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Seismic Instrumentation at Nuclear Power Plants

Instrumentation Needs for Supporting the Continuation or Resumption of Plant Operation Following an Earthquake

January 2012

Abstract

When a nuclear power plant experiences ground motion due to an earthquake, an evaluation may be needed to allow the plant to continue operating or to resume operating if it has been shut down. The Electric Power Research Institute (EPRI) has previously conducted research to develop guidance regarding the types of evaluations and inspections that would be necessary to ensure that the earthquake had not caused damage that could affect safe operation of the plant. This paper focuses on the guidance relating to the types of instrumentation necessary to determine the extent of the ground motion at the plant site as one indication of the potential for the earthquake to have damaged structures or equipment.

Introduction

When a nuclear power plant operating in the United States experiences an earthquake, it may need to perform certain reviews and evaluations to continue in power operation. For each plant, an operating basis earthquake (OBE) has been established. The OBE has been defined such that if it can be determined that the ground motion experienced at the plant site did not exceed that level, the plant can continue to operate (or can return to operation if it has been shut down). If the ground motion exceeds the OBE or if it cannot reliably be established whether the OBE has been exceeded, the plant may need to shut down and remain shut down until the plant can demonstrate that the earthquake caused no damage that could affect safe operation.

Although the OBE is often characterized in terms of a single parameter, the *peak ground acceleration*, it is actually defined by a response spectrum. A *response spectrum* relates the maximum acceleration or velocity experienced at a particular location to the frequency associated with the vibrations caused by the earthquake. The response spectrum is typically presented in the form shown in Figure 1.

To determine whether the OBE has been exceeded when an earthquake occurs, it is necessary to collect and evaluate information related to the time history of the ground motion experienced. This paper summarizes an approach that EPRI developed to address the response to an earthquake that may have affected a nuclear power plant, with an emphasis on the nature of instrumentation systems needed to provide the information required for an effective review and evaluation. Equipment and installation options and costs also are discussed.

Definitions

The following definitions may be useful with respect to descriptions of appropriate seismic instrumentation systems:

- *Digital triaxial time history recorder (accelerograph)* – A device that records motion (normally, acceleration) of the object to which it is attached (that is, a structure or piece of equipment) in each of three orthogonal directions.
- *Free-field* – A point near enough to plant structures that the ground motion is representative of that at the structures. The free-field point should be located on soil similar to the conditions for the plant buildings, but far enough from the buildings so that they do not influence the motion. Generally, an optimal location for this point is a distance on the order of one to three times the controlling building dimension away from the buildings.
- *Response spectrum* – A plot of maximum acceleration, velocity, or displacement caused by the recorded earthquake at a range of frequencies associated with the vibrations caused by the earthquake.
- *Cumulative absolute velocity* (CAV) – A parameter that indicates the potential for a recorded earthquake to cause damage to nuclear plant structures. It is the absolute area under the acceleration vs. time plot as recorded by a time-history digital recorder.
- *OBE exceedance criterion* – The combined conditions under which the OBE is considered to be exceeded. A summary chart is given in Figure 2.

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Guidance for Assessing Earthquake Damage

In the late 1970s and mid-1980s, several small-magnitude earthquakes occurred near nuclear power plants in the central and eastern United States. Some of these resulted in vibratory ground motion that exceeded the plants' respective OBE response spectra. These occurrences included the following:

- The 1978 Monticello Reservoir, South Carolina, earthquake recorded near the V. C. Summer Nuclear Power Plant
- The 1986 Chardon, Ohio, earthquake recorded at the Perry plant
- The 1987 Lawrenceville, Illinois, earthquake recorded at the Clinton plant

In each case, the OBE response spectrum was exceeded only at frequencies above 10 Hz. This is significant because research and experience have shown that there is limited potential at relatively high frequencies for damage to structures and major equipment in a nuclear power plant [1]. Moreover, these earthquakes lasted only a short time and did no observable damage. Thus, it became evident that further definition of the OBE was necessary to provide a better means of capturing the potential for such an earthquake to cause damage.

More recently, the 2011 Mineral, Virginia, earthquake near the North Anna Power Station has provided further indication that procedures for addressing earthquake impacts in a timely manner are important.

