Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division V

EVALUATION OF SEISMIC DAMAGE INDICATING PARAMETERS AT NUCLEAR POWER PLANTS AFFECTED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE

Fred F. Grant[1], Greg S. Hardy[2], Yuchuan Tang[3], and Robert Kassawara[4]

[1] Sr. Staff II, Structural Mechanics Group, Simpson Gumpertz & Heger Inc., Newport Beach, CA (FFGrant@sgh.com)
[2] Senior Principal, Structural Mechanics Group, Simpson Gumpertz & Heger Inc., Newport Beach, CA
[3] Staff II, Structural Mechanics Group, Simpson Gumpertz & Heger Inc., Waltham, MA
[4] Senior Project Manager, Structural Reliability and Integrity, EPRI, Palo Alto, CA

ABSTRACT

The 2011 Great East Japan (GEJ) earthquake affected four nuclear power plants (NPPs) along the eastern coast of Honshu, Japan: Fukushima Daiichi, Fukushima Daini, Onagawa, and Tokai Daini. The earthquake motions recorded at these plants were severe. By some measures, the motions were roughly thirty to fifty times greater than current U.S. regulatory threshold levels intended to quickly identify whether an earthquake motion is potentially damaging. Yet despite the severe shaking, the plants' safety-related systems apparently incurred no significant shaking-induced damage. In this study, several seismic damage-indicating parameters are computed from the motions recorded at these four sites. The results are examined in light of the lack of reported damage to safety-related systems, and are compared to regulatory threshold values. Insights from this study may be used to guide regulation and industry methods for quickly evaluating the damage potential of earthquakes affecting NPPs.

BACKGROUND

In the 1970s and 1980s, several U.S. NPPs were subjected to ground motions caused by nearby low-magnitude earthquakes. The recorded motions exceeded the operating basis earthquake (OBE) design response spectra at high frequencies as reported in Electric Power Research Institute (EPRI (1988)). Although there was no damage in either case, extensive analyses were required to verify that the safety-related equipment had not been degraded. These events prompted EPRI to initiate research to develop a rational criterion for determining when the OBE design limit has been exceeded at an NPP and, hence, when actions are required in accordance with United States Nuclear Regulatory Commission (USNRC (1973)). The primary goal of the research was to define criteria that could rationally and quickly determine whether an earthquake could have potentially caused damage that might preclude continued safe operation.

EPRI (1988) reviewed various scalar seismic damage-indicating parameters (DIPs) derivable from an instrument recording. Since the OBE definition was generally based on free-field motion, the research focused on various methods of using the recorded motion obtained from free-field recording instruments. The study considered DIPs such as peak ground acceleration, Arias intensity, and root-mean-square (RMS) acceleration, and introduced a new instrumental parameter denoted cumulative absolute velocity (CAV). The study concluded that CAV was the best single instrumental parameter for determining the damage potential of earthquake ground motion.

The computational algorithm for CAV was further refined and standardized in EPRI (1991) to make the CAV value representative of strong ground shaking rather than coda waves (small amplitudes that can continue on for a long time after the strong shaking). Using the standardized CAV, EPRI (1991) proposed 0.16g-sec as the CAV threshold. The deterministic threshold was intended to conservatively represent the level below which an earthquake could be characterized as "non-damaging." The CAV threshold of 0.16g-sec was adopted in USNRC (1997) for determining OBE exceedance. The underlying basis for the CAV threshold criterion was the large volume of measured and empirical data that verified that damage would not occur to structures and equipment of “good design and construction.” Specifically, the CAV value of 0.16g-sec is intended to represent the earthquake severity on the threshold between Modified Mercalli Intensity (MMI) VI and VII, which is characterized as being “at least two MMI units less than the earthquake intensity required to potentially damage buildings of good design and construction (i.e., failure requires at least MMI VIII)” in EPRI (1988).

In the years prior to the 2011 GEJ earthquake, several NPPs in Japan had experienced earthquake motions with CAV values on the order of ten to twenty times the USNRC CAV threshold and had sustained no damage to safety-related systems according to EPRI (2009). These observations demonstrated that the onset of damage that might preclude continued safe operation of a NPP would likely occur for CAV values at least an order of magnitude greater than the conservative 0.16g-sec threshold. The seismic data collected at the four Japan NPPs affected by the 2011 GEJ earthquake provide additional evidence that the 0.16g-sec threshold is very conservative.

