SEISMIC EARLY WARNING SYSTEM FOR A NUCLEAR POWER PLANT

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SUMMARY

Reviews of several Soviet-built nuclear power plants have shown that most of them have an unknown earthquake safety or are under-designed seismically. In the cases where seismic strengthening of the buildings and equipment is not feasible due to economical, political and timing reasons, an active reactor protection system based on an earthquake early warning system may be the answer, similar to the one installed recently in the Ignalina Nuclear Power Plant (INPP) in Lithuania.

This early warning system consists of six seismic stations encircling INPP at a radial distance of approximately 30 km and a seventh station at INPP. Each station includes three seismic substations each 500 m apart. The ground motion at each station is measured continuously by three accelerometers and a seismometer. The data is transmitted via telemetry to the control centre at INPP. Early warning alarms are generated if an acceleration threshold is exceeded.

The alarm is used to stop the nuclear reaction by insertion of the control rods. In the RBMK reactors at Ignalina, only 2.5 seconds are required for the insertion of the control rods. The pre-warning time provided by the seismic alarm system for earthquakes occurring at distances greater than 30 km from the site is approximately 4 seconds. Therefore, the nuclear reaction can be stopped before the earthquake arrives.

This paper discusses the recently installed early warning system at INPP and the possible application of this system to other types of Soviet-designed nuclear reactors.

INTRODUCTION

It is internationally accepted that the Soviet-designed nuclear power plants require seismic upgrading to various degrees (Fraas et al., 1997). Seismic upgrading by strengthening of the buildings and components is an expensive and time-consuming procedure. Therefore, alternative approaches have to be taken into consideration.

The International Atomic Energy Agency (IAEA) has been carrying out assessments of seismic upgrading of the Soviet-designed nuclear reactors over the past few years (Gürpinar et al., 1997). The Group of Seven Industrialized Nations (G-7) agreed in March 1992 on an action plan to upgrade the safety of Soviet-designed reactors. From the fund, called the Nuclear Safety Account, administered through the European Bank for Reconstruction and Development (EBRD), a grant of USD 38 million was allocated in 1994 for projects to upgrade the safety of the Ignalina Nuclear Power Plant (INPP), which consists of two 1500 MW RBMK reactors.

The Soviet nuclear power plants were designed for two types of earthquakes. These are the design earthquake and the maximum possible earthquake having peak ground accelerations ranging from 1.2% to 10% of the acceleration due to gravity. With regard to INPP, the reactor building was designed for peak ground accelerations of 0.026 to 0.051g, which reflect the moderate seismicity of the Baltic states. Some of the buildings and equipment of the first and second units of the INPP do not comply with modern seismic safety

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standards and need to be strengthened. However, as shutting down the reactors was not considered to be economically and politically feasible, solutions have been studied to reduce the seismic risk in the short-term. In order to reduce the risk of release of radioactive matter during an earthquake, it was decided to install an earthquake early warning system and to shut down the reactor immediately should a hazardous earthquake occur in the vicinity of INPP. Accordingly, six seismic stations were planned in a ring centred on the plant at a distance of approximately 30 km. The stations are uniformly distributed as shown in Fig. 1. Each consists of three independent substations which are approx. 500 m apart. The ground motion is recorded continuously and transmitted to the control centre via telemetry as discussed in the subsequent sections.

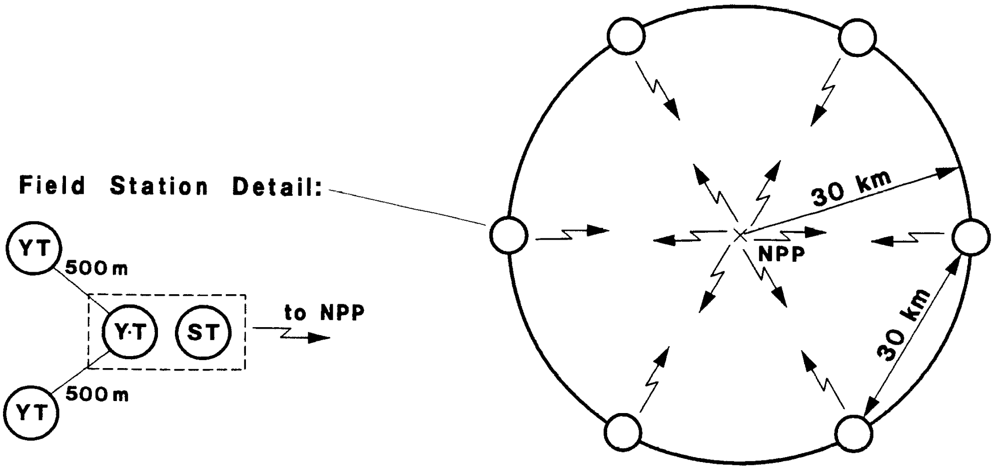

Fig. 1 Layout of earthquake early warning system of Ignalina Nuclear Power Plant (INPP) (YT: accelerometer, ST: seismometer)