As a result of the earlier experiences, EPRI developed an approach to evaluate the effects of small, apparently non-damaging earthquakes. As this approach evolved, it focused on verifying that a plant had not incurred damage. This is important in determining whether additional, more extensive examinations of plant structures and equipment might be needed, which could entail a longer plant shutdown. EPRI documented this approach in the following series of reports:

- NP-5930 [1] established criteria for determining when an OBE had been exceeded by considering a new damage parameter called the *cumulative absolute velocity* (CAV), which is the integrated absolute value of the acceleration time history. The CAV, together with a check to ensure that the spectrum had not been exceeded at lower frequencies (that is, in the range from about 2 to 10 Hz), provides a better measure of the potential for damage to plant systems and structures for a specific earthquake than does a comparison of the experienced accelerations to the design response spectra.
- TR-100082 [2] extended the criteria in EPRI NP-5930 by limiting the range over which the acceleration time history should be integrated to calculate the CAV. More specifically, the integration is limited to accelerations above 0.025 g.
- TR-104239 [3] provides detailed guidance for selecting and implementing the seismic instrumentation needed for obtaining the measurements against which the criteria set forth in EPRI NP-5930 and TR-10092 can be applied.
- Finally, NP-6695 [4] provides explicit guidance for overall management of the earthquake response, with particular focus on walkdown inspections of sensitive equipment. These inspections offer more direct means to assess the impact of the earthquake on the plant.

The U.S. Nuclear Regulatory Commission (NRC) recognized a need to redefine the criteria for when a shutdown might be acceptable in order to allow for a more careful inspection and evaluation after an earthquake. In particular, the NRC recognized that such criteria should provide a better

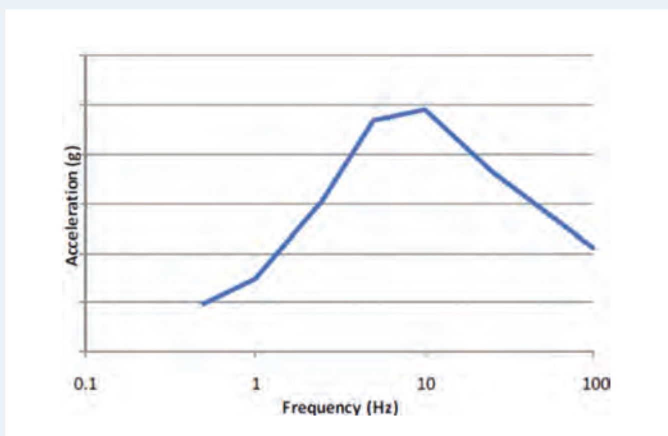

Figure 1. Typical form of an earthquake response spectrum

characterization of the potential for damage to the plant. In 1997, the NRC accepted the approach presented in EPRI NP-5930, TR-100082, and NP-6695. The NRC's endorsement of this approach, with some specific qualifications, was reflected in two regulatory guides. Regulatory Guide 1.166 [5] endorses the EPRI criteria for OBE exceedance. Regulatory Guide 1.167 [6] provides guidance for pre-planning and for steps that should be taken immediately after an earthquake. Figure 2 provides a flow chart from Regulatory Guide 1.166 for determining whether the OBE has been exceeded for plants at which digital seismic instrumentation has been installed.[1] The NRC also embraced the implementation of digital seismic instrumentation in Regulatory Guide 1.12 [7].

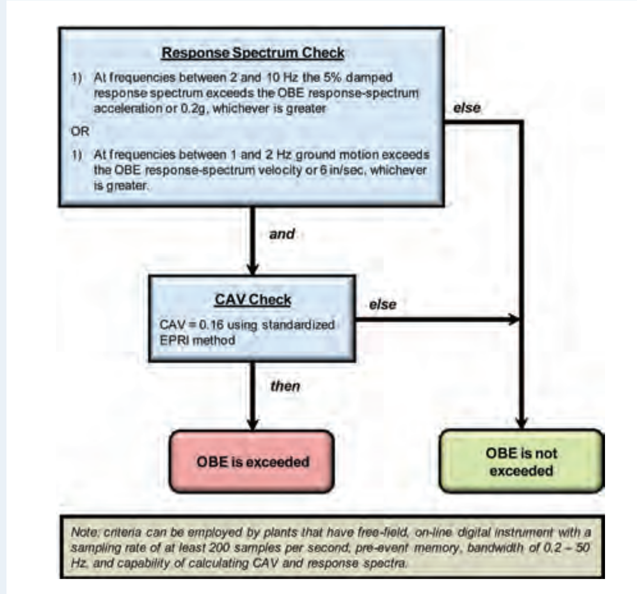

Figure 2. Flow chart of the process for determining whether the OBE has been exceeded [5]

Application of the OBE exceedance criterion requires not only measurement of the OBE parameters (that is, the response spectrum and CAV), but also walkdown inspections of the plant. If the OBE criterion is not exceeded and the inspections yield no evidence of significant damage, the plant can remain in operation or be restarted. Valid instrumental data, available within 4 hours after an earthquake, are necessary to support such a determination. Thus, it is very important that nuclear power plants install and maintain appropriate seismic instrumentation that can facilitate prompt evaluations of earthquake data.

