nuclear power plants directly affected were Onagawa, Fukushima Daiichi, Fukushima Daini, and Tokai; they are approximately 90km, 160km, 170km, and 260km from the epicentre, respectively. The largest city in Tōhoku, Sendai, is approximately 150km from the epicentre.

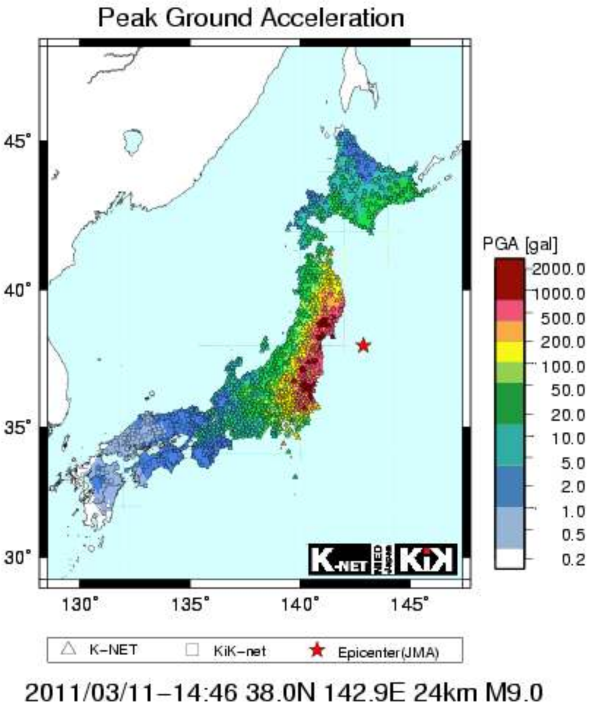
There were earthquake induced shutdowns of several conventional power plants and all nuclear power plants, 11 units, in Tōhoku.



Western and eastern Japan have different electrical frequencies, the western section at 60Hz and the eastern section at 50Hz. The reason for this difference is historical and although a unified electrical grid has been suggested many times since World War II, the high cost of the venture was always deferred since the investment of capital into actual power generation was deemed more important as post-war Japan recovered. As a result, there are only three frequency converters with a total capacity of approximately 1GW.

When the shutdown of 11 units caused a 10GW shortfall in electricity, rolling blackouts occurred all through eastern Japan for several weeks. While not usually thought of as a risk, the frequency incompatibility contributed to slow recovery during emergency operations, hospital service, and even some deaths of the elderly and infirm from failures of medical devices and heat. Moreover, this summer when electrical consumption reaches its peak, power shortages will affect an already fragile economy.

The PGA of the earthquake and the design basis of the Fukushima plants and units are shown in the shake map and table below.



Fukushima	PGA in cm^2		
	Horizontal		Vertical
	N-S	E-W	
Daiichi 1	460	447	258
Daiichi 2	348	550	302
Daiichi 3	322	507	231
Daiichi 4	281	319	200
Daiichi 5	311	548	256
Daiichi 6	298	444	244
Design Basis	441	438	412
Daini 1	254	230	305
Daini 2	243	196	232
Daini 3	277	216	208
Daini 4	210	205	288
Design Basis	415	415	504
SCRAM Limit	135 - 150		100

The values in red show that measured acceleration values in the east-west direction were on the average 10% greater and in one case 26% greater than the design basis for the Daiichi units.

In Japan, the regulatory seismic design basis for NPP is measured in PGA, not magnitude. This is proper, since the fragility studies in a seismic PRA always use the PGA ranges as the initiating events and for calculating the hazard curves and fragility curves for components to understand system failures given an earthquake with a given PGA.

The ground type can significantly influence ground acceleration, so PGA values can display extreme variability over distances of a few kilometres, particularly with moderate to large earthquakes. Due to the complex conditions affecting PGA, earthquakes of similar magnitude can offer disparate results, with many moderate magnitude earthquakes generating significantly larger PGA values than larger magnitude quakes.

A digression in the spirit of risk assessment: the Kashiwazaki NPP on the Japan Sea in Niigata Prefecture has more units than any other site in the Japan. There are five BWR based on GE-BWR-5, and two ABWR. In the Niigata earthquake of 2007, both the older and newer units suffered accelerations 200% to 300% greater than design basis. There was no major damage to safety systems; however TEPCO did release radioactive water into the Japan Sea and vented contamination into the air without informing the local or central governments. In fact, TEPCO initially covered up the incident and only received a light admonishment by the regulator.

Three important lessons can be learned from Kashiwazaki. First, safety cannot be measured by an absence of accidents, which is largely dependent on luck, but is the result of constant, active identification of hazards and their elimination. Near misses, such as no major damage to safety systems, are not testimonials to safe practices. Second, beliefs that near misses, or invocations of backup systems, prove a plant to be robust is the first step into safety complacency. Third, a cultural of misrepresentation will eventually earn the enmity of everyone.

Seconds after the initial earthquake, the 11 units at Fukushima Daiichi, Fukushima Daini, Onagawa, and Tokai went into automatic shutdown. There was a turbine room fire at Onagawa-1 which was extinguished in 3 to 4 hours. Fukushima Daiichi suffered loss of offsite power as a result of the earthquake. The emergency generators started as did emergency cooling.

In a private interview with a worker at Fukushima Daini we learned that 3 out of the four power lines from the offsite grid failed after the earthquake, taking offsite power away from one of the units. The on-duty manager quickly understood the situation and distributed the remaining power line to the unit without power. It is unknown to us if the diesel generators at Daini were operable after the tsunami.

Dr. Robert Geller, of the Tokyo University Earth Science department, has a unique view as to why TEPCO, the central Japanese government, and the regulators were unprepared for such a large earthquake and tsunami. Even though seismic experts such as Dr. Katsuhiko Ishibashi, of Kobe University, and Dr. Ryohei Morimoto, retired professor of volcanology, repeatedly warned about the dangers of earthquakes and tsunami to NPP, their voices went unheeded. Dr. Morimoto said, “I’ve heard the government and TEPCO say they couldn’t predict the tsunami would reach that high, but that is ridiculous, as any history book would have set them straight … and even if they could not predict, they should have been prepared for waves similar to the past.”

Dr. Geller believes that the government focuses on “foreseeable” earthquakes based on questionable modelling. He says that this in turn takes focus and emergency preparations away from other possibilities, particularly the dangers to areas considered to be less at risk by the model predictions, but with high consequences. Here are two short excerpts from his April 27, 2011 article in Nature, which is included in the appendix:

> The modellers assume that ‘characteristic earthquakes’ exist for various zones, choose the fault parameters for each zone as the input to their model, and then produce probabilistic hazard maps.
>
> Although such maps may seem authoritative, a model is just a model until the methods used to produce it have been verified. The regions assessed as most dangerous are the zones of three hypothetical ‘scenario earthquakes’ (Tokai, Tonankai and Nankai). However, since 1979, earthquakes that caused 10 or more fatalities in Japan actually occurred in places assigned a relatively low

> probability. This discrepancy — the latest in a string of negative results for the characteristic earthquake model and its cousin, the seismic-gap model, strongly suggests that the hazard map and the methods used to produce it are flawed and should be discarded. [Nature, Vol. 472, pg. 408]

and he goes on:

> It is time to tell the public frankly that earthquakes cannot be predicted, to scrap the Tokai prediction system and to repeal the LECA [a law which mandates government earthquake prediction systems]. All of Japan is at risk from earthquakes, and the present state of seismological science does not allow us to reliably differentiate the risk level in particular geographic areas. We should instead tell the public and the government to 'prepare for the unexpected' and do our best to communicate both what we know and what we do not. And future basic research in seismology must be soundly based on physics, impartially reviewed, and be led by Japan's top scientists rather than by faceless bureaucrats. [ibid, pg. 409]

Dr. Geller correctly points out that one of the leading contributors to "what went wrong" at Fukushima Daiichi was an inability by anyone involved in decision making or regulation to "expect the unexpected".

Even as late as January 1, 2011, NIED was representing only the Hamaoka NPP as having a probability higher than 10% during the next 30 years. The table below presents the original document and a translation.

Probability of an earthquake Greater than Shindo 6 During the Next 30 Years

NPP	Prefecture	Probability in %	
Tomari	Hokkaido	0.4	
Higashi Dori	Aomori	2.2	
Onagawa	Miyagi	8.3	
Kashiwazaki	Niigata	2.3	
Fukushima Daiichi	Fukushima	0.0	
Fukushima Daini	Fukushima	0.6	
Tokai Daini	Ibaraki	2.4	
Hamaoka	Shizuoka	84.0	
Shika	Ishikawa	0.0	
Tsuruga	Fukui	1.0	
Mihama	Fukui	0.6	
Ooi	Fukui	0.0	
Takahama	Fukui	0.4	
Shimane	Shimane	0.0	
Ikata	Ehime	0.0	
Genkai	Saga	0.0	
Sendai	Kagoshima	2.3	
Monju	Fukui	0.5	

