Saving Nuclear Power Plants from Earthquakes

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Design of NPPS for Seismic Loads

Seminar on Seismic Base Isolation

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Objectives of a SHA

- Derivation of the Design Basis Ground Motion Values for New NPPs
- Seismic Evaluation for NPPs
  - Seismic PSA
  - Seismic Margin Analysis

Building up of a Database

- Introduction of 4 scales of investigation
  - Regional (R~150 km) 1 : 500 000
  - Near regional (R~25 km) 1 : 50000
  - Site vicinity (R~5 km) 1 : 5000
  - Site area (fenced area) 1: 500

The ‘Near Field’ Issue

The site for the NPP is generally chosen at a relatively ‘aseismic’ part of the country. This generally means that well known seismogenic sources are more than at least 50 kms from the site. Consequently the seismic source that contains the site is a ‘zone of diffuse seismicity’ (to use the terminology of the IAEA Safety Guide). Because there are few dispersed epicentres and that these are not well correlated with tectonic structures, these areas generally do not attract the interest of researchers and therefore contain the least amount of both geological and seismicity data that is available prior to the selection of the site.

Dealing with Uncertainties

- Random (aleatory) uncertainties – inherent in the variable
- Modeling (epistemic) uncertainties
- Balance between data generation and coping with uncertainties
- Only some part of the uncertainty can be reduced by additional data – imported uncertainties cannot be reduced

DSHA vs. PSHA

- Both methods need to transform the ‘seismic event’ to ‘ground motion’. This transformation is the major source of variability
- In PSHA the rate of earthquake recurrence is an important parameter
- In DSHA it is not a parameter but it may be used to distinguish between seismic sources

DSHA vs. PSHA

- ►It is difficult to say which method is more conservative – depends on the safety factors (in the DSHA) and the probability of exceedance considered
- ►The treatment of uncertainties (both aleatory and epistemic) should be similar in PSHA and DSHA
- ►At 10E-4 mean annual probability of exceedance level DSHA is expected to result in somewhat lower values in "high seismicity" areas and vice versa

Using PSHA in Design

- Need to identify reference values that correspond to different design levels
- Use of a performance based approach – USNRC RG 1.208 (i.e. first onset of inelastic deformation – FOSID)
- For the performance based approach both 10E-4 and 10E-5 levels are needed

Two Recent Earthquakes

- The Niigata-ken Chuetsu Oki (NCO) earthquake of 16 July 2007 – causes damage to the non-safety SSCs of the biggest NPP in the world, the Kashiwazaki-Kariwa NPP in Japan
- The Great Tohoku Earthquake of 11 March 2011 (and the following tsunami) - causes a nuclear accident at the Fukushima Daiichi NPP in Japan and impacts three other NPP sites (Fukushima Daini, Onagawa and Tokai)

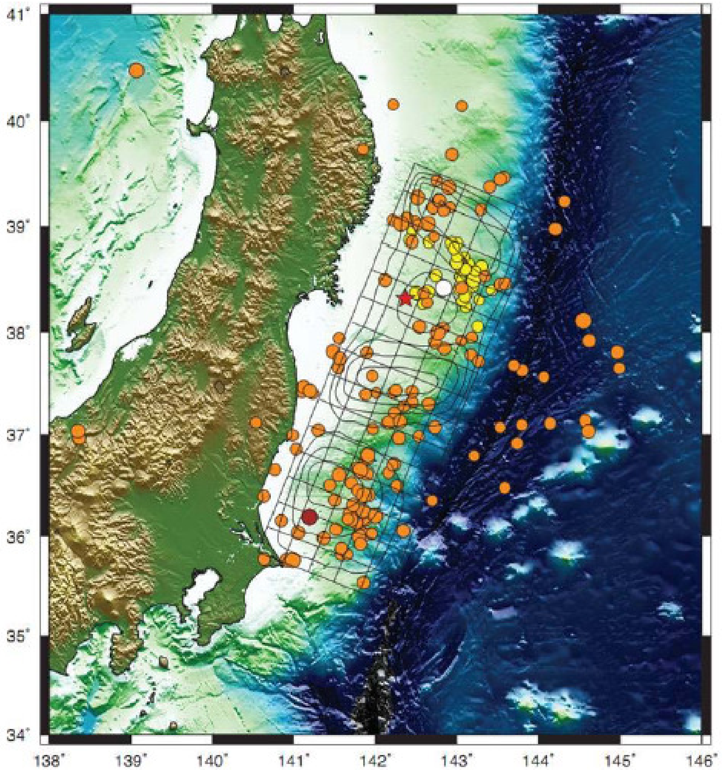
Background to the Earthquake and the Tsunami - 11 March 2011