[1] In the absence of digital seismic records, the NRC provides alternatives in Appendix A of Regulatory Guide 1.166.

Requirements and Options for Instrumentation Systems

To assess most effectively whether an earthquake has exceeded the OBE for a nuclear power plant, it is important for a modern, on-line, digital seismic instrumentation system to be in place. EPRI guidance is presented in the context of three fundamental options for a seismic instrumentation system:

- A minimum system
- A basic automatic system
- A "complete" system that complies with NRC Regulatory Guides 1.166 and 1.167

The basic characteristics of and differences among these systems are depicted in Figure 3. Each category of system is described further in the sections that follow.

The Minimum System

The minimum system would include one or two accelerographs, depending on how the OBE was defined for the plant. If the OBE had been defined in the free-field, one instrument in the free-field would be sufficient. On the other hand, if the OBE had been defined at a building location (for example, at the top of the basemat of the reactor containment), both an instrument at that location and one in the free-field would be required. In addition to being placed in the locations at which the OBE is defined, these instruments would need to meet minimum qualifications.

In general, the following are minimum characteristics for these instruments:

1. The accelerographs would need to have battery backup, with pre-event memory sufficient to record the entire earthquake motion and a storage device that could accommodate rapid data retrieval.

2. The instruments must be digital, with a sampling rate of at least 200 samples per second.

3. The instruments would need to cover a frequency bandwidth of 0.2–50 Hz.

4. A stand-alone desktop or laptop computer equipped with software to perform the necessary calculations on the collected data is required. The software would need to generate the CAV and the response spectra. The nature of the data retrieval and transfer to the computer would need to be such that the calculations could be completed within 4 hours after the earthquake.

The Basic Automatic System

Improved functionality can be achieved by automating certain steps that must be performed manually using the minimum seismic instrumentation system. The basic automatic system would add a dedicated online computer to automatically retrieve data from the accelerographs and perform the calculations related to possible exceedance of the OBE. Such a capability would expedite the process of assembling the information needed to make a decision with regard to whether a plant shutdown is required.

To upgrade from the minimum system to the basic automatic system, a dedicated cable would be needed from each instrument to the recording location (typically, the main control room) to