30年以内に震度６強以上の地震が起きる確率

〔算定基準日は
2011年１月１日〕

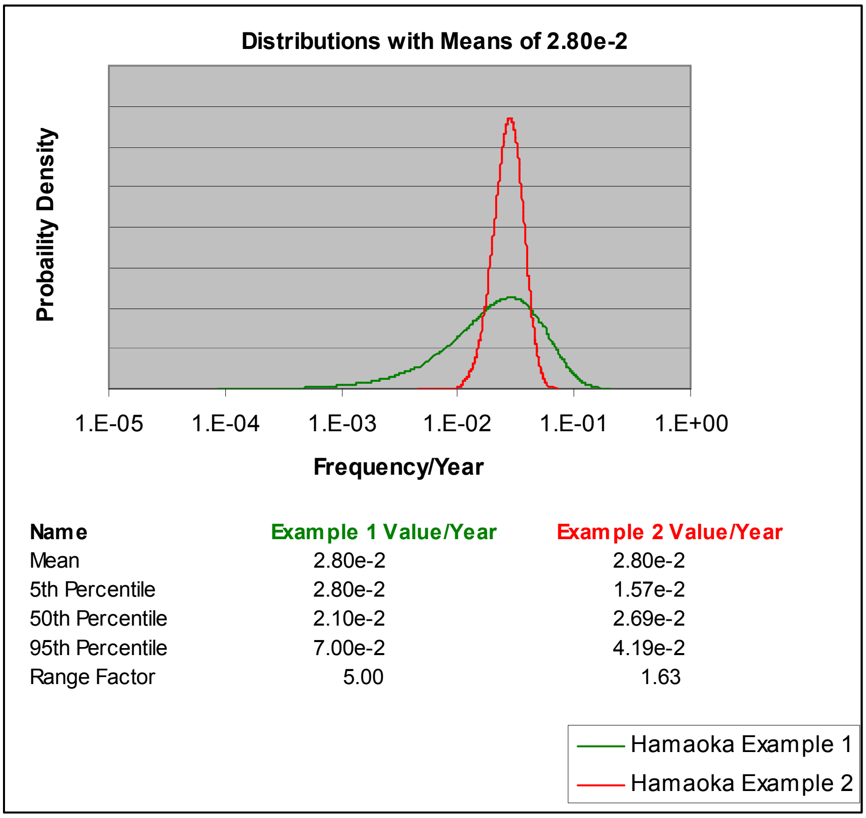
原　発	確率
泊　　　（北海道）	0.4%
東　　通（青　森）	2.2
女　　川（宮　城）	8.3
柏崎刈羽（新　潟）	2.3
福島第１（福　島）	0.0
福島第２（福　島）	0.6
東海第２（茨　城）	2.4
浜　　岡（静　岡）	84.0
志　　賀（石　川）	0.0
敦　　賀（福　井）	1.0
美　　浜（福　井）	0.6
大　　飯（福　井）	0.0
高　　浜（福　井）	0.4
島　　根（島　根）	0.0
伊　　方（愛　媛）	0.0
玄　　海（佐　賀）	0.0
川　　内（鹿児島）	2.3
もんじゅ（福　井）	0.5

（注）原子炉の炉心での確率。カッコ内は所在地。福島原子力発電所事故対策統合本部の資料による

There are some disturbing aspects to this table.

The first is the notion of a “30 year event”, which originated in the insurance industry by actuaries to characterize payback periods. This is a misrepresentation, in the above case, of probability. For example, the Tomari NPP is given a 0.4% probability of a Shindo>=6 earthquake within the next 30 years. What this really means is that the probability of the event at Tomari is 1.33e-04/year. From a probabilistic standpoint, a Shindo>=6 earthquake could happen tomorrow, or perhaps never. Probability measures a state of knowledge or belief. Even from a statistical point of view we would say that as time approaches infinity, we could expect the yearly average of Shindo>=6 earthquakes to approach a rate of 1.33e-04/year.

The second aspect is that these percent per year values can only represent a mean value of some underlying probability distribution, which is not presented to us. The probability distribution represents our uncertainty, which is not some noisy variation around a mean value that represents the true situation. Variation itself is nature's only irreducible essence. Variation is the hard reality, not a set of imperfect measures for a central tendency. Means and medians are the abstractions. Moreover, it is possible to have many probability distributions with the same mean value, but represent entirely different ranges of uncertainty. Below, we present an example of two imagined distributions for the Hamaoka NPP, each with a mean value of 84% within 30 years, or 2.80e-2/year, as suggested by the NIED chart in 2.2.23.



Name	**Example 1 Value/Year**	**Example 2 Value/Year**
Mean	2.80e-2	2.80e-2
5th Percentile	2.80e-2	1.57e-2
50th Percentile	2.10e-2	2.69e-2
95th Percentile	7.00e-2	4.19e-2
Range Factor	5.00	1.63

The two distributions represent entirely different states of knowledge. Example 1 has a long tail on the left and a broad uncertainty; example 2 is focused, with little variability and a smaller uncertainty than example 1. The decisions made for consequence preparation differs depending on which distribution actually represents our state of knowledge.

The third problem is the false sense of security that small numbers give to regulators, the government, and most importantly to the public. The small numbers produced by simulations, widely seen as involving complicated calculations, have the effect of what might be termed false or misplaced correctness, especially on policy makers and the general public. As a result, many people in evacuation centres told us that the government and TEPCO constantly assured them that the plant was 100% safe from natural hazards. TEPCO, the regulators, and the government considered the event as *sōtēgai,* out of imagination. Perhaps they knew better, or perhaps they believed, incorrectly, that since some of the plants would be decommissioned within 30 years there was no immediate threat. Ironically, Daiichi was scheduled for decommission, but was given a 10-year extension by the regulators and the government in February, 2011, one month before the earthquake and the tsunami. So much for 30 years.

And finally is the presentation of 6 plants as having a probability of 0.0% of a Shindo>=6 earthquake within the next 30 years. We assume that this means a probability of less than 0.05% (5.0e-4), since the other values all have one decimal place, with assumed round-up. Representations such as this only reinforce the belief that there is no danger; zero is a dangerous number to present, especially if the truth is greater than zero.

TEPCO and Toshiba have claimed that there was no damage to safety systems caused by the earthquake. Perhaps this is true. We may never know.

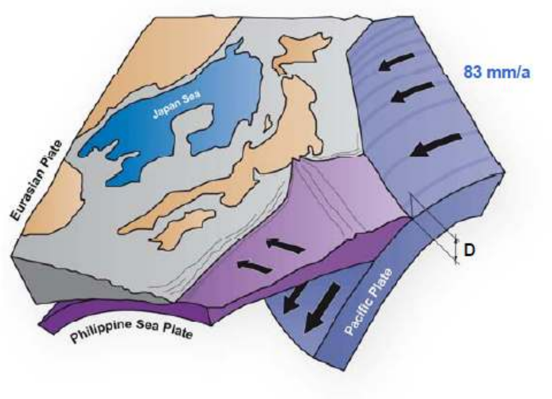
About 41 minutes after the earthquake the first of the tsunami arrived at Daiichi.

The Tsunami

It is usual that an inter-plate earthquake occurring in a trench region can be accompanied by tsunami (called an *earthquake-induced tsunami*). Since the magnitude of this earthquake was so great, the scale of generated tsunami was also. In the case of the earthquakes that have occurred in recent years, a relationship between the Mw value determined by a seismic wave analysis and the assumed Mw value of tsunami has been observed. In particular, the Pacific Ocean shows a trend in which the Mw value of the tsunami generally exceeds the Mw value of the earthquake

In Japan, large tsunami have occurred along the Pacific coast, from Hokkaido to Okinawa, and tsunami have also been observed along the coast of the Japan Sea, the Okhotsk Sea, and the East China Sea.

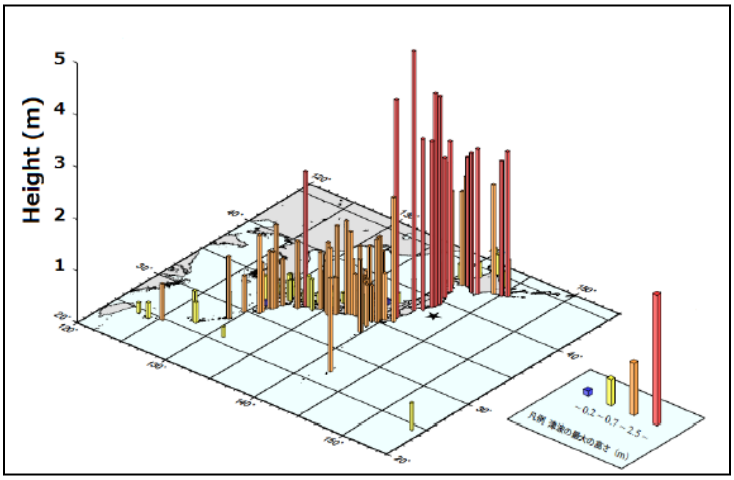
The Great East Japan Earthquake took place along the fault known as the Japan Trench Megathrust, in a subduction zone where the Pacific Plate, the Eurasian Plate, and the Philippine Sea Plate all meet.