- Several NPP Sites were subjected to an offshore M9 earthquake and a major tsunami 45 minutes later
- The region was devastated with major damage to infrastructure and about 25000 casualties
- No apparent significant damage to the NPPs due to the earthquake. Tokai 2, Fukushima Daiichi and Fukushima Daini experienced flooding


HIGASHI
DORI NPP
ONAGAWA
NPP
Epicenter
Tokyo
FUKUSHIMA
DAI-ICHI NPP
TOKAI
DAI-NI NPP
FUKUSHIMA
DAI-NI NPP
Osaka
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Data © 2011 MIRC/JHA
© 2011 Cnes/Spot Image
Image © 2011 TerraMetrics
lat 34.739059° lon 143.047655° elev -5779 m


Unit 6
Unit 5
Unit 1
Unit 2
Unit 3
Unit 4

Source Fault of 2011 Great East Japan Earthquake



Source of this earthquake
【By Earthquake Research Institute, The University of Tokyo】

Largest earthquakes in the world
【From USGS】

Earthquake		Mw
1960	Chile	9.5
1964	Alaska	9.2
2004	Sumatra	9.1
2011	Great East Japan	9.0
1952	Kamchatka	9.0

The March 11th earthquake occurred as multiple sources where earthquakes had occurred in the past interlocked, and the magnitude was the largest in recorded history for earthquakes occurring in the area surrounding Japan and the 4th largest in the world.


Date : 2011/3/11 15:42


Date : 2011/3/11 15:43

External factors that made field work difficult (yard)

- During the initial response, there were several aftershocks, and work was conducted in extremely poor conditions, with uncovered manholes and cracks and depressions in the ground (in particular, nighttime work was conducted in the dark).
- There were also many obstacles blocking access routes.

Depressions in roads, etc.
Areas that were dangerous even to walk. Particularly dangerous at night.

Obstacles on access routes
Fire hoses, etc., were laid around access routes. After the explosion, rubble and damaged fire tucks became additional obstacles.

Access to lay temporary power sources
In order to enter the building, the large object delivery entrance was destroyed using heavy equipment.

Laying of temporary power sources
Employees other than electricity-related personnel helped in laying the cables.

External factors that made field work difficult (inside the building)

- As there was no power, work inside the building was conducted in complete darkness.
- As there was no power, temporary instrument power had to be installed separately for each instrument.

Work in complete darkness

Photo of the Service Building entrance taken from inside the building. Objects were scattered on the floor.

Temporary instrument power

As there was no power, temporary batteries were connected and used as a power supply for instruments.

Monitoring by the assistant shift supervisor

Confirmed readings in complete darkness using a light

Monitoring by the assistant shift supervisor

Condition of the assistant shift supervisor's desk. Monitoring in complete darkness wearing a full-face mask


IAEA

Maximum acceleration value of standard ground motion Ss Kashiwazaki-Kariwa NPP

(The “horizontal” figures represent the greater of the figures for the NS and EW components.)

(Unit: Gal)

Standard ground motion	unit 1	unit 2	unit 3	unit 4	unit 5	unit 6	unit 7
Ss－1 (F-B fault / JEA spectrum)	Horizontal: 2280 Vertical: 1010				Horizontal: 1040 Vertical: 630		
Ss－2 (F-B fault / Empirical Green's function)	Horizontal: 1354 Vertical: 402				Horizontal: 1156 Vertical: 501		
Ss－3 (Nagaoka plain western boundary fault zone / JEA spectrum)	Horizontal: 600 Vertical: 400				Horizontal: 600 Vertical: 400		
Ss－4 (Nagaoka plain western boundary fault zone / Empirical Green's function)	Horizontal: 589 Vertical: 314				Horizontal: 826 Vertical: 332		

Revised New Seismic Hazard at the K-K NPP Site

- The following faults were taken into consideration upon determining the design-basis seismic motion.

Active fault		Length of fault	Scale of earthquake [*1]		Angle of inclination [*2]	Notes
F-B fault		About 34km[*3] (About 27km)	34km	M7.0	Southeastern inclination 35•	As a conservative approach, the total length of the fault was identified as about 34km.
Nagaoka Plain Western Boundary Fault Zone	Kakuda-Yahiko fault	About 54km	91km	M8.1	Western inclination 50•	As a conservative approach, these faults were assumed to move together.
	Kihinomiya fault	About 22km				
	Katagai fault	About 16km				
F-D fault • •		About 30km	55km	M7.7	Southeastern inclination 35•	As a conservative approach, these faults were assumed to move together.
Takada-oki fault		About 25km				