CONCEPT OF SEISMIC ALARM SYSTEMS

Research in earthquake prediction has shown that we are still quite far away from the accurate prediction of the time, location and magnitude of strong earthquakes. However, present technology in seismic instrumentation and telecommunications permits the implementation of systems for early warning of earthquakes based on the real-time measurement of ground motions. Such systems are capable of providing a warning of several seconds to tens of seconds before the arrival of the strong ground tremors caused by a large earthquake.

An earthquake early warning system has the potential for the optimum benefit as it can provide the critical alarms and information needed (i) to minimize loss of lives and property, (ii) to direct rescue operations, and (iii) to prepare for recovery from earthquake damage (Lee et al., 1996).

The basic features of a seismic alarm network are shown in Fig. 2 (Heaton, 1985). Ground motions recorded by an array of seismometers are telemetered to a central processing site. The main parameters of an earthquake, i.e. the location, time of origin, magnitude, amplitude of ground tremors and reliability estimates are computed. Based on the location and the geological conditions the nature of the ground motions expected at the site is determined. On the basis of this information the appropriate action is taken.

The problem of false alarms is minimized by continuous updates regarding the size of the ground motions at different stations in the seismometer array or by redundancy from several measurements at the same geographic location.

After the occurrence of an earthquake, the seismometer array provides information regarding the intensity of ground shaking at different geographic locations. This information can be used to estimate regions of substantial damage, so that emergency services can be allocated promptly and properly. Because the seismometers in a modern array would have a large dynamic range, the seismic network may routinely record ground motions from numerous small earthquakes and teleseismic events. Such data are important for basic research. Also, the routine use of a seismic network for studies of small events would help to ensure that the system operates properly when relatively rare large events occur.

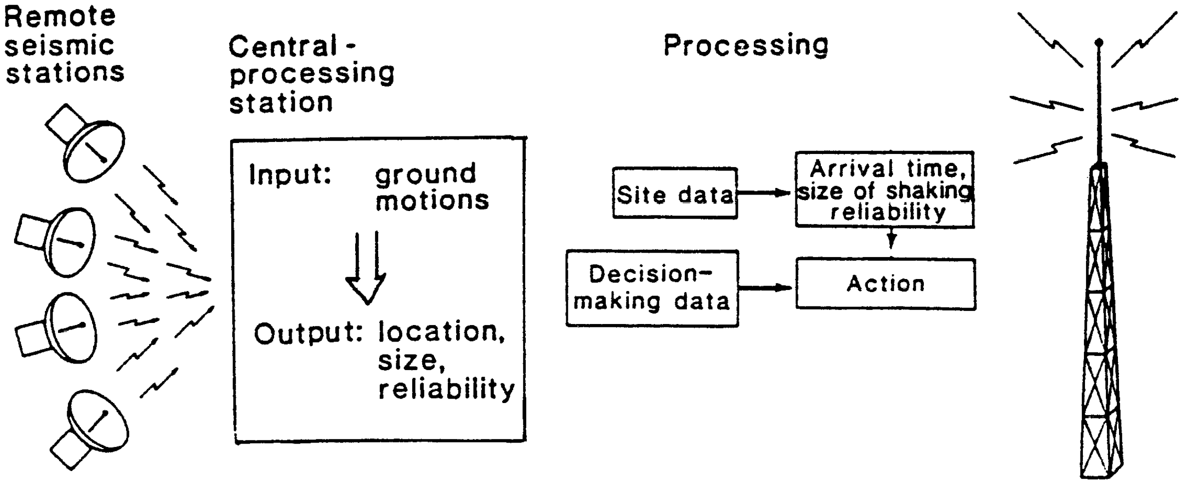

Fig. 2 Conceptual design of an earthquake early warning system

Although relatively large peak accelerations occur at small distances from small earthquakes, they rarely cause damage because the duration of intense shaking is short. The value of the response spectral velocity of 1 second is usually considered to give a better estimate of damage potential than the peak ground acceleration (Heaton, 1985).