Measure Name	Amount (estimated)
Vertical Displacement (D)	7m – 10m
Peak Displacement (D_{max})	17m – 25m
Rupture Zone (A)	500km x 100km
Hypocenter Depth (Z_H)	20km – 25km
Crack Velocity (v)	2 km/s
Water Depth (Z)	8km

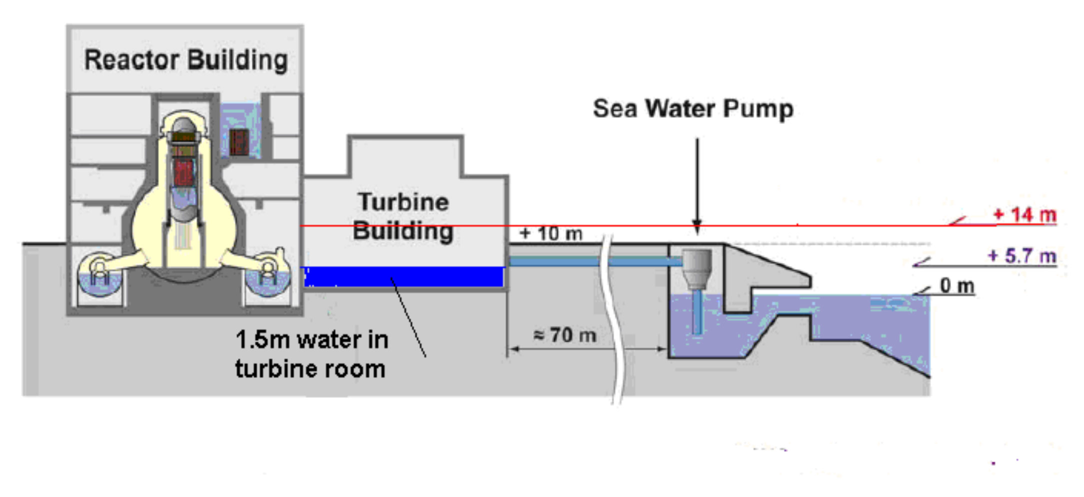
The volume of water displaced can be calculated as V = A x ¼D = 125km^3. This large, sudden displacement of water was the tsunami.

At the coastal cities of Kamaishi, Ishinomaki, and Ofunato, the first tsunami arrived at 14:46, simultaneously with the earthquake. The tsunami of maximum height reached these cities at approximately 15:20, 30 minutes after the earthquake. The maximum height of tsunami was recorded at more than 8.5m at Miyako, Iwate Prefecture, more than 8.0m at Ofunato, Iwate Prefecture, more than 7.3m at Soma, Fukushima Prefecture, and 4.2m at Oarai, Ibaraki Prefecture.

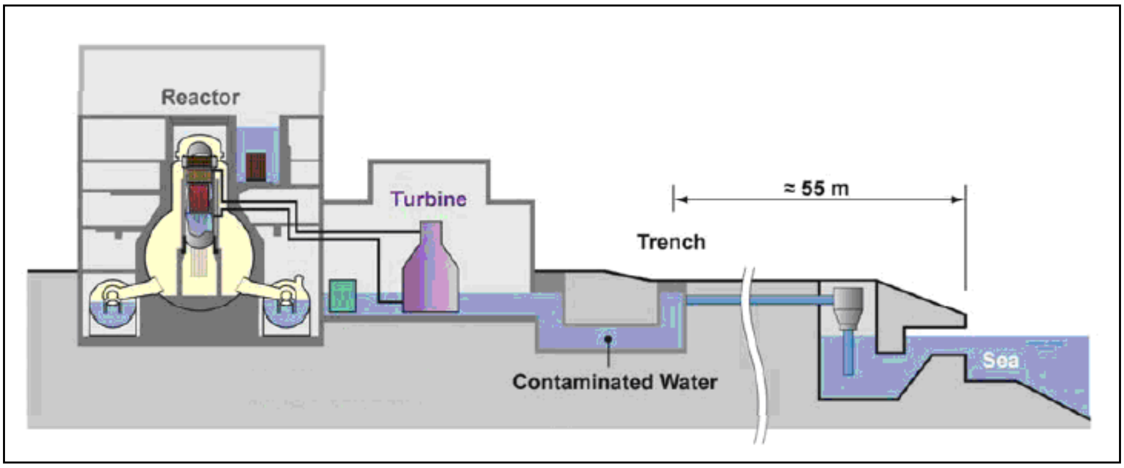


The JMA issued Major Tsunami Warnings at 14:49, 3 minutes after the earthquake, to Iwate, Miyagi, and Fukushima Prefectures. It was extended to Aomori, Ibaraki, and Chiba prefectures at 15:14, followed by warnings to the Japan Sea coast, the Bonin Islands, Sagami Bay, and to Shizuoka and Wakayama Prefectures. Subsequently they were downgraded to Tsunami Warnings, then to Tsunami Advisories for each region. All warnings and advisories were rescinded by 17:58, March 13th.

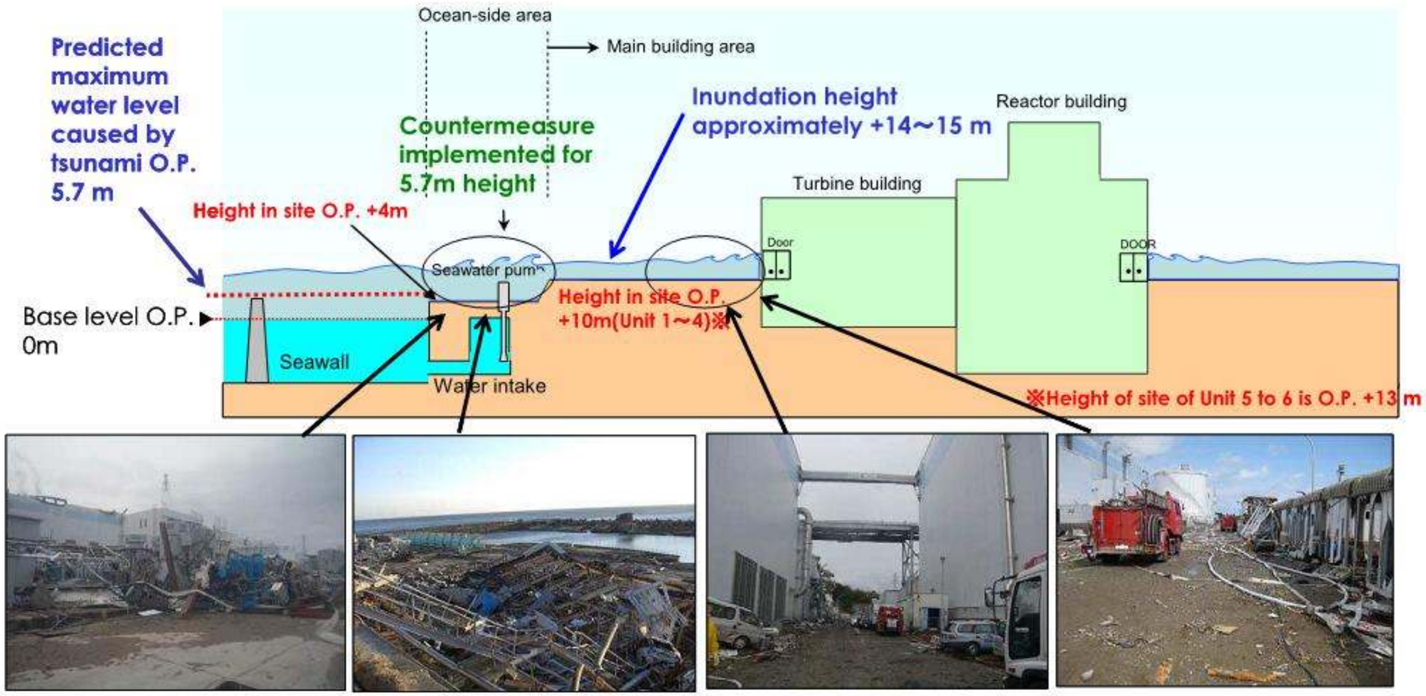
About 41 minutes after the active units at Fukushima Daiichi SCRAMed and emergency AC power generation began via the diesel generators, the first tsunami arrived. About 14 minutes later, a TEPCO estimated +14m tsunami overwhelmed the tsunami wall, which was 5.7m above the normal water level of Onahama Bay. The height of this wave has been estimated by water and debris marks on building walls. The diesel generators were completely taken out, as they were located in the basement of the turbine building, approximately 3m above sea level, as in the illustration below.



Each unit has an underground trench for piping and cabling which run from the basement of the turbine building. These trenches were found to be flooded, also, and the water contaminated, as shown below.



A more interesting illustration is from the TEPCO document, “Result of the Investigation on Tsunami at Fukushima Daiichi Nuclear Power Station” (sic), on the next page. Notice that the doors to both the reactor building and the turbine building are shown as inundated. The caption for the illustration is taken directly from the report.



“We have conducted the investigation on Tsunami arrived at Fukushima Daiichi Nuclear Power Station generated by the Tohoku-Chihou-Taiheiyo-Oki Earthquake on March 11th, 2011. Result of the investigation on height and area inundation and run-up height are as follows. We did not consider the effect of diastrophism [Author’s note: deformation of the earth caused by a seismic event]. (1) Inundation height: Considering the vestiges on buildings and facilities, approximately O.P. +14 to 15m (inundation depth: approximately 4 to 5m) in most of the ocean-side of main building area. (2) Inundation area: Most of the ocean-side area (height of site: O.P. +4m) and the main building area. (3) Run-up height: Considering the vestiges in slope and surface of road, approximately O.P +14.5m.” – Appendix A [in the TEPCO report]

The first question which comes to mind is why was the turbine building located near to the ocean and the floor of the building, where the diesel generators were located, below ground level? The diesel generators therefore were at risk from flood from any flooding source: tsunami, typhoon, or pipe breaks.

Fukushima Unit No.1 in at Daiichi was designed by GE and constructed by Ebasco in the 1960s. The placement of buildings, including the below ground level diesel generators, was done by Babcock & Wilcox. The tsunami wall was constructed in 1966. There remains no evidence as to whether historical tsunami data were referenced, or not. We believe that the current tsunami analysis was performed by a subsidiary company of TEPCO other than TEPSYS (TEPCO Systems), which has primary responsibility for TEPCO’s PRA.

The second question is why did TEPCO choose a tsunami wall height of 5.7m? Was this wall high enough? On what evidence was this height chosen?