This paper begins with an overview of the 2011 GEJ earthquake and its effects on the nearby NPPs. Several seismic DIPs are then computed from the acceleration recordings at the plant sites. The DIP results and the associated regulatory threshold values are then discussed in light of the seismic performance of the NPPs during the 2011 GEJ earthquake. The results are also analyzed for effects such as soil-structure interaction (SSI), which produces differences between CAVs computed from free-field and foundation recordings.

NUCLEAR POWER PLANTS AFFECTED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE

On March 11, 2011 at 2:46 p.m. local time, a M_w9.0 earthquake occurred off the Pacific coast of Northeastern Japan, rupturing an area approximately 450 km (280 miles) long and 150 km (93 miles) wide (Government of Japan (2011)). The earthquake caused a massive tsunami that inundated over 561 km^2 (217 square miles) of land along the Northeastern Japan coastline (Government of Japan (2011)). The International Atomic Energy Agency (IAEA (2011)) reported that the epicenter of this earthquake was off the coast of Miyagi Prefecture with a focal depth of approximately 24 km (15 miles).

The earthquake directly affected four Japanese NPPs: Onagawa, Fukushima Daiichi, Fukushima Daini, and Tokai No.2. The Fukushima Daiichi NPP was at a distance of about 180 km (112 miles) from the epicenter; the epicentral distance for Onagawa NPP site was about 130 km (81 miles) (IAEA (2011)). The earthquake resulted in the automatic shutdown of eleven operating power generating units at the four sites, namely Onagawa Units 1–3, Fukushima Daiichi Units 1–3, Fukushima Daini Units 1–4, and Tokai No.2 (single unit). Prior to the earthquake, Fukushima Daiichi Units 4–6 had been shut down and in an outage for routine refueling or maintenance. With data obtained from IAEA (2011), Table 1 summarizes the basic information of the eleven units and their status before and after the 2011 GEJ earthquake and tsunami. In the following, the abbreviations of the four NPPs are used (i.e., 1F for Fukushima Daiichi, 2F for Fukushima Daini, O for Onagawa, and T2 for Tokai No.2).

Table 1: Summary of nuclear power generating units affected by the 2011 GEJ earthquake.

Unit	Model	Contain-ment	Capacity (MWe)	Commercial Operation Started	Status during 2011 GEJ Earthquake and Tsunami		
					Before Earthquake	After Earthquake	After Tsunami
1F1	BWR-3	Mark I	460	1971	Operating	Automatic scram	Loss of cooling
1F2	BWR-4	Mark I	784	1974	Operating	Automatic scram	Loss of cooling
1F3	BWR-4	Mark I	784	1976	Operating	Automatic scram	Loss of cooling
1F4	BWR-4	Mark I	784	1978	Outage	Cold shutdown	Loss of SFP cooling
1F5	BWR-4	Mark I	784	1978	Outage	Cold shutdown	Cold shutdown
1F6	BWR-5	Mark II	1,100	1979	Outage	Cold shutdown	Cold shutdown
2F1	BWR-5	Mark II	1,100	1982	Operating	Automatic scram	Cold shutdown
2F2	BWR-5	Mark II R	1,100	1984	Operating	Automatic scram	Cold shutdown
2F3	BWR-5	Mark II R	1,100	1985	Operating	Automatic scram	Cold shutdown
2F4	BWR-5	Mark II R	1,100	1987	Operating	Automatic scram	Cold shutdown
O1	BWR-4	Mark I	524	1984	Operating	Automatic scram	Cold shutdown
O2	BWR-5	Mark I	825	1995	Reactor Start	Automatic scram	Cold shutdown
O3	BWR-5	Mark I	825	2002	Operating	Automatic scram	Cold shutdown
T2	BWR-5	Mark II	1,100	1978	Operating	Automatic scram	Cold shutdown

The four NPPs were subjected to strong ground shaking in the 2011 GEJ earthquake. Government of Japan (2011) estimated the seismic intensities at the plant sites at the level of 5 strong to 6 strong on the Japan Meteorological Agency (JMA) scale. In terms of the MMI scale, the United States Geological Survey (USGS, 2011) estimated the intensities as 7.72 at Fukushima Daiichi, 7.76 at Fukushima Daini, 7.34 at Onagawa, and 7.72 at Tokai. According to American Nuclear Society (2012), the measured accelerations from the 2011 GEJ earthquake exceeded the design basis for Fukushima Daiichi and Onagawa NPPs.