For earthquakes with epicentres within a radius of 30 km of INPP the alarm time is very short However, as a seismic station has been installed within the compound of INPP a seismic alarm can still be released if the intensity of ground shaking at the power plant exceeds a given threshold. At Ignalina, this aspect may be of lesser significance due to the geology and historically low seismic activity at the site. With regard to other nuclear power plants, the seismic properties of the site should be carefully investigated. An extended seismic array could provide seismic protection for seismically active sites.

EXPERIENCE WITH EARLY WARNING AND SEISMIC ALARM SYSTEMS

Besides the early warning system at INPP, which was completed in 1999, there are two other systems in operation for civilian purposes, i.e.

(i) Urgent earthquake detection and alarm systems (UrEDAS) in Japan

This real-time earthquake disaster prevention system was developed for railways. The special feature is the rapid alarm using information from P-wave data. Systems for different railways have been in operation since 1983 (Nakamura, 1996). UrEDAS detects initial P-wave motions, estimates location of epicentre and magnitude of earthquake, calculates epicentral distance and focal depth. This system is not only useful for railways but also for nuclear power plants, etc.

(ii) Seismic alert system (SAS) for Mexico City

Most of the large earthquakes which are likely to cause damage in Mexico City have their source in the subduction zone of the Pacific coast at a distance of about 320 km. The seismic detector system consists of 12 digital strong motion field stations located along a 300 km stretch of the Guerrero coast, arranged 25 kilometres apart. The warning time in Mexico City varies between 58 and 74 seconds. By means of a radio warning system up to 4.4 million people can be reached during rush hours.

Other early warning systems have been reported by Shin et al. (1996), however, these are still in an experimental phase.

CHARACTERISTICS OF IGNALINA NUCLEAR POWER PLANT

The Ignalina NPP contains two RBMK-1500 reactors. This reactor type is the most advanced and powerful version of the RBMK reactor design series. The first unit went into service at the end of 1983 and the second unit in August 1987. Their design life is about 30 years. A total of 17 such reactors have been built in the former Soviet Union. In August 1991 INPP came under the authority of the Lithuanian Republic.

INPP belongs to the category of channel-type boiling-water reactors. The entire building of the two units covers an area of 600 m by 51 m and the reactor building is 61 m high.

The Baltic region is usually regarded as a region of relatively low seismicity. In comparison to Latvia, Estonia and Belarus, Lithuania has the lowest seismic activity. However, the available data indicates, that there is a possibility of strong earthquakes at a distance of some 50 km from INPP. The maximum possible earthquake in the surroundings of INPP is estimated to have a magnitude of 4.5 and a focal depth of 5 to 8 km.

For Soviet-designed nuclear power plants two levels of earthquakes were taken into account, i.e. the design earthquake and the maximum possible earthquake. The first is the maximum earthquake which may happen during the service life of a plant . The second is the maximum possible earthquake in the area. For the different structures and components of INPP, the design and maximum possible earthquakes have peak ground accelerations, respectively, of 0.012 to 0.05g and 0.025 to 0.1g. At the time of the design, this was considered adequate for a site with relatively low seismicity.

Depending on their function during and after an earthquake, all buildings and equipment were subdivided into different seismic categories. For each category, different seismic design criteria were applicable. The earthquake analyses were performed using the response spectrum method.

A review of the structural integrity of the plant was carried out in 1995. Measures aimed at strengthening the building structures and equipment were considered and judged to be uneconomical. Consequently, it was decided to install an earthquake warning system as a first step to increase the plant safety in the event of a strong earthquake.

CHARACTERISTICS OF THE IGNALINA SEISMIC ALARM AND MONITORING SYSTEM

Description of the System

Usually, a time period of 2 seconds is required for the insertion of the control rods in an RBMK nuclear reactor. After that, the nuclear thermal capacity is strongly reduced and the reactor core is prevented from meltdown in the case of a severe accident. A core meltdown would entail the risk of radioactivity release to the environment.