In 1990, the safety assessments for nuclear power plants were carried out based on NSC “Guideline about Safety Design for Light Water Nuclear Power Generating Facilities”, and only considered regulations and authorized methods and codes for ground motion hazard calculations for NPPs. Never the less, no such guidelines were presented for tsunami hazards and the choice of method was left to the operators of each NPP, as the guideline states, “[the effect by] tsunami should be considered in design”,

Beginning in 1999 the Tsunami Evaluation Subcommittee of the Nuclear Civil Engineering Committee of the JSCE began to create a unified methodology for the risk assessment of tsunami to NPPs. The subcommittee members were taken from academia, research institutions, and 11 nuclear power utilities. The report, “Tsunami Assessment Method for Nuclear Power Plants in Japan” (referred to hereafter as TAMNPP), was published in 2002 and is contained in the Appendix to this report. The method used was dubbed a deterministic method, as opposed to a probabilistic method, with the goal of presenting the minimum and maximum water levels, or run-ups, which an NPP could expect from tsunami by doing a parametric study of fault parameters by numerical simulation. The maximum and minimum run-ups refer to tidal or storm influences.

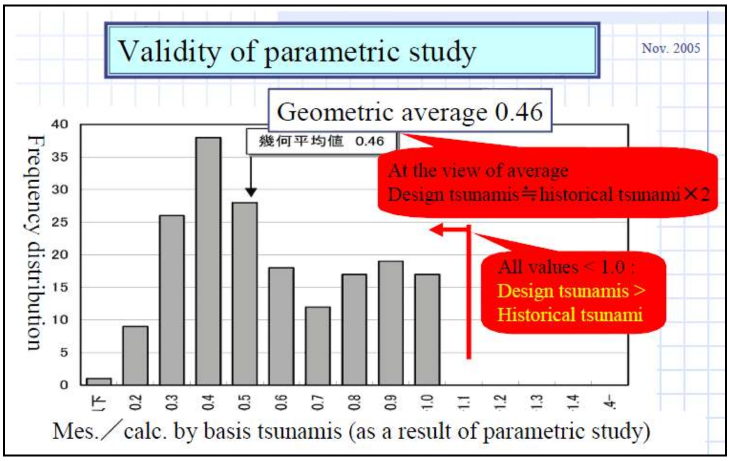
From 2003 to 2005, a probabilistic method was developed for run-ups which used numerical simulations of nonlinear dispersion wave theory with soliton fission, as well as simulations of split wave-breaking tsunami wave force on breakwaters and tsunami walls. The development of a methodology for probabilistic tsunami hazard analysis was undertaken from 2006 to 2008, and the revision of the TAMNPP was begun in 2009. Ironically it was to be published by the end of the 2011 fiscal year.

Because the tsunami defences at Fukushima Daiichi should not be judged by the availability of the yet to be published revised TAMNPP, we will limit our discussion here to the deterministic methodology and its results. In the Appendix we will include a conference paper, “Logic-tree Approach for Probabilistic Tsunami Hazard Analysis and its Applications to the Japanese Coasts” which includes many details for the revised TAMNPP. Interestingly, two TEPCO staff members are co-authors.

The methodology for the deterministic TAMNPP was:

a. to create a database of historical tsunami and to choose, for each NPP site, a “scenario tsunami” by maximum run-up;
b. to validate the numerical simulations by comparing the actual run-up with the simulated run-up;
c. to create a design basis tsunami for each NPP with the simulation;
d. and finally to validate the results against the historical records.

The goal was to calculate a design basis tsunami height which exceeded all the recorded and calculated historical tsunami heights at the target site. .In the vicinity of the target site, the envelope of the scenario tsunami heights should exceed all the recorded calculated historical tsunami heights. The step 2 validation results are show in the graph below:



The x-axis of the graph represents the ratio of the scenario tsunami to the simulated design basis tsunami. In all cases, the simulations calculated ratios less than, or equal to, 1, with a median ratio of about 0.46, indicating that the proposed method can be considered conservative and purports to give design values 2 times the scenario basis.

What is not clear from the TAMNPP is how many NPPs were considered in the validation study. We only know that 185 scenario tsunami were validated. The NPP examples given in the report are from the northwest Japan Sea coastl[illegible]n Niigata Prefecture, Aomori Prefecture, and Hokkaido. Each utility was required by NISA to do a study following the TAMNPP guidelines. It is not clear if each NPP wrote their own simulation software, or if the software written by JSCE was used by all NPPs. The simulation software was never verified by an independent group.

After the NSC revised the Seismic Design Guide in 2006, all operators of NPP in Japan were requested to conduct a seismic PRA including tsunami risk according to the JSCE guidelines in TAMNPP, which will be finalized within a few years. We have included presentations of the preliminary results from 4 NPP sites: Fukushima Daiichi, Kashiwazaki, Onagawa, and Hamaoka.

From the author’s conversations with Dr. Hakata, from THK Consulting and formerly of the NSC and a seismic expert, we have the following information: TEPCO did follow the JSCE tsunami calculation method (TMANPP) for their NPP, but did not adopt probabilistic method (LTA) since it had not yet been accepted by JSCE, scheduled as previously mentioned for acceptance at the end of fiscal 2011.

We are also not sure how TEPCO applied the JSCE guidelines. The presentation made by TEPCO in 2008, after their preliminary tsunami risk assessment, only indicates that they used the Chilean Tsunami of 1960 as the scenario tsunami for the far field study; there is no mention of the scenario for the near field study which produced the results of a 5.7m design basis for Daiichi. Perhaps the correct application of the JSCE methods, both historical data collection and implementation of the mathematics, was beyond the scope of TEPCO PRA analysts.

In contrast, the Onagawa NPP tsunami risk assessment is quite clear about the choice of scenario tsunami. By making bore holes in the hills about 1km behind the NPP, it was estimated that the largest local tsunami run-up height was between 6m and 8m caused by the 1611 earthquake. They therefore constructed a tsunami wall of 10m. But from a reactor operator at Onagawa we have the following story:

> After the earthquake, we lost offsite power. The tsunami run-up height was 50cm below the ground level of the NPP, but the force of the wave hitting the wall made the water jump over the wall. The inundation took out the diesel generators, just as it had at Daiichi. But unlike Daiichi, the offsite power was quickly restored. Only by luck we did not have the same consequence as Daiichi.

If the TAMNPP methodology is correct, why did TEPCO’s implementation of it indicate a tsunami wall of 5.7m was sufficient?

There are two possibilities. The first is that the implementation was correct, the second that it was wrong. If correct, then perhaps the tsunami of March 11th was absolutely unpredictable, and we will look at this possibility in Section 2; if the event was predictable, then we must consider

TEPCO negligent in their stewardship of a nuclear power plant and the regulatory culture of Japan complicit in an enormous disaster by not improving defences. However, the TAMNPP provided an excuse for TEPCO by assuring the utilities that what they previously had done (prior to the new 2006 regulations) considered tsunami safety and the latest information:

> By referring to the guideline, the design tsunami has been determined site by site by a numerical simulation based on information regarding the maximum historical tsunami and the greatest influenced submarine active fault induced tsunami. Accordingly, the safety design has been implemented based on the tsunami thus determined. It is considered that the guideline by the Nuclear Safety Commission of Japan will not create problems in the near future for the following two reasons: various safety insurances have been considered in the process of tsunami evaluation, and the latest information has been taken into account for the assessment. (TAMNPP, Page 3);

Amazingly, the tsunami wall, built in 1966 with a height of 5.7m, was high enough to conform to the guidelines published in 2002. As presented in 2008, TEPCO said that "We have assessed and confirmed the safety of the nuclear plants [at Daiichi] based on the JSCE method published in 2002." ["Tsunami Study for Fukushima 1 and 2", pg. 14, contained in the appendix]. We hope that during final review the regulators review and confirm the calculations.

As for the second possibility, in what way could the implementation have been wrong? Let us quote some passages from the guidelines and a conference companion paper, "Tsunami Assessment for Risk Management at Nuclear Power Facilities in Japan" (referred to as TARM), from 2007, included in the Appendix. First, from the paper:

> In Japan, old tsunami records documented before the 1896 Meiji-Sanriku tsunami are less reliable because of misreading, misrecording (sic), and the low technology available for the measurement itself. The data can be compared with that from other documents and plotted on the map. Tsunami run-up records that appear unreliable should be excluded. TARM, (Page 568);
>
> As earthquakes and tsunamis are natural phenomena, their variable and uncertain aspects should be considered. In the process of tsunami assessment, uncertainties and errors in many important parameters are unavoidable, including the tsunami source, fault position, depth of the upper edge of the fault plane, strike direction, dip angle, dip direction, slip angle and combination of segments. In the numerical simulation, the governing equations, boundary conditions, initial conditions, grid division, modeling of bathymetry data and reliability of run-up heights may also involve uncertainties. However, it is rather difficult to estimate those uncertainties quantitatively and to deal with them one by one. <u>**Consequently, only uncertainties concerning the tsunami source are dealt with in this study, because they can significantly influence tsunami assessment**</u>. (TARM, Page 570) [bold underling by the author];

A seismic engineer from NIED remarked that the slip angle of the Pacific plate during the March 11th event was much more acute than had been predicated along the fault line and this was the major cause of such a large tsunami. The uncertainties in the model which were not addressed caused the failure of the simulation to perform accurately as a prediction tool.