In spite of the strong ground shaking, the safety-related structures, systems, and components (SSCs) at the four NPPs remained functional until the arrival of the tsunami wave 30 to 45 minutes after the main shock. The structural elements of the Onagawa NPP were "remarkably undamaged" according to IAEA (2012). The Fukushima Daiichi nuclear accident is commonly attributed to the tsunami flood. It may be difficult to conclusively differentiate between shaking and tsunami damage at Fukushima Daiichi, but the successful start of diesels and successful rod insertion prior to the tsunami inundation suggest safety systems were likely intact after shaking and before flooding. The earthquake shaking is generally not considered responsible for the damage to safety-related SSCs according to the Tokyo Electric Power Company (TEPCO) and as reported by The National Diet of Japan (2012). At Fukushima Daini and Tokai No.2, the observed ground motions did not exceed the design basis, and no shaking damage to safety-related SSCs is reported in IAEA (2011).

RECORDED STRONG MOTIONS AND SEISMIC DAMAGE INDICATING PARAMETERS AT PLANT SITES

Seismometers have been installed throughout the Fukushima Daiichi and Daini, Onagawa, and Tokai No.2 sites. For example, Figure 2 shows some of the seismometers in the Onagawa Unit 1 Reactor Building. Acceleration recordings of the main shock of the 2011 GEJ earthquake have been retrieved by the plant operators and released by the Japan Association for Earthquake Engineering (JAEE (2011a, 2011b, and 2011c)). The acceleration data used in this study and presented in this paper are obtained from the JAEE database. The copyright of the data belongs to the utility companies that provided the data (TEPCO provided Fukushima Daiichi and Daini data, Tohoku Electric Power Company provided Onagawa data, and Japan Atomic Power Company provided Tokai data). The distribution license of the data belongs to JAEE.

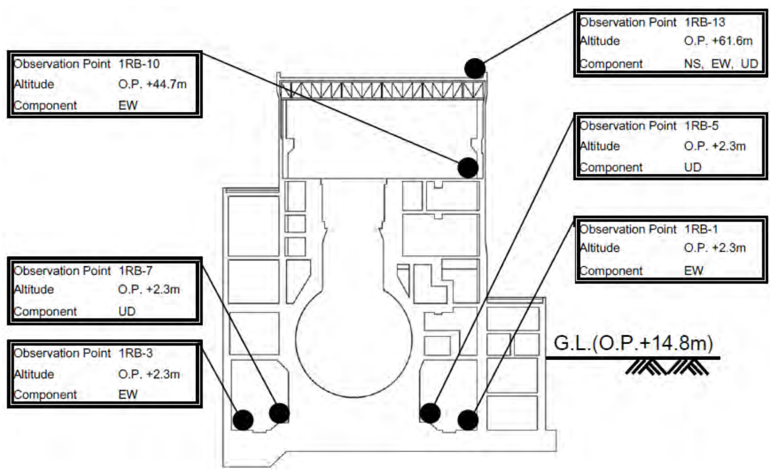

Figure 2. Location of Seismometers at Onagawa Unit 1 Reactor Building (JAEE (2011a, 2011b, and 2011c)).

The JAEE database includes a total of 141 seismometers at the four plant sites that recorded acceleration time histories during the main shock of the 2011 GEJ earthquake. At each site, the seismometers are distributed at various locations, including free-field boreholes, ground surface, and several elevations in each Reactor Building (RB) and Turbine Building (TB). The seismometers and their recordings are categorized in this paper based on location in order to investigate the spatial variation of the motions. Table 2 lists the number of seismometers in each of eight location categories for each plant. Note that many seismometers recorded accelerations in all the three orthogonal directions (i.e., E-W, N-S, and U-D), while some did not.

Table 2: Number of Seismometers at Various Locations with Acceleration Recordings Retrieved.