The existing earthquake early warning systems discussed earlier require by far more than 2 seconds to indicate a seismic event. Therefore, a system had to be designed specifically suitable to nuclear power plants. In the INPP Seismic Alarm System (SAS), six seismic stations equipped with accelerometers are installed at a distance of 30 km from the power plant. The signals are transmitted to INPP by radio waves, which require virtually no time. Assuming a seismic shear wave velocity of 3.5 km/s, the pre-warning time would be about 8.5 s for earthquakes occurring outside the seismic belt. In practical terms, this is reduced to ca. 4 s by the required transfer and processing times. It is concluded that the Ignalina SAS enables the insertion of the control rods before the arrival of the damaging seismic waves, i.e. the shear waves, at the reactor.

At each seismic station (Fig.3), three accelerometers are located at substations 500 m apart (Fig.4). The SAS accelerometers input to seismic switches with an acceleration threshold of 0.025 g. When this value is exceeded, the seismic switch produces an alarm signal. These signals are digitally encoded and sent via a separate transmission channel to the control centre of INPP.

Here a 2-out-of-3 voting logic is used to determine if a real seismic event has occurred and to generate a seismic alarm in the main reactor control rooms.

The alarm system is complemented by a seismic monitoring system (SMS) for seismic data recording and processing. One seismometer is located at each seismic station. In addition, the SMS includes sensors inside of the reactor building and on two key items of equipment, namely, the cooling water pump and the steam separator drum of each unit. The data is processed by two redundant central computers located at each unit.

Fig. 3 Photograph of a typical seismic station (left: completed station with aerials for telemetry; right: foundation plate with openings for instrument locations)

Fig. 4 Photograph of seismic substation (left: substation with 500 m long cable trench to seismic station; right: instrumentation of seismic substation)

INPP is the first nuclear power plant with an earthquake early warning system using both accelerometers with seismic switches and seismometers. Four out of the six stations of the seismic belt are already in operation. It is unclear when the remaining two stations, located in neighbouring countries, will get installed.

Technical Outline of the Seismic Alarm System

The SAS is outlined in the block diagram of Fig. 5. The SAS system is seismically qualified. It is based on three separate measurements, transmission and reception channels and a 2-out-of-3 voting logic. This gives a high degree of reliability, operability and protection against false alarms. An external power supply is required for each seismic station. Triaxial accelerometers are used as sensors in each substation. To reduce the effect of signal noise the analog signals from each sensor are digitized at its substation. The seismic switches and radio frequency data transmission telemetry equipment of the three substations are located in the cabin of the seismic station. The signals of the seismic switches are transmitted to the power plant by radio communication in the Ultra High Frequency (UHF) band. UHF communication requires line of sight conditions, which poses comparatively little difficulty in the flat area of Lithuania.

The trigger threshold of each seismic switch is software adjustable. The initial setting of 0.025g will be assessed after a trial period and optimized. The records of the Seismic Monitoring System will be used for this assessment.

Receiving antennas are mounted on the reactor building roof. The telemetry equipment is located nearby. For each seismic station, this equipment and the associated cables are separated into three measurement channels up to the 2-out-of-3 voting logic located adjacent to the reactor control room. This logic initiates the alarm signals to the main control room for each reactor.

The seismic alarm system for INPP has been designed to provide an economical and adequately comprehensive solution to concerns regarding the seismic integrity, with respect to Western standards, of some of the INPP buildings and equipment. The use of accelerometers and seismic switches by the seismic alarm system maximizes the available warning time.

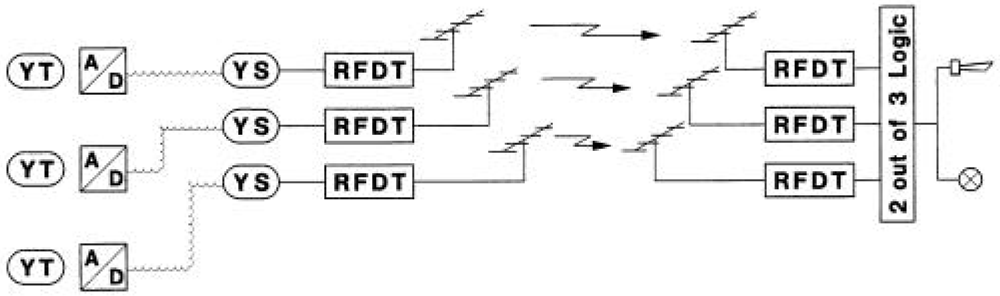

Fig. 5 Seismic Alarm System (SAS): block diagram of one of six stations (YT: accelerometer, A/D: analog-digital converter, YS: seismic switch, RFDT: radio frequency data transmission)