More on uncertainty from the TAMNPP:

> The run-up heights of tsunamis older than the 1896 Meiji-Sanriku earthquake tsunami have been assumed by researchers on the basis of old records, documents etc.; the reliability of the data must be closely examined. In the case of the run-up heights of comparatively recent tsunamis that occurred after 1896, the investigation method should focus on the heights mentioned in individual documents and their reliability. If the reliability of any run-up height is doubtful, the accuracy of the data must be re-examined based on the original document. Further, if the reliability is too low, they can be eliminated when the goodness of fit is evaluated. (TAMNPP, Page 28)

These excerpts focus on two uncertainties: the uncertainty of historical records and oral histories; and the uncertainties inherent in the parameters used in mathematical modelling. Interestingly, software and mathematical errors are not addressed, but must be considered.

The historical records and oral history accounts before 1896 may be considered unreliable by laboratory bound researchers. However for those of us who have been to Tōhoku, especially to the Sanriku countryside, there are tsunami stones (*tsunami-seki*), some more than 400 years old, placed in the ground to mark tsunami inundation points, such as the photograph below, and to serve as reminders to villagers.

During volunteer work at an evacuation centre in Watari, Miyagi Prefecture, the author made a special visit to one such stone in Aneyoshi, a village halfway between Sendai and Aomori in Iwate Prefecture on coastal Route 45. In the recent tsunami, inundation at Aneyoshi was more than 1.8km and stopped about 100m short of the stone. Was this type of evidence considered reliable by the authors of the TAMNPP report?

Another source of historical data that was probably ignored is the rich Japanese oral tradition and village historians. Miyamoto Tsuneichi, a leading Japanese folklorist of the mid-twentieth century, travelled all through the villages of Japan conducting interviews and capturing a vanishing way of life. During his travels he met many older Japanese villagers who passed down written ledgers and accounts about tsunami, because, as one village historian said, "… as time passes, people inevitably forget, until another tsunami comes that kills 10,000 more people;" (The Forgotten Japanese: Encounters with Rural Life and Folklore, 1960).

0.1.1 More disturbing is the statement in the TAMNPP that only tsunami run-ups near the actual sites of the NPP were considered, instead of looking at historical run-up affects a hundred kilometres north or south of the site for evidence. As probabilistic risk analysts, we strongly take issue with the TAMNPP and we believe that this was a source of error. The large amount of model uncertainty requires the analyst to consider large tsunami even if that tsunami had little effect on the exact location of the target NPP.

> In principle, the design tsunami should satisfy the following two points in order to confirm its adequacy.
>
> a. At the target site, the height of the design tsunami should exceed all the calculated historical tsunami heights.
>
> b. In the vicinity of the target site, the envelope of the scenario tsunami heights should exceed all the recorded historical tsunami heights (see Figure3-2). "The vicinity of the target site" should be appropriately set taking into account the following three points: the number of run-up heights by the dominant historical tsunami, the distribution of run-up heights by the dominant historical tsunami, and the similarities between submarine topography and coastal landform. Here, the historical tsunamis that have no recorded tsunami run-up heights in the vicinity of the target site can be excluded from consideration. However, if the following three points are satisfied, the abovementioned criteria need not be met: existence of a tsunami run-up trace by the dominant historical tsunami at the target site, slight variation between submarine topography and coastal landform, and the design tsunami exceeding the historical tsunami run-up height at the target site. (TAMNPP, Page 10);
>
> As shown in Figure3-2, it is necessary that all the scenario tsunami heights exceed all the recorded historical tsunami heights. Since the tsunami sources of the historical tsunamis may differ from that of the design tsunami, it is not necessary to compare the design tsunami with the neighbouring recorded historical tsunami heights. (TAMNPP, Page 12)

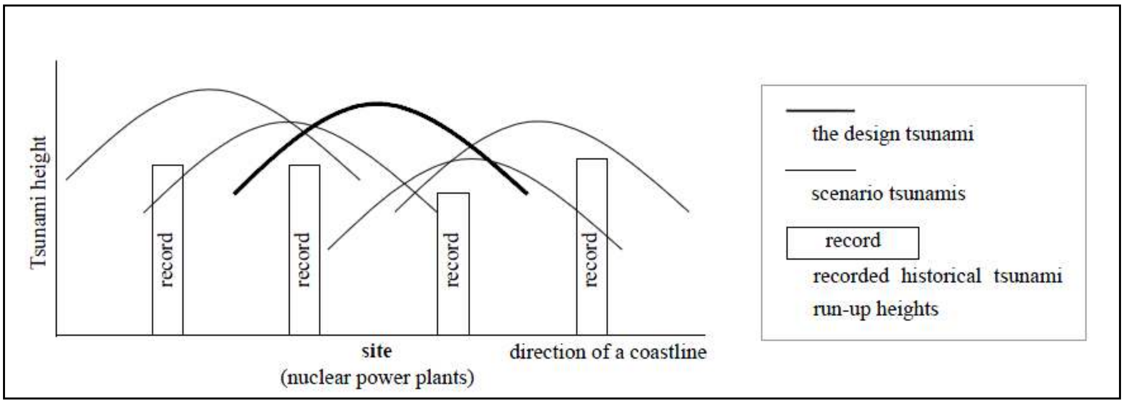


Figure3-2 Relationship between scenario tsunamis and recorded historical tsunami-run up heights

Perhaps, also, there is misunderstanding of mathematical uncertainty, as exemplified by the claims that the average ratio of scenario tsunami to design basis tsunami is 2 to 1:

> In this framework, in which the design tsunami is compared with the historical tsunamis, it might appear as though their heights are identical. However, it is confirmed the height of the design tsunami that is obtained in this paper is twice that of historical tsunamis on an average.
>
> …… even if a calculation reproduces the recorded historical tsunami heights well on average, which implies K = 1.0, there is a 50% possibility that the true historical tsunami heights are not exceeded. That is because uncertainties and errors exist. In other words, it is possible that the calculated heights do not exceed the recorded historical tsunami heights. (TAMNPP, Page 10);

It is not clear what this observation means. It could mean either:

a. There is a 50% possibility that the true historical tsunami heights are not exceed by the calculation of the design basis because of errors and uncertainties in the method and/or parameters, or
b. There is a 50% probability that the chosen scenario tsunami are actually lower than the true historical tsunami;

In either case, to our way of thinking, this means that the methods, parameters, and data are not of much use; a 50% probability represents a prediction which is no better than a coin toss. It means we may be right, but we may be wrong.

There is one more source of historical tsunami that we believe was not used to create the historical database, and therefore caused the Jōgan tsunami, in 869, to be ignored: geological inference. Three studies which we have read, “The 869 Jōgan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan” [2001], “Unusually large earthquakes inferred from tsunami deposits along the Kuril trench” [2003], and “Tsunami Inundation History in Sendai Plain, Inferred from Tsunami Deposits” [2007], all seem to be of good scholarly pedigree, and seem to indicate that the recurrence probability of large tsunami in the Sendai region is between 1.25e-03 and 9.09e-04 per year.

And finally, the Fukushima accident could perhaps have been mitigated to some extent if the backup diesel generators had not been located in the basement of the turbine building. TEPCO had been warned against this, and were aware of countermeasures. At a 1998 risk meeting in Japan, which the author attended, a presentation and description of the independent emergency shutdown system building at the Beznau NPP in Switzerland was given. Mr. Martin Richner of the Beznau NPP risk assessment group has sent to us this simplified explanation:

> The Notstand (independent emergency shutdown system) building represents a bunkered (1 m of concrete wall) safety facility with double water-tight entrances that provides the following major features:
>
> - an independent Notstand feed water system;
> - an independent RCP seal injection system;
> - an external recirculation system;
> - one of the three safety injection pumps replaced by a new pump in the bunker;
> - two ECCS accumulators;
> - a separate offsite grid supply and an independent diesel generator (with a crosstie to the other unit);
> - a separate cooling water supply by a independent well water system (with a crosstie to the other unit);
> - an independent instrumentation and control system;
> - a separate control room to actuate and control the Notstand equipment.
>
> These Notstand systems are designed as a single-train redundant backup to the other plant systems. However, at any single failure of an active component, the operators can align another component to enable core cooling (for example by alignment of a crosstie to the other unit).
>
> The first and automatic train of the Notstand systems is designed to start and run automatically for at least 10 hours. All equipment and structures are designed to meet the current licensing requirements for external events (seismic, fire separation, flooding). The Notstand systems of Unit 2 went into operation in 1992, those of Unit 1 in 1993.

TEPCO seems to have ignored the need for a structure and facility like this. In fact, TEPCO over the last 2 years has repeatedly delayed performing a Level 2 flood PRA on the grounds that it was too expensive and of low priority. It seems, in retrospect, to be less expensive than the current situation.

Japan has implemented an extensive program of building tsunami walls in front of populated coastal areas. Some localities have also built floodgates and channels to redirect the water from incoming tsunamis. However, their effectiveness has been questioned, as tsunamis are often higher than the barriers. For instance, the tsunami which hit the island of Hokkaido on July 12, 1993 created waves as much as 30 m (100 ft) tall - as high as a 10-story building. The port town of Aonae was completely surrounded by a tsunami wall, but the waves washed right over the wall and destroyed all the wood-framed structures in the area. The wall may have succeeded in slowing down and moderating the height of the tsunami, but it did not prevent major destruction and loss of life.

Peter Yanev, a seismic expert and former president of Earthquake Engineering International (EQE), in a private conversation recounted to the author that in 1993, when he went to see the damage in Okushiri Island after the Hokkaido Nansei Oki M7.8 earthquake, he observed a 5 meter tsunami wall but the resulting tsunami was 5-10 meters. In 1983 when he toured Shizuoka, in the predicted Tokai earthquake zone, he observed 5-7 meters tsunami walls at the Hamaoka NPP. On May 7th, Chubu Electric, the operator of Hamaoka, announced plans to build a 15m tsunami wall in back of 10m sand dunes.