Location Category	1F	2F	O	T2
Free-field at grade	21	3	1	1
Free-field at RB foundation elevation	2	3	1	1
Other depths in borehole	9	5	2	2
RB foundation	8	10	18	5
RB, roughly mid-height	1	5	3	1
RB operating deck	2	2	11	1
Other locations in RB	2	3	3	1
Turbine Building	2	12	0	0
Total	47	43	39	12

The acceleration recordings in the main shock of the 2011 GEJ earthquake exhibit some distinguishable features as demonstrated by the free-field ground surface motion in Figure 3. Firstly, the peak ground acceleration is very high (0.566g for the case in Figure 3). Second, the effective duration, calculated as the time interval between 5% and 75% of the cumulative energy, lasted quite long (57.23 sec for the case in Figure 3), with the trace of successive ruptures of multiple fault segments. The third feature is strong spectral content at high frequencies above 10 Hz, compared to the recordings at NPPs under other historical Japan earthquakes (e.g., the Kashiwazaki–Kariwa NPP under the 2007 Niigata Chuetsu-Oki earthquake).

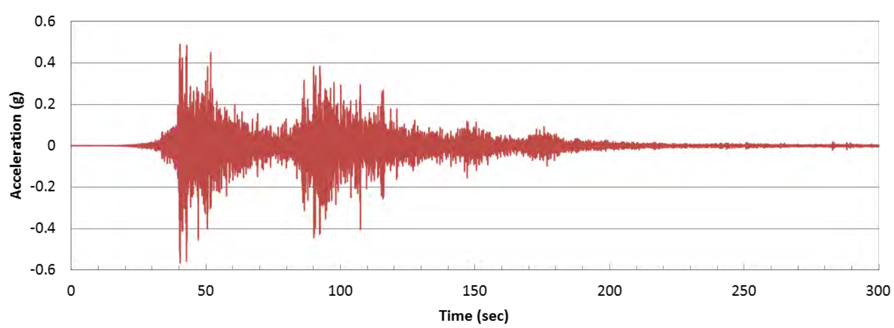

Figure 3. E-W Recording by Seismometer G-4 near Grade Level in Free-Field Borehole at Onagawa NPP.

In this study, both graphical and scalar DIPs were computed from the acceleration recordings. The graphical DIPs include 5% damped response spectra, Fourier amplitude spectra, power spectral density, and the Husid curve of cumulative energy. The scalar DIPs considered include CAV, RMS acceleration, zero period acceleration (ZPA), Arias intensity, and effective duration (see for example, Kramer (1996)). For select scalar DIPs, Figure 4 shows the mean value and 1-standard deviation range for five location categories (refer to Table 2) at each site. In this figure, each colored marker represents the mean value while the black bar shows the 1-standard deviation range. Figure 4 provides a straightforward comparison of the scalar DIPs across various location categories, as well as across plant sites. In general, the DIPs were amplified by the soil site from depth to ground surface. At a given site, there is very little difference between the free-field and in-structure DIPs at the RB foundation elevations. The foundation motion was amplified to the mid-height and further to the operating deck. The DIPs of the mid-height and the operating deck recordings have large variation due to the complexities in the structural responses.