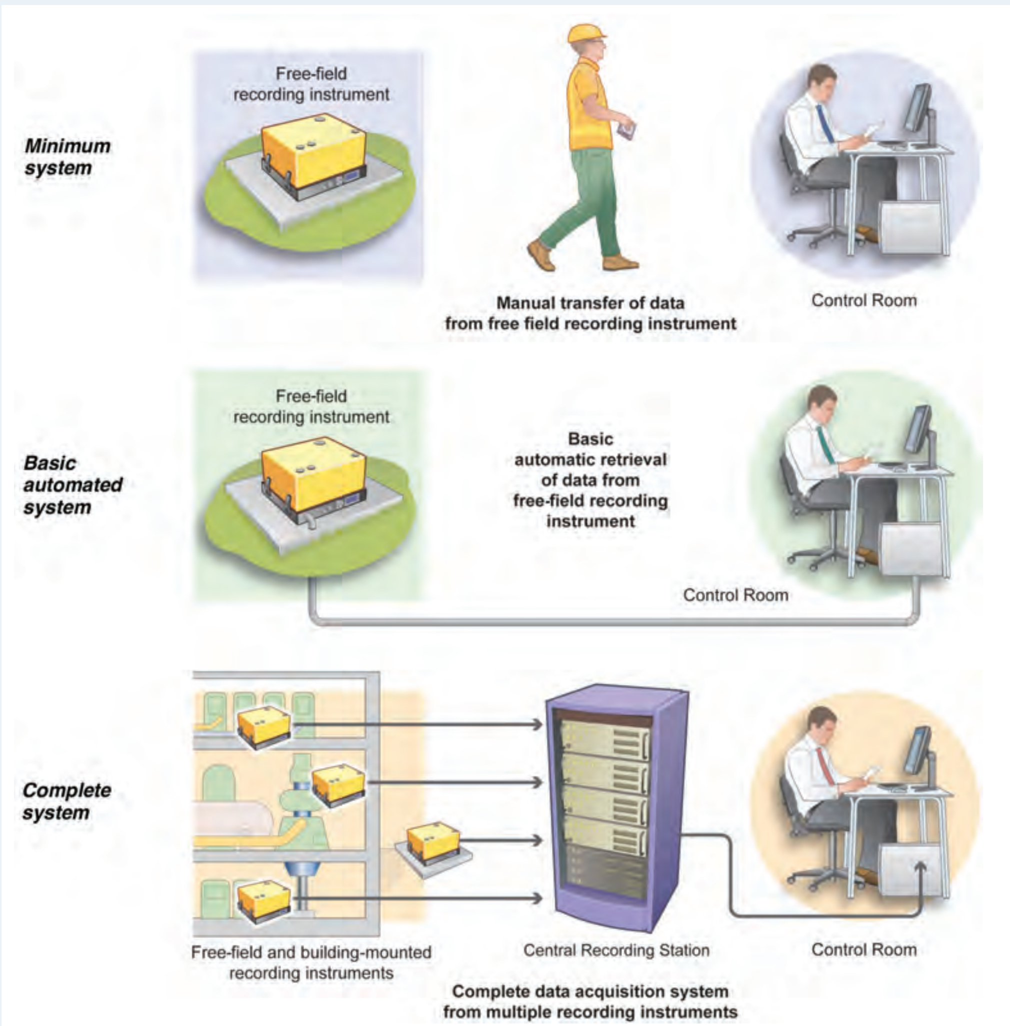

Figure 3. Functional representations of seismic instrumentation systems

capture the acceleration time history. The analysis results should be displayed to the control room operators in a form that is easy to understand. An uninterruptable power source for the computer that records and analyzes the data would also be needed to ensure that the results could be available within the 4-hour timeframe.

The Complete System

The complete system is the most advanced of the three. Such a system would incorporate an online computer for data acquisition and analysis along with more extensive instrumentation. The system could be configured so that it complies with Regulatory Guide 1.12 [7]. Although the minimum and basic automatic systems could facilitate short-term response, the complete system would facilitate the collection of more extensive response data from within plant structures, enabling more comprehensive long-term evaluations of the earthquake's damage potential [3].

A complete system would incorporate additional accelerograph locations, rather than accounting only for the free-field and the location at which the OBE is defined, Data collected from other response locations within the containment and auxiliary buildings would provide more definitive information regarding the impact of the earthquake. The system would be fully battery-backed.

As stated in EPRI NP-6695 [3], "such instrumentation is considered to be prudent and worthwhile for most nuclear power plants." This system is strongly recommended as the best option for ensuring timely and effective response to earthquakes and to more quickly and confidently determine whether plant shutdown is necessary.

Considerations in Locating Seismic Instruments

The NRC has taken the position in Regulatory Guide 1.166 [5] that only data from free-field instrument locations are appropriate for use in applying the OBE exceedance criteria from EPRI NP-5930 [1] and TR-100082 [2]. Accordingly, the following options are recommended:

- For all sites (rock and soil), seismic instrumentation should be placed in the free-field, with data evaluated using both the CAV and response spectrum criteria.
- As an alternative, seismic instrumentation may be placed at locations other than the free-field. In this case, data should be evaluated using only the criteria related to exceedance of the OBE response spectrum if it can be shown that the location at which data were collected is consistent with that used in the licensing basis.

For the alternative case, comparing only to the response-spectrum criterion is equivalent to assuming *a priori* that the CAV has been exceeded.

Remote sensors must be mounted in such a way that they measure the desired motion. For concrete structures, the sensors only need to be rigidly attached to the structure to ensure proper recording of the response. Raised pads may be appropriate in galleries where periodic flooding might be a possibility. Protection against accidental impact should also be provided.