Mr. Yanev believes that while a tsunami wall is not a total solution, it could moderate the tsunami; but if it traps the water between itself and the land, and there are more tsunami waves, the wall could exacerbate the situation. Imagine a bath tub half-full of water, and one throws a bucket of water into the tub, sloshing the water in a to and fro motion. Now imagine the same tub completely full and one throws a bucket of water into the tub; in this situation, the water will overflow the tub’s rails. Entrapment of water by the tsunami wall can have the same effect. Even though there is an open gap between the tsunami walls (see the illustration on page 13) the strong on-shore flow can trap the water on the land-side of the tsunami wall.

There is also a large enough probability that a tsunami wall would fail in places from the force of the tsunami (at Sendai the force was estimated at 40 tons/m^2 and at Daiichi 100 tons/m^2) and from the lateral and vertical motion from the earthquake acceleration. As estimated in 2007 by the Ministry of Land, Infrastructure, Transport, and Tourism, 63% of the tsunami walls on the Japan coast could not withstand a Shindo +6 earthquake. Since all near field tsunami are caused by an earthquake, the Japan coast is at severe risk. In large land structures, there are many built-in safety factors for earthquakes. But with tsunami walls, there are no such known factors. The size and strength of tsunami depends on the distance from subduction zone and is difficult to predict.

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How did tsunami walls fare in Tōhoku after the earthquake? The 2.4km long tsunami wall in Miyako, Iwate Prefecture was destroyed. The 6m, 2km long wall in Kamaishi, Iwate Prefecture was overwhelmed, but delayed the tsunami inundation by 5 minutes. The 15.5m tsunami wall in Fundai, Iwate Prefecture, provided the best protection, but it is good to note that the original design was only 10m. The village mayor fought to make it higher from information in the village historical records. The biggest problem is that tsunami walls give a false sense of security and other preparedness measures may not be undertaken.

The author believes that tsunami walls cannot be the total solution to, or the last defence against, tsunami inundation of a nuclear power plant. As implemented today in Japan, there are no defence in depth countermeasures against tsunami at nuclear power plants.

But most importantly, there is growing evidence that height of the largest tsunami wave was not 14 to 15 meters, as reported by TEPCO, but a maximum of 10 meters. There is no evidence of a wave of 14m making landfall to the south or north of Daiichi. There is evidence of a run-up height of 14m at the plant itself, but that does not necessarily translate into a wave height of 14m. Also there are no known differences in the topography of the sea bottom at Daiichi which would amplify the height in comparison with points south or north.

In a recent lecture by Dr. Fumihiko Imamura, from Tōhoku University and a member of the Willis Research Network, a non-profit research group sponsored by Willis, an insurance broker, Dr. Imamura said that his examinations of the photographs released by TEPCO show the tsunami as only slightly higher than a 10m levee. The height of the wave might have been amplified by the previously entrapped water behind the tsunami wall, as well the funnelling of the water between buildings as shown below:

Dr. Imamura said that proper countermeasures must distinguish between tsunami wave height and tsunami run-up height; he continued that it is quite normal that run-up can become higher than the wave itself after it comes in contact with the land and buildings.

Since many tidal gauges near the coastline have not provided consistent or accurate data, and the coastline at Daiichi is off limits for investigations because of high radiation levels, we will have to wait some time before we can get accurate measurements.

One only hopes that TEPCO is not exaggerating the tsunami height so as to avoid paying compensation to Fukushima residents by claiming that the accident at Fukushima was an unforeseen Act of God. TEPCO is now arguing that according to the law on nuclear accident compensation it has immunity from compensation liability in such a situation.

We are only in the first 6 weeks of this disaster. Over the next year there will be several commissions of inquiry, both inside and outside of Japan, who will investigate this accident and try to uncover the root causes to better prepare the international nuclear community for the possibility of severe accident initiation and propagation, as well timely and effective mitigation. We hope that our early contribution to this discussion is informative and germane.

HOW LIKELY WAS IT?

“But one could hardly imagine that such an event would recur nor the greater event would happen in the land of the living.” -- Yoshimitsu Okada, President, Japan National Research Institute for Earth Science and Disaster Prevention, March 25th, 2011

Preliminary Considerations

We have established that the Fukushima Daiichi core damage and radioactive release had three main causes: loss of offsite power from the earthquake; station blackout from the tsunami; and an underlying organizational culture which could not react quickly to rare events and could not tell the truth, even to themselves.

In this section we will ask the question, “how likely was it?” by examining two categories of unconsidered actions which may have prevented or mitigated the accident:

a. an alternative way to understand the probable frequency of an earthquake and tsunami of the magnitude experienced;
b. impediments to possible mitigation and recovery.

Bayes’ Theorem

Bayes’ Theorem provides a mathematically rigorous method, called Bayesian updating, for increasing our state of knowledge about the probability of an uncertain event based on new evidence. The theorem is named for Thomas Bayes and often called Bayes' law or Bayes' rule. Bayes' theorem expresses the conditional probability, or "posterior probability", of an event A, given evidence B is observed, Pr(A|B), in terms of the "prior probability" of A, Pr(A), the prior probability of B, Pr(B), and the conditional probability of B given A, called the “likelihood”, Pr(B|A):

$$\Pr(A, B) = \Pr(A) \bullet \Pr(B|A) = \Pr(B) \bullet \Pr(A|B)$$

$$\Pr(A)\Pr(B|A) = \Pr(B) \bullet \Pr(A|B)$$

$$\Pr(A|B) = \frac{\Pr(B|A)\Pr(A)}{\Pr(B)}$$

$A \rightarrow$ The frequency of some event takes on a specific value.

B → The accumulation of evidence about the frequency of the event.

Pr(A) → Probability of "A" prior to, or without knowledge of, the evidence of event B ("The Prior").

Pr(A|B) → Probability of "A" after, or given knowledge of, the evidence of event B ("The Posterior").

Pr(B|A) → Probability of observing evidence B given A; i.e., given the event frequency takes on a specific value (The Likelihood").

Pr(B) → Probability of observing evidence B.

For example, imagine an elementary school student. The student comes into the medical office with red spots on his belly. One possible childhood illness is Chicken Pox. So the school nurse reasons from symptoms and an etiology to a diagnosis thusly: the chance that in the general population an elementary student will get Chicken Pox during childhood is n%, the **prior**. That there are red spots on the belly, GIVEN that Chicken Pox is the illness is m%, is the **likelihood**. So the chances that the illness is Chicken Pox, GIVEN that red spots are observed is n% * m%, the **posterior** (with a "correction" factor left out).

Bayesian methodology has three import characteristics: all types of information are used, the use of judgment is visible and explicit, and it handles the case of no events being experienced. The important properties of Bayesian Updating are: with weak evidence, the prior probability dominates results; with strong evidence, the results are insensitive to prior, they are dominated by the evidence; and successive updating gives the same result as one-step updating with consistent evidence.

In what follows, please consider the Bayesian analyses to be rough, first cuts. Perhaps incorporating expert opinion and data from geographical areas outside of the Sanriku and Sendai regions with a Bayesian 2-stage analysis would give more accurate estimates.

The following calculations are meant to be bounding calculations, not final words, to complement the simulations and theoretical considerations used by the JSCE and NIED. However, we believe that analyses such as we have done were not considered at all, and that the simulations and attendant theories were believed prima facia. Our analyses give an entirely different picture.

Bayesian Analysis of Seismic Recurrence Frequency at Daiichi

In Section 1, we presented a table from NIED which depicted the recurrence frequency mean value for a Shindo>=6 earthquake at Daiichi as being less than 0.05% within 30 years. This value was arrived at by numerical simulations using such models as the characteristic earthquake model and its cousin, the seismic-gap model.

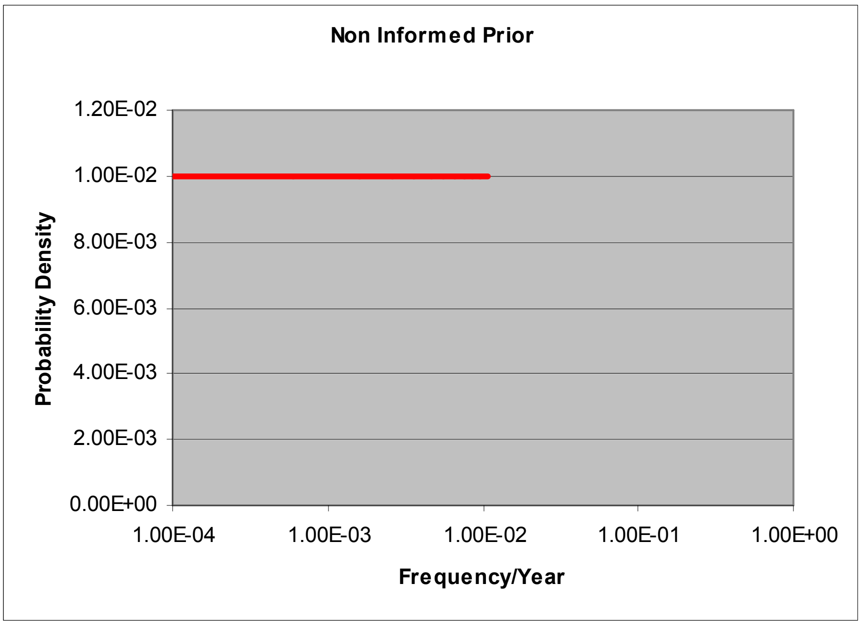
Our historical research shows that there have been six earthquakes greater than, or equal to 8 $M_{w,}$ along the Sanriku and Sendai coasts, excluding the event of March 11:

Year	Magnitude	Interval in Years
869	8.6	
1611	8.1	742
1793	8.2	182
1896	8.5	103
1933	8.1	37
1960	8.5	27

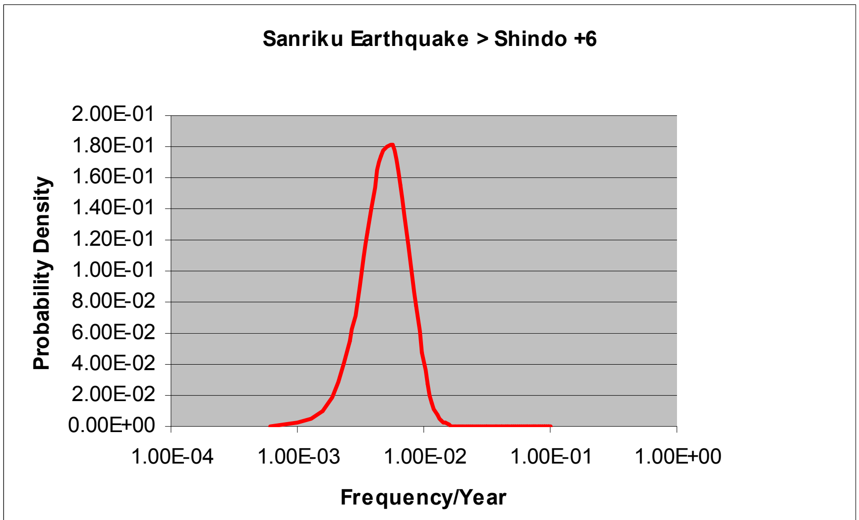
We will estimate the probability before March 11th, using Bayesian Analysis. We will make five reasonable assumptions:

a. Historical data is consistently given in M_w values. We will assume that all earthquakes greater than $8.0M_w$ have a Shindo of greater than 6;
b. We will only look at earthquakes which affected the Sendai coast;
c. We will begin with the prior probability distribution known as the non-informed prior, which means that we have no prior knowledge as to the actual recurrence probability;
d. To be conservative, since we do not have evidence of an earthquake with Shindo 6 or greater before 869, we will start the analysis with the Jōgan earthquake and we will do a 1-step update with 6 events in 1141 years (869-2010). One step updates take into account long time intervals with no events.
e. We will assume that the range of the probability can be between 1/10,000 years and 1/100 years for the non-informed prior.

The prior can be seen below:



and after the Bayesian update of 6 events in 1141 years:



Name	Value/Year	Recurrence/yr	% Recurrence/30 yr
Mean	6.13e-3	1/163	18.39%
5th Percentile	1.83e-3	1/546	5.49%
50th Percentile	4.85e-3	1/206	14.55%
95th Percentile	9.41e-3	1/106	28.23%
Range Factor	2.27		

A mean value of 6.13e-3 gives us a mean recurrence fraction of approximately 1/163 years, but we do not know when, if ever, such an event will occur. Bayesian analysis is not a prediction method such as that used by NIED, presented in Section 1, where NIED predicts an earthquake at Daiichi of less than 0.05% within the next 30 years. The method presented here is simply a probability distribution based on historical data: a Shindo 6+ earthquake in Sanriku or Sendai could happen again tomorrow, or perhaps never again.

It must be strongly pointed out that the Bayesian analysis only reflects assumptions and our state of knowledge from historical events, just as the NIED values only reflect assumptions and a state of knowledge given by the numerical simulation and the modelling methods. All sets of values need to be considered when making a judgement under uncertainty. However, NIED, NSC, and information released to the public ignored presentation of the historical evidence and presented the results from the simulation as fact.

The mean value of an uncertainty distribution should never be taken as the final word in risk assessment; doing so is to miss the point of PRA. In PRA quantification, or measuring, the risk/safety of a situation is to explicitly make clear our state of knowledge. The act of trying to measure the risk involved, and learning about the facility being investigated, is the goal. The acts of trying to assign values, combining them, questioning their validity, building the model, and understanding our own uncertainty are the great treasure of probabilistic risk assessment and the source of knowledge. To be prepared for the unforeseen event, a good analyst must constantly change the model, question assumptions, run scenarios, examine results, and understand the uncertainty.

It is our opinion that TEPCO, and probably all NPP operators in Japan, paid little attention to the NIED methods. Each of the major nuclear facility construction companies in Japan (Kajima, Obayashi, Taisei, and Shimizu) has their own seismic research centres and proprietary simulation software. All NPPs in Japan do extensive fragility analysis probabilistically, based on the seminal work done by PLG, Inc in 1981. The article, “A Methodology for Seismic Risk Analysis of Nuclear Power Plants”, is included in the appendix. The author spent many years working with all three authors of the article in creating seismic risk assessment software methodologies. These methods are the most pervasive in Japan.

The design basis for Daiichi was a Shindo 6. The PGA experienced was, for the most part, designed for; a 23% exceedence of the design basis PGA seems to have done no damage to the important structures, but the jury is still out. There seems to be radioactive water leaking from the reactor buildings which may have been caused by the earthquake; we know nothing with respect to the spent fuel pools.

However, even after the earthquake at Kashiwazaki in 2008, where the PGA of the earthquake exceeded the design basis by almost 300%, the NPP was able to go to cold shutdown with no problems with minimal damage to safety systems.

Bayesian Analysis of Tsunami Recurrence Frequency at Daiichi

In Section 1, we presented the guidelines published by the Japanese Society of Civil Engineers to be used in the tsunami risk assessment of NPPs. By application of these guidelines, TEPCO believed that the 5.7m tsunami wall built in 1966, during the construction of the Daiichi NPP, was sufficient to withstand any reasonable tsunami which could arrive at the plant. In particular, the historical scenario tsunami which they chose for the design basis (which is not given in their presentation) was expected to be below 5.7m.

Since no defence in depth existed for tsunami at Daiichi, particularly the undefended location of the backup diesel generators in front of the reactor building, we hope that TEPCO's choice of the height of the scenario tsunami was well below 5.7m. We have been told that around 2003, NISA recommended to TEPCO that the existing tsunami wall was not high enough; TEPCO rejected this suggestion, and the regulator did not press the point, as there was no official regulation about tsunami risk in effect at that time.

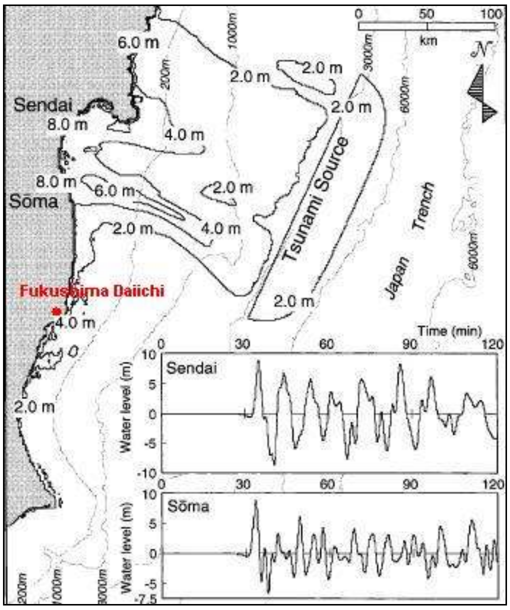
Our analysis will neither depend upon, nor comment on, the models used and simulations performed by TEPCO. Instead, we will look at historical evidence; we will look not only at modern, recorded history, but on well founded geological inference of tsunami run-up distance and height on the Sanriku and Sendai coasts from the aforementioned articles, mentioned on page 50 and contained in the appendix. We will also focus on the Hama-dori coastline where Daiichi and Daini are located.

The investigation of the Jōgan tsunami of 869 employed sediment analysis and numerical hydrodynamic models, the results of which indicate that the tsunami was approximately 8m in height with a run-up of 4 to 5 kilometres. Further analysis based on sediment depositions and ^{14}C dating suggests that there were two other gigantic tsunami of the same height and extent: the first between 910 BCE and 670 BCE, the second between 140 BCE and 150 CE, with a standard deviation of 1σ (the underlying probability distribution is not available).