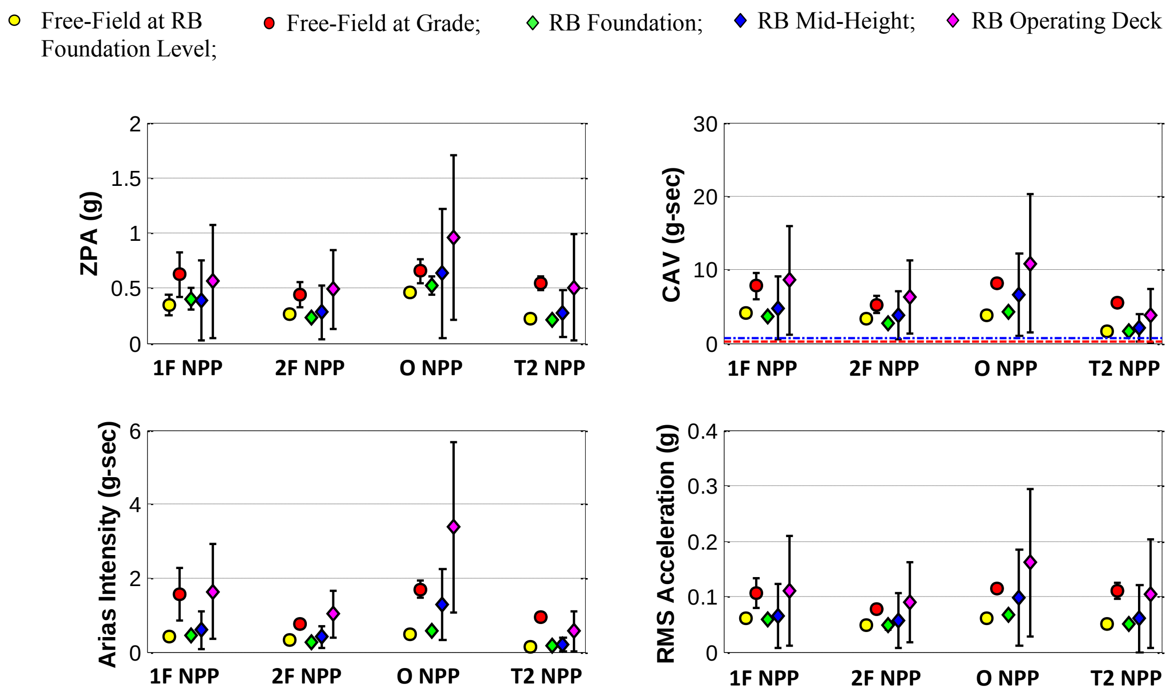

Figure 4. Statistics of DIPs from Horizontal Recordings in Five Different Location Categories by Plant Site.

Observed CAV Values and Current Regulatory Threshold

The CAV values of the recordings observed at the four plant sites significantly exceed the regulatory threshold. USNRC (1997) specifies 0.16g-sec as the free-field ground motion CAV threshold used to evaluate OBE exceedance for NPPs. This regulatory threshold is shown as the horizontal red dash line in the CAV panel in Figure 4. The blue dash-dot line shows 0.77g-sec, which is the lowest level at which shaking-induced damage is known to have occurred at a heavy industrial or conventional power generation facility (i.e., El Centro Steam Power Plant during 1979 Imperial Valley earthquake per EPRI (1991)). The observed CAV values at the four NPPs under the 2011 event are much higher than the current regulatory threshold. Table 3 lists the mean, upper bound (UB), and lower bound (LB) of the observed CAV for three location categories: free-field recordings at grade level, free-field recordings at the level of RB foundation, foundation recordings, and operating deck recordings for the RB. The mean CAV values associated with the free-field ground surface motions are approximately thirty to fifty times greater than the 0.16g-sec regulatory threshold, and roughly an order of magnitude greater than the 0.77g-sec level associated with damage to an industrial/power facility.

Table 3: Observed CAV at NPPs under the 2011 GEJ Earthquake (unit: g-sec).

Plant	Free-field at Grade			Free-field at RB Foundation Level			RB Foundation			RB Operating Deck		
	Mean	UB	LB	Mean	UB	LB	Mean	UB	LB	Mean	UB	LB
1F	7.79	12.15	4.98	4.14	4.22	4.00	3.60	4.09	3.09	8.57	9.86	7.49
2F	5.26	7.09	3.85	3.40	3.62	3.15	2.74	3.45	2.19	6.29	7.58	4.79
O	8.09	8.33	7.85	3.81	3.82	3.80	4.21	4.67	3.96	10.87	13.86	8.89
T2	5.47	5.58	5.36	1.60	1.71	1.50	1.68	1.80	1.59	3.76	3.82	3.70

The current regulatory CAV threshold is conservatively based on ground motions measured at commercial and industrial facilities and characterized by the threshold between MMI VI and VII (EPRI (1988)). MMI VII was regarded as a conservative estimate of the onset of potentially damaging ground motion for "buildings of good design and construction." There is additional conservatism in the threshold since the MMI scale describes effects on the general built environment, which is known to be less seismically rugged than NPPs. Based on the data presented above from the 2011 GEJ earthquake, several sources of conservatism combine to result in a regulatory threshold that may be at least an order of magnitude lower than the true threshold for the onset of damage to NPPs.