Note 1: With regard to the F-B fault, the scale of magnitude was determined by the scale of the assumed fault surface
• •between the magnitude and the size of the fault surface at the hypocenter of the Niigata-Chuetsu-Oki earthquake.
• • • •magnitude was determined by the length of ground surface faults using the formula of Matsuda (1975).
Note 2: Angle of inclination: the inclination of fault surface against the horizontal surface.
Note 3: The length of the fault, according to our survey, is 27km, but taking a conservative approach, it is assumed to

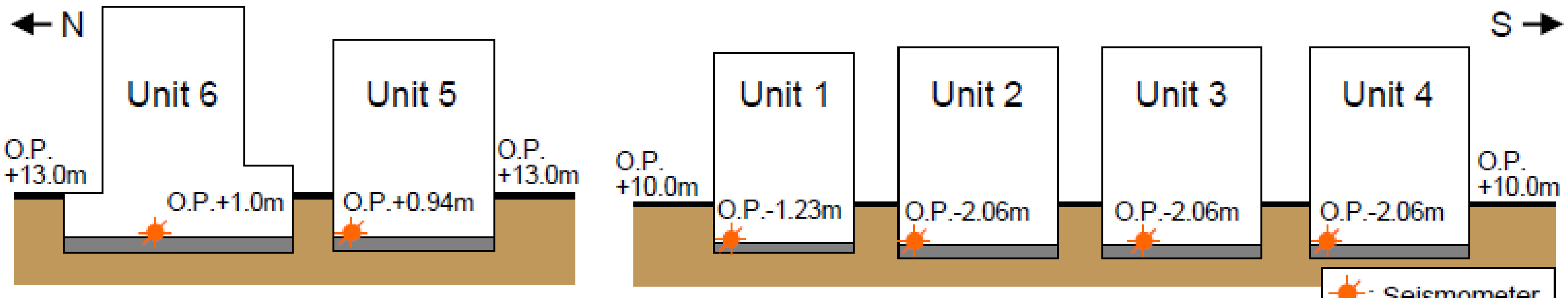
Seismic motion	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7
Niigataken Chuetsu-oki Earthquake (observed on the foundation of reactor building)	680	606	384	492	442	322	356
Response to the design basis seismic motion Ss (on the foundation of reactor building)	829	739	663	699	543	656	642
The peak value of the design basis seismic motion Ss (on the free surface of base stratum)	2,280				1,156		

The value represents the larger value among horizontal ones (south-north and east-west). (Unit: Gal)

Records of Observations at Base-mat Slab of Reactor Building at Fukushima Daiichi NPS

	Maximum acceleration value from observation records (Gal)			Maximum response acceleration value (Gal)					Static horizontal acceleration (Gal)
				New design-basis seismic ground motion Ss			Original design-basis seismic ground motion		
	NS	EW	UD	NS	EW	UD	NS	EW	
Unit 1	460	447	258	487	489	412	245		470
Unit 2	348	550	302	441	438	420	250		
Unit 3	322	507	231	449	441	429	291	275	
Unit 4	281	319	200	447	445	422	291	283	
Unit 5	311	548	256	452	452	427	294	255	
Unit 6	298	444	244	445	448	415	495	500	

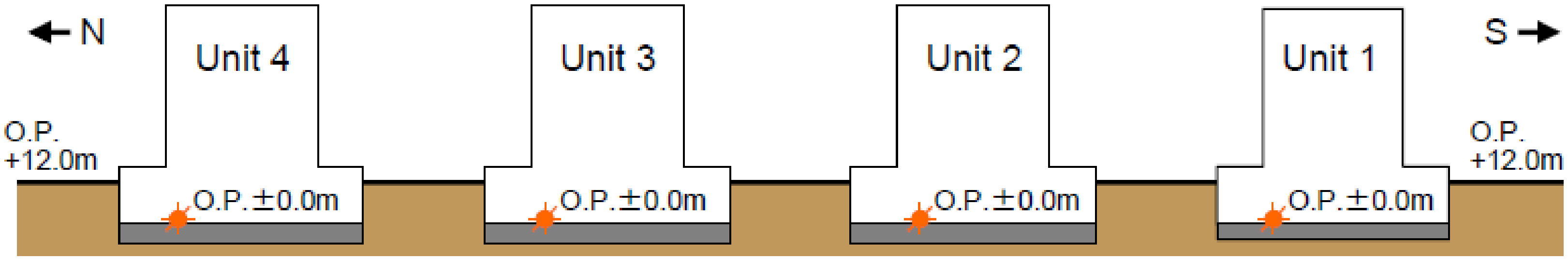
* ☐ indicates the observed value was beyond the response of Ss, the others were under the response of Ss.