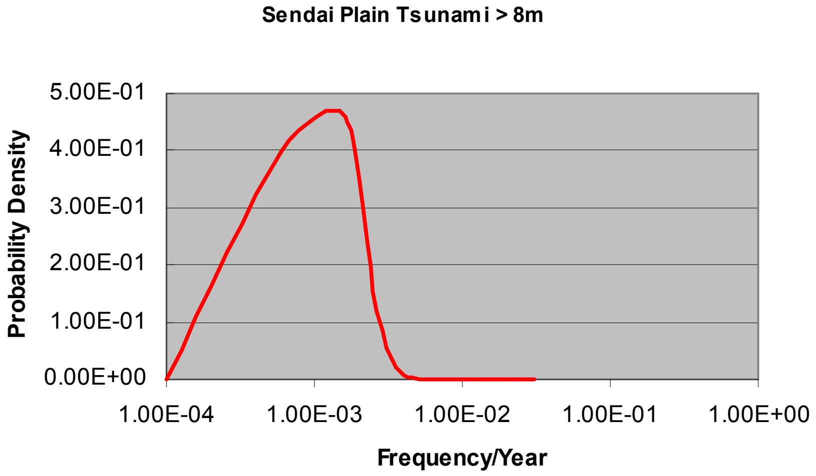
As in the Bayesian study of seismic recurrence, we present the following table, using the midpoints of the estimated occurrences of the two pre-historical tsunami. We will use information from the Sendai plain and Hama-dori regions only, since the coastal topography of the Hama-dori coast, at Daiichi, is more similar to the Sendai region than it is to Sanriku, although the Sanriku coast is only 260km further north. If we included run-up heights from Sanriku, the 1896 and 1933 tsunami had run-up heights of 38m and 29m, respectively:

Year	Estimated Maximum Run-up Height	Interval in Years
790 BCE	8m	
5 CE	8m	795
869	8m	865

The inferred run-up heights for the Jōgan tsunami at different locations on the Sendai coast are depicted below. Please note the location of Fukushima Daiichi indicates the inferred run-up height was about 4m. Our analysis, however, does not assume that the run-up height was actually the maximum, 8m; it is simply an analysis of the recurrence frequency of very large tsunami on the Sendai coastal plain. We will discuss the run-up height assumptions after the analysis. As an aside, one of the articles predicts, “Our numerical findings indicate that a tsunami similar to the Jōgan one would inundate the present [Sendai] coastal plain for about 2.5 to 3 km inland.” It was uncannily accurate.



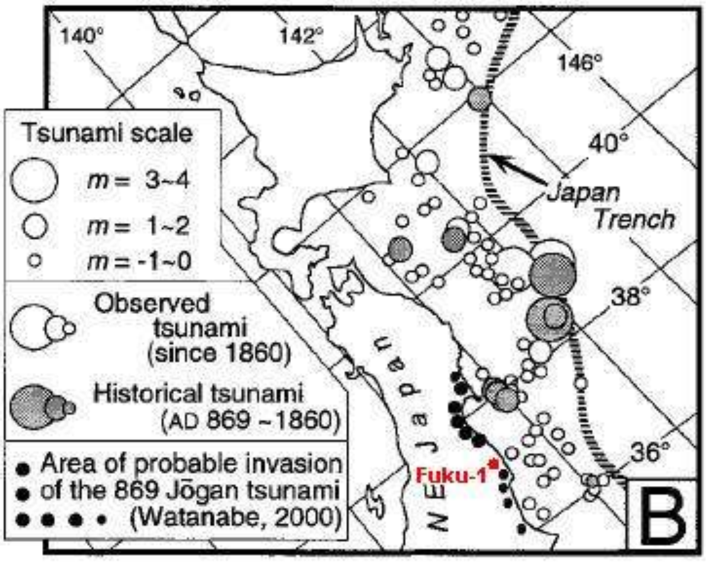
We will start with the same non-informed prior as we did with the earthquake study. To be conservative, we have done a 1-step update of three events in 2800 years (790BCE to 2010). The results are depicted below:



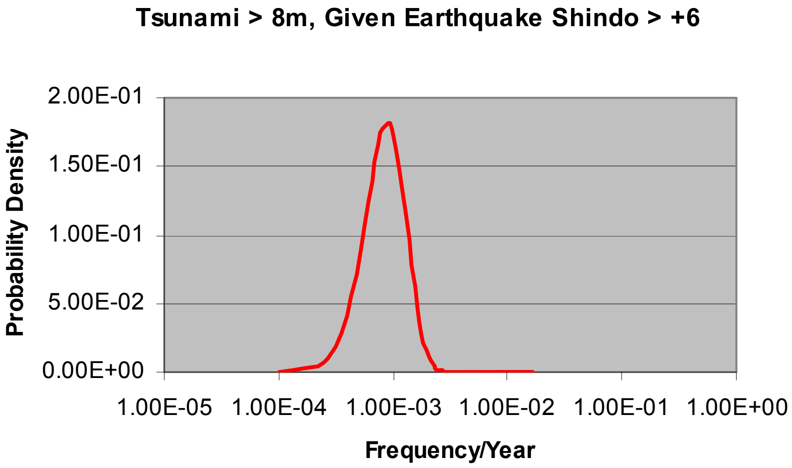
Name	Value/Year	Recurrence/yr	% Recurrence/30 yr
Mean	1.37e-3	1/730	4.11%
5th Percentile	1.00e-4	1/10,000	0.30%
50th Percentile	4.22e-4	1/2381	1.27%
95th Percentile	1.87e-3	1/614	5.01%
Range Factor	4.32		

More importantly, it is necessary to calculate the joint probability of an earthquake greater than Shino 6 and a tsunami with a run-up of 3 to 4 kilometres and maximum run-up height greater than 5.7m. This probability will let us understand if the tsunami wall at Daiichi was large enough.

Let us use the distribution calculated for the probability of an earthquake with a Shindo greater than 6 in the previous section, Pr(Shindo>=6); then by looking at the 6 earthquakes with a Shindo greater than six, we can see that only one of them was accompanied by a tsunami with a height greater than 5.7m, the Jōgan earthquake of 869, and it had an estimated height of 8m. We verified this historically from the geological papers already sited. An illustration of the history of such tsunami is shown below; note the location of Daiichi in red:



One such tsunami out of six Shindo 6 events gives us a mean occurrence probability of 1.67e-01, which is the conditional probability that given a Shindo 6 event, the probability of a tsunami height of approximately 8m: Pr(Tsunami≈8m | Shindo>=6). We then multiply the two probabilities and obtain get the joint probability of both the earthquake and the tsunami: Pr(Shindo>=6) * Pr(Tsunami≈8m | Shindo>=6) = Pr(Shindo>=6 , Tsunami≈8m). The results are depicted below:



Name	Value/Year	Recurrence/yr	% Recurrence/30 yr
Mean	1.02e-3	1/980	3.06%
5th Percentile	2.79e-4	1/3584	0.84%
50th Percentile	8.02e-4	1/1247	2.14%
95th Percentile	1.57e-3	1/637	4.17%
Range Factor	2.37		

These statistics agree well with the estimated range in the sited articles: 1.25e-3/year to 9.09e-4/year.

What does a mean value of 1.02e-3 indicate in terms of CDF in a risk assessment? Consider this as the mean value of the initiating event. Then a tsunami height of approximately 8m and run-up of 4km would surely overrun the tsunami wall at Daiichi, inundate the turbine room, destroy the diesel generators, make the batteries inoperable, cause loss of offsite power, and therefore cause total station blackout for a period of more than 8 hours. Given the devastation to the equipment on site and total loss of offsite power from such an event, we can estimate that this one sequence would have a probability of 1.00e-3/year and lead to core damage; this one sequence alone would be 10 times greater than the regulation for CDF of 1.00e-4/year.

Moreover, in Japan the regulation for an uncontrolled release of radioactive material, called LERF (large early release factor) is 1e-6/year per unit.

The maximum tsunami run-up heights in the data used for the analysis was 8m, while the one inferred data point estimates the Jōgan run-up near the Daiichi site was about 4m. What should we infer for the purpose of insuring safe operations of the NPP?

Conservatism is an earmark of good risk assessment, especially with model, simulation, and data uncertainties which are large. Indeed, as we mentioned before, both the numerical simulations by JSCE and the Bayesian analyses done by the author should be used as bounding studies to inform risk management. As researchers such as Dr. Robert Geller have pointed out, we cannot predict where on a fault a rupture will occur, nor can we predict all of a rupture's actual attributes; in the March 11th earthquake, most experts had not predicted that the angle of subduction would be so acute, the effect of which was the large tsunami.

Japanese NPP operators constantly say that they build structures which are able to withstand 2 times the anticipated M_W. The JSCE wrote that their methodology in the TAMNPP consistently showed that that their design tsunami exceeded the scenario tsunami by a 2 times height, on average. [TAMNPP pg.10]. Surely, therefore, TEPCO should have built a tsunami wall capable of withstanding an 8m run-up (2 times 4m), given that 8m was historically encountered from reliable sources.

Should TEPCO have anticipated a tsunami run-up of 14m? The consequences of a tsunami which could breach the tsunami 5.7m wall were especially high, given that there was no tsunami defence in depth and the turbine building was especially vulnerable because of its location. Even if the initiating event mean value of an 14m tsunami run-up height at Daiichi was 100 times smaller than 1.0e-3/year, in other words 1.0e-5/year, the dominant accident sequence would have a value uncomfortably close to the total CDF/year of 1.0e-4 and equal to uncontrolled release regulations of 1.0e-5/year. We therefore believe that NPP operators in Japan should prepare for the maximum tsunami run-up height which could happen within a large radius, make extensive changes in plant layout, and create defence in depth capabilities, such as the Notstand system at the Beznau NPP mentioned earlier.

As an aside, when the author asked a TEPCO analyst why TEPCO did not do bounding analyses, the answer he received was that bounding analyses were not included in the guidelines, therefore TEPCO felt comfortable only doing what was asked by the regulators, nothing more.

Two final observations:

TEPCO's and the regulators' complacency that a 5.7m tsunami wall was adequate, given that it was constructed more than 35 years before the 2002 study by JSCE and given that building new defences was extremely expensive, is highly suspect. TEPCO will book a group net loss of JPY 1.2 trillion ($1.49 billion) from the Fukushima Daiichi accident. The lessoned learned is that the accident always costs more than the defence.

In a meeting in April, 2009, with a top official from the Atomic Energy Commission of Japan, we asked what the most important risk problem was for Japanese NPPs. He said, "There are three problems: (1) Seismic, (2) Seismic, and (3) Seismic. Now we can add tsunami.