The results in Table 3 also demonstrate that the CAVs of the free-field motions are generally amplified from the depth at RB foundation elevation to the ground surface. The CAVs associated with the basemat recordings slightly deviate from the CAVs of the free-field recordings at the same elevation, probably due to SSI effects. The next section further investigates the variation of DIPs at different locations.

Amplification and Deamplification of Seismic DIPs in NPP Structures

The recordings at different elevations in each RB allow investigating the spatial variation of seismic DIPs within the building. Figure 5 compares the 5% damped acceleration response spectra of the recordings at the foundation, the operating deck (refueling floor), and the roof of the Onagawa Unit 1 RB. Figure 5 also shows the response spectra of the free-field ground surface motion and the free-field borehole motion close to the elevation of the RB foundation. Generally, the ground motion was amplified with increasing elevation in the borehole. The spectrum of the ground surface motion is higher than that of the foundation motion in the range of 1 to 10 Hz. In the RB, the foundation motion was amplified to the operating deck and further to the roof. A similar trend is evident in Figure 4 for the scalar DIPs. These trends generally hold for all four NPP sites affected by the 2011 GEJ earthquake.

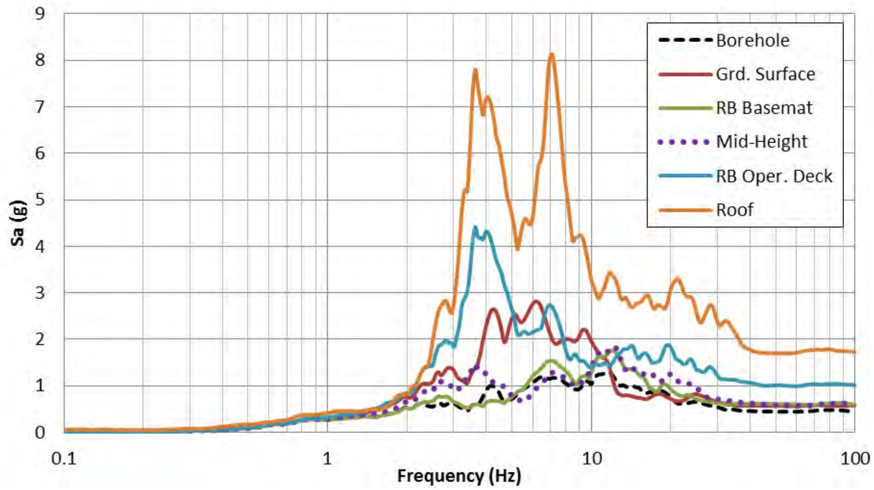

Figure 5. 5% damped response spectra of the EW components at different locations of Onagawa Unit 1.

The observations in this study support the suggestion in EPRI (2009) that foundation CAV may be a better predictor of damage at NPPs than the CAV associated with free-field surface motions. For the four plant sites, the mean CAV values of the operating deck recordings are consistently 2.2 to 2.6 times the mean CAV values of the foundation recordings. On the other hand, the mean CAV at the RB operating deck can be as large as 34% higher (at Onagawa) or as small as 31% lower (at Tokai No.2) than the mean CAV at ground surface (see Table 3). It is evident, then, that structure responses and equipment mounting point motions (and therefore damage) should be expected to have a stronger correlation to CAV computed from foundation motions than to CAV computed from free-field surface motions.

CONCLUSIONS

Based on 263 historical earthquake recordings, EPRI developed the CAV threshold of 0.16g-sec to establish a conservative threshold for the onset of damage to conventional buildings of good design and construction. USNRC adopted this CAV threshold to define OBE exceedance criteria that permit licensees to continue operation after earthquake events that can be confidently characterized as non-damaging to NPP SSCs.