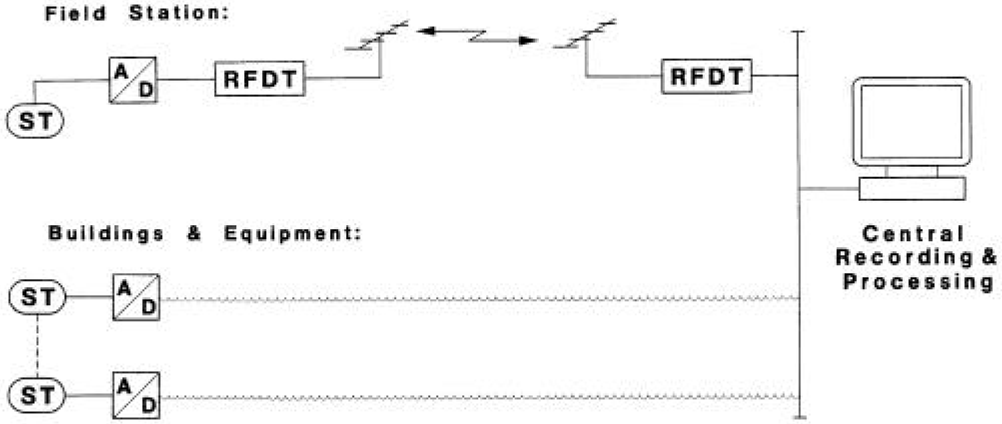

Fig. 6 Seismic Monitoring System (SMS): block diagram of one of six field stations and typical instrumentation of buildings and equipment (ST: seismometer, A/D: analog-digital converter, RFDT: radio frequency data transmission)

Technical Outline of the Seismic Monitoring System

The SMS is outlined in the block diagram of Fig. 6. The system includes six seismometers, one at the cabin of each seismic station, plus one seismometer and two accelerometers at INPP. Each seismometer is located in a bore hole. The locations of the seismic stations have been chosen so as to be remote from environmental noise.

Four triaxial accelerometers are located in each of the two reactor buildings, i.e. three on the base of the building and one at the 20 m level. Biaxial accelerometers are located on the cooling water pump and on the steam separator drum of each unit.

The values measured by the field SMS seismometers are combined into data packets, which are transmitted to the power plant by radio communication. Separate radio frequencies are used to permit continuous transmission of data. At the power plant, the data is digitized and input to the central processor unit using RS-485 links. Sampling rates up to one or two hundred samples per second is possible. The data is stored and processed in two central computers.

Central Data Recording and Processing

In the central computers, a QNX multi-tasking, multi-user operating system is installed. The management of data acquisition is performed by the SEISLOG application software (Utheim and Havskov, 1997) and the analysis is accomplished using the SEISAN earthquake analysis software (Havskov and Utheim, 1997). SEISLOG and SEISAN were developed by the Institute of Solid Earth Physics, University of Bergen, Norway. The SEISLOG data acquisition system is used as the major data collection system in the national seismic networks of Norway, United Kingdom, Ireland and in several countries of Central America. In addition, SEISLOG is used at about 40 stations in eight other countries in Europe, Africa and Asia.

The digitized data packets, sent from the Seismic Monitoring System, are displayed on the central computer terminal by SEISLOG. When each page of data is accumulated, it is printed out in the analog mode. This approach of printout is recommended because it provides the most economical and reliable method of obtaining hard copies of the signals. Alternative plotting methods are possible. SEISLOG has flexible user-defined trigger criteria which can be tailored to both local and distant earthquakes. The system can be set up with up to five different sets of trigger criteria in order to be independently triggered by local and distant earthquakes.

The data sets are transferred by means of a floppy disk, a tape or Ethernet from SEISLOG for processing and analysis using software SEISAN. SEISAN has been in operation since 1988. It is used as the main processing tool in the SEISLOG installations mentioned above. SEISAN has the advantage of being a complete system with a database and integrated processing tools.

SEISAN can calculate all normally used magnitudes. It locates earthquakes with the latest global model (IASP91) or with user-defined models. The location of an earthquake can be determined based on the arrival times of seismic waves at several stations.