At free-field locations, sensors or accelerographs should be installed in such a way that the recording of motion influenced by the enclosure or mounting pad is minimized. The degree to which soil-structure interactions may affect the recorded ground motions is influenced by factors that include the following:

- The size of the concrete pad
- The amount of embedment of the concrete pad
- The location of the instrument on the pad
- The size, weight, and stiffness of the shelter and its attachment to the pad
- The properties of the foundation medium

To reduce possible amplification effects, the installations should be as small as possible. Some minimum size is necessary to provide satisfactory housing of the system. A typical concrete pad for the instrument would be 1 m square and about 20 cm thick. The pad should be embedded or anchored in the ground (for example, by extending steel-reinforced concrete footings approximately 0.5 m into the soil) to increase the foundation stiffness. The accelerograph should be mounted at the center of the pad, close to the ground surface. Mounting instruments on pedestals should be avoided. The enclosure mounted over the instrument on the pad should be as light and stiff as possible to avoid further affecting the motion experienced at the instrument. EPRI TR-104239 [3] provides examples of appropriate pads and enclosures.

Costs of Seismic Instrumentation Systems

The costs to implement a seismic instrumentation system will vary from plant to plant depending on many factors: what options are desired for the instrument, where might the sensors need to be located (that is, in the free-field or at the containment basemat), and whether the instrumentation will augment or replace an existing instrument system. Table 1 outlines the costs of implementing the minimum and basic automatic systems (both with free-field accelerograph locations), and an upgrade to a complete system that complies with Regulatory Guide 1.12 [7] (using existing remote acceleration sensors on the containment foundation and structure). These costs were previously presented in EPRI TR-104239, but have been converted from 1994 dollars to a present value using a Consumer Price Index (CPI) conversion factor of 0.67.

Licensing Considerations

A seismic instrumentation installation or upgrade at a nuclear power plant is subject to certain licensing considerations. It should be noted first that voluntary implementation of the earthquake-response guidelines provided in the four EPRI reports, including installing new seismic instrumentation, does not generally require prior NRC approval. An exception would be the case in which a licensee wanted to remove antiquated seismic instrumentation from the plant's technical specifications. In its policy statement on technical specifications, however, the NRC specifically identified seismic instrumentation as an example of a system for which controls did not need to be retained in technical specifications [8]. In light of this policy statement, replacement of antiquated instrumentation with a modern digital system is a logical course of action when combined with a change to a plant's technical specifications.

Conclusions

An earthquake near a nuclear power plant can compel a determination as to whether the plant has sustained damage that could affect safe operation. EPRI has published a series of reports that identify criteria for assessing the earthquake's potential for causing damage. A vital element in making this assessment is access to information that characterizes the ground motion associated with the earthquake. This paper outlines the types of instrumentation systems that can be useful in providing this necessary information. This process has been endorsed by the NRC via regulatory guides.

Although the process remains sound, the four reports that document the approach developed by EPRI merit periodic review. EPRI intends to perform this review and initiate such an update during 2012.

Table 1. Composition and Approximate Cost for the Instrumentation Systems

Features and Requirements	System Configuration Minimum	 Basic Automatic	 Complete
Hardware and Software			
Three-component accelerograph (includes three orthogonal accelerometers and a digital event recorder)	**1**	**1**	**2**
Portable computer for data retrieval	**X**		
Desktop PC for high-speed analysis		**X**	
Dedicated computer for integrated analysis system (automated data retrieval and analysis, display, printout, and associated software)			**X**
Provision for backup to data-retrieval computer	**X**	**X**	**X**
Printer for output of analysis results	**X**	**X**	
Software for data retrieval, analysis, and display	Manual retrieval	Automatic retrieval	Incorporated above
Provision for remote access to data	Optional	Optional	**X**
Power panel upgrade			Optional
AC adaptor/alarms			Optional
Uninterruptible power source			Optional
System Implementation			
Installation and commissioning services (manufacturer)	**X**	**X**	**X**
Installation of cable(s) from remote location to dedicated computer		**X**	**X**
Control-room annunciation			
Engineering design changes		Optional	**X**
Cabling for control-room annunciators		Optional	**X**
Training, including provision of manuals (manufacturer)	**X**	**X**	**X**
Site selection, preparation, installation, and testing	**X**	**X**	**X**
Operator training	**X**	**X**	**X**
Shutdown and restart procedures			
Plant-specific procedures	**X**	**X**	**X**
Sensitive components for walkdowns	**X**	**X**	**X**
Seismic response system testing and operator training	**X**	**X**	**X**
Revision of plant technical specifications and final safety analysis report		Optional	Optional
Review and approval		Optional	Optional
Estimated Cost	$120–$180K	$150–$270K	$225–$300K

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8. *Final Policy Statement on Technical Specifications for Nuclear Power Reactors*. U.S. Nuclear Regulatory Commission, Federal Register Notice 58FR39132, July 22, 1993.

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Nuclear Power

1024889 January 2012

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