This paper presents insights on the relationship between seismic damage parameters (e.g., CAV) and the actual seismic-induced damage observed at the Onagawa, Fukushima Daiichi, Fukushima Daini, and Tokai Daini NPP under the 2011 GEJ earthquake. Free-field surface motions at Onagawa NPP have CAV values of 7.9 to 8.3g-sec with no damage to safety-related nuclear SSCs. At Fukushima Daiichi NPP, the recorded free-field surface motions have CAV values ranging from 5.0 to 12.2g-sec. The free-field CAV range is 3.9 to 7.1g-sec and 5.4 to 5.6g-sec for Fukushima Daini and Tokai No. 2, respectively. These values suggest that the safety factor of the current regulatory CAV threshold may be as large as 24 to 76. The data reviewed for this study were limited to the four Japanese NPPs discussed above. The authors recommend further study to include the data from all NPPs (as complete as possible) that have been subjected to reasonably large earthquakes.

The CAVs of the RB foundation motions in the 2011 GEJ earthquake are as large as 4.67g-sec, twenty-nine times the threshold, with no known earthquake-induced damage to safety-related SSCs. If sufficient data can be gathered and evaluated at the basemat and at the in-structure floor levels at nuclear and non-nuclear power facilities, the CAV threshold may be alternately defined at the foundation or building floor levels instead of at the free-field. As demonstrated by the 2011 GEJ motions, the in-structure CAVs are better predictors of the building responses and the equipment mounting point locations. An in-structure threshold would therefore be a better characterization of the damage potential of a given seismic event.

REFERENCES

American Nuclear Society. (2012). "Fukushima Daiichi: ANS Committee Report," ANS, LaGrange Park, Illinois, USA.

Electric Power Research Institute. (1988). "A Criterion for Determining Exceedance of the Operating Basis Earthquake," Report NP-5930, EPRI, Palo Alto, California, USA.

Electric Power Research Institute. (1991). "Standardization of the Cumulative Absolute Velocity," Report TR-100082, EPRI, Palo Alto, California, USA.

Electric Power Research Institute. (2009). "Evaluation of CAV and Other Seismic Damage Parameters at Several Japanese Nuclear Power Plants," Report LR-2009-003, EPRI, Palo Alto, California, USA.

Government of Japan. (2011). "Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety – The Accident at TEPCO's Fukushima Nuclear Power Stations," Nuclear Emergency Response Headquarters, Japan.

International Atomic Energy Agency. (2011). "IAEA International Fact Finding Expert Mission of the Fukushima Dai-ichi Accident Following the Great East Japan Earthquake and Tsunami," IAEA Mission Report, IAEA, Vienna, Austria.

International Atomic Energy Agency. (2012). "IAEA Mission to Onagawa Nuclear Power Station to Examine the Performance of Systems, Structures and Components Following the Great East Japan Earthquake and Tsunami," IAEA Mission Report, IAEA, Vienna, Austria.

Japan Association for Earthquake Engineering. (2011a). "Acceleration Time-history Waveforms of the 2011 off the Pacific coast of Tohoku Earthquake observed at Fukushima Daiichi and Daini Nuclear Power Plant," Tokyo Electric Power Company, CD-ROM, Japan.

Japan Association for Earthquake Engineering. (2011b). "Acceleration-Time History Waveforms of the 2011 off the Pacific coast of Tohoku Earthquake and related data collected at Onagawa Nuclear Power Plant," Tohoku Electric Power Co., Inc., CD-ROM, Japan.

Japan Association for Earthquake Engineering. (2011c). "Acceleration-Time History Waveforms of the 2011 off the Pacific coast of Tohoku Earthquake Collected at Tokai No.2 Power Station," Japan Atomic Power Co., Inc., CD-ROM, Japan.

Kramer, S.L. (1996). *Geotechnical Earthquake Engineering*, 1st Edition, Prentice Hall, New York, New York, USA.

The National Diet of Japan (2012). "The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission," Japan.

United States Geological Survey. (2011). "ShakeCast Report of Magnitude 8.9 – Near the East Coast of Honshu, Japan," Version 4, USGS, USA.

United States Nuclear Regulatory Commission. (1973). "Seismic and Geologic Siting Criteria for Nuclear Power Plants," 10 CFR Part 100, Appendix A, Federal Register, Vol. 38, No. 31282, USNRC, Washington D.C., USA.

United States Nuclear Regulatory Commission. (1997). "Pre-Earthquake Planning and Immediate Nuclear Power Plant Operator Post-Earthquake Actions," Regulatory Guide 1.166, USNRC, Washington, D.C., USA.