Commissioning

From March to June 1999, the commissioning took place. As first the communication system was put in operation. The INPP has an internal trunking system, allowing in-house voice communication. For the INPP SAS/SMS, the system was extended to be usable for the outside stations too. After having the voice communication up and running, the rest of the instrumentation was put in operation. In parallel to the commissioning, a detailed training has taken place to allow the local personnel to execute the service and maintenance works.

The INPP operating procedures must be adapted so that the operator reacts correctly in the case of a seismic alarm. The operators must be given the proper training and clear instructions to deal with such an eventuality.

The computers for data processing were also put in operation including the various software packages, i.e. SEISLOG, SEISAN and Geoview. In this way, the SMS is now able to evaluate seismic events in accordance with international standards. This allows the seismic data exchange with other countries. It should be noted that Lithuania was not able to participate in such international data exchange in the past.

The commissioning was successfully carried out without any major problems. Since the radio frequencies were selected carefully, interference problems were not encountered.

Although the INPP SMS/SAS has been fully accepted by the client, the following points remain open:

1) The two outside stations in the countries Belarus and Latvia have to be installed. INPP is still in negotiation with the country representatives in order to get the approval for installation.
2) The acquired seismic data is of great interest for the Lithuanian Seismological Survey. Besides the technical issue of how to transfer the data from the INPP to the Lithuanian Seismological Survey, the formal question of ownership of the data and the access rights must be resolved.

POSSIBLE APPLICATION TO VVER TYPE REACTORS

The VVER nuclear reactor is a pressurized water reactor (PWR). Due to the low power density in the fuel, coupled with the large inventory of primary water, more time is available than in Western-style PWR’s for operator actions before fuel failure would occur in case of an accident. In order to assure the power production, the resistance against the design earthquake is considered to be achieved by strengthening of the buildings and components. However, depending on the specific conditions at the site, upgrading for the maximum possible earthquake is economically not feasible. For this, the Seismic Alarm and Monitoring System outlined in the present paper might be a suitable alternative.

The emergency shutdown of the VVER nuclear reactors is characterized by an increased insertion time of the control rods compared to the RBMK reactors. The pre-warning time provided by the Seismic Alarm System will, in most cases, not be sufficient for the control rods to reach their lower position in the reactor core. It is to be noted that the control rod insertion consists of several steps:

Step 1: Issuing of the control rod insertion signal,
Step 2: Release of the control rods from their positioning mechanism, and
Step 3: Dropping of the control rods into the reactor core by gravity.

This process requires 4 seconds at the VVER compared to only 2.5 seconds at the RBMK.

The pre-warning time provided by the Seismic Alarm System will be sufficient to issue the control rod insertion signal and to release them from the positioning mechanism. The control rods may not have reached the lower position in the reactor core before the earthquake arrives at the site, but the dropping down of the rods is at least in progress and this action could only be impaired by the distortion of the control rod channels in the reactor core. This would require that a severe damage of the reactor core has already occurred in the very first seconds of an earthquake. This is highly unlikely to happen.

Moreover, the tubine-generator fast shutdown will be initiated by the seismic alarm protecting this equipment from severe damage in case of an earthquake. It is concluded that the Seismic Alarm System outlined in the present paper will also be beneficial to the VVER type nuclear reactors.

CONCLUSIONS

A seismic "fence" having a radius of 30 km is being installed around the Ignalina Nuclear Power Plant to provide an alarm before potentially damaging earthquake tremors reach the reactors. The alarm threshold is preset at 0.025 g, which will be adjusted according to the experience gained.

Seismic safety upgrading of a nuclear power plant by means of a seismic fence is an economical solution for existing plants with inadequate or unknown seismic resistance of vital components in the case of strong earthquakes. It is also a recommended solution for existing power plants where earthquakes have occurred exceeding the level anticipated at the time of the design and construction of the power plant.

This system not only reduces the consequences of a reactor accident caused by an earthquake but also helps to ensure plant integrity following an earthquake.

Because of the many benefits and the relatively low cost, earthquake early warning systems have excellent prospects for short-term increase of safety levels at nuclear power plants with inadequate seismic safety. However, it has to be pointed out that an early warning system is not a substitution for the long-term upgrading of under-designed critical components of a nuclear power plant.

For the reliable operation of the earthquake early warning system, a reliable discrimination technique is a prerequisite to clearly distinguish seismic activity from environmental noise and man-made signals.

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