Records of Observations at Base-mat Slab of Reactor Building at Fukushima Daini NPS

	Maximum acceleration value from observation records (Gal)			Maximum response acceleration value (Gal)					Static horizontal acceleration (Gal)
				New design-basis seismic ground motion Ss			Original design-basis seismic ground motion		
	NS	EW	UD	NS	EW	UD	NS	EW	
Unit 1	254	230	305	434	434	512	372	372	470
Unit 2	243	196	232	428	429	504	317	309	
Unit 3	277	216	208	428	430	504	196	192	
Unit 4	210	205	288	415	415	504	199	196	

* All observed maximum acceleration values were under the response of Ss.



Base mat motions at Daiichi and Daini

- For approximately the same epicentral distance and distance from fault rupture (about 200 kms) the base mat motions at the two plants (only 10 kms apart) are significantly different
- The soil properties are similar (~50 meters to Vs = 700 km/s layer)
- Plant structures are also similar and the embedment depth ~ 10 – 12 m for all units

Curious statistics

Dai-ichi (average for 6 units):

- NS: 367
- EW: 469
- UD: 249
- NS/EW: 0.78
- UD: lowest component

Daini (average for 4 units):

- NS: 246
- EW: 212
- UD: 258
- NS/EW: 1.16
- UD: highest component

Curious statistics

Daiichi Averages / Daini Averages

- NS: 1.49
- EW: 2.21
- UD: 0.97

Conclusions

- Recent data from Kashiwazaki-Kariwa, Fukushima Daiichi and Fukushima Daini NPPs could not have been predicted by the conventional use of GMPEs and site response analyses
- There is a need for looking at site vicinity and site area scales holistically

Conclusions - Earthquake

- Although the Great East Japan earthquake exceeded the licensing based design basis ground motion of the F1 plant at the level of the foundation base mat in all units, the operating plants were automatically shutdown and all units behaved in a safe manner, during and immediately after the earthquake
- It was also confirmed that in some cases the observed values even exceeded the recently determined maximum response acceleration values showing apparently an underestimation of the new DBGM Ss

Conclusions - Earthquake

- Based on the reports from Japanese experts and plant personnel, safety related structures, systems and components of the plant seemed to have behaved well for possibly due to conservatisms in the various steps of the design process
- The combined effects of these conservatisms were apparently sufficient to compensate for uncertainties in the data available and the methods applied at the time of the design of the plant and also the re-evaluated ground motions

AG Observation

At the moment, it is very difficult to separate earthquake damage from others; i.e. tsunami, three explosions and possible thermal related failures due to sea water cooling (e.g. to the spent fuel pools from helicopters). As there was not enough time for a seismic walkdown in 45 minutes (before the tsunami came), it is not possible to rule out at least some damage due to the earthquake

Conclusions - Earthquake

The underestimation of the hazard in the original hazard study as well as in more recent re-evaluations mainly result from the use of recent historical seismological data in the estimation of the maximum magnitudes especially associated with the neighbouring subduction zone east of the sites.

Lesson Learned

- ►Suppliers should understand that standard designs for ‘0.25g’ or ‘0.3g’ are inadequate for many parts of the world – economic pressure in ‘new build’ countries to decrease hazard estimates (may have happened at F-1 in the 1960s)
- ►In the past 25 years
  - Seismic hazard values increased by a factor of about 2
  - Maximum observed accelerations increased by about 4 (from 1g to 4g)
  - Standard seismic design values more or less stayed the same

Lesson Learned

- In seismic design a “beyond design” concept already existed. For example
  - In EUR the beyond design is 1.5 times the design with different acceptance criteria
  - In USA Regulations, the Applicant must demonstrate that the plant HCLPF value is 1.67 times the design value
- After Fukushima all external hazards are being considered also for “beyond design”
- Need to check for cliff edge effects – e.g. European Stress Tests

New Build NPPs

- Even in low to medium seismicity countries (such as Hungary) the newly calculated seismic hazard will be not less than 0.3g with beyond design values approaching 0.5g
- With most suppliers delivering standard designs of 0.25g – 0.3g, is it time for Base Isolation for NPPs?

Experience in Base Isolation for NPPs

- Cruas NPP (France) – with elastomer pads – superstructure designed for 0.2g
- Koeberg NPP (South Africa) – with elastomer and brass sliding elements – superstructure designed for 02.g (sliding starts at 0.2g because of the coefficient of friction)
- Karoon NPP – Iran (similar to Koeberg concept – designed but never built)

Base Isolation for NPPs

- Advantages: High seismic loads which are becoming common would not cause a hindrance
- Challenges: FOAK situation – regulatory issues need to be resolved
- Need to:
  - Check cost benefit for various levels of seismic design
  - Check potential regulatory issues and address them in design