The seismic safety of Paks Nuclear Power Plant

Nuclear power plants are required to be safe and duly protected against the potential impacts of natural disasters and catastrophes caused by human activity. This is underlined by the warning events: the earthquake that hit Onagawa nuclear power plant in 2005, the case of Shika and Kashiwazaki-Kariwa power plants in 2007, the event that occurred at Hamaoka nuclear power plant in 2009 and the flooding of Blayais power plant in 1999 and 2005. The recent earthquake that occurred on 11 March 2011 near the east coast of Honshu Island and the subsequent tsunami, which led to a nuclear catastrophe in the Fukushima Daiichi nuclear power plant, warns us of this requirement again.

Fundamental safety requirements

Nuclear reactors are considered safe if the reactor can be shut down and cooled down under any circumstances, the cooling can be continuously maintained, and no radioactive medium is released into the environment.

The first requirement is clear: the power generation by chain reactions has to be terminated and a criticality accident, i.e. the uncontrolled excursion of the reactor, can also be excluded this way. This can be achieved by addition of neutron absorbing materials into the reactor in the form of absorbent rods, or absorbing material, in the practice boron, dissolved in the coolant.

The cooling of a shut down reactor is required because, as a consequence of the fission, fission fragments, i.e. unstable nuclei, are produced from the nuclei of the fuel material (such as ^{235}U), which, as result of the decay and due to the nature of the unstable nuclei, transform into stable nuclei during a certain period of time. This process results in generation of heat, which is called decay heat generation. This heat has to be removed from the system for several reasons:

- To prevent the fuel from overheating, to maintain its structural integrity, which is a precondition of both the coolability and the control of reactivity but, at the same time, it is equally important for the confinement of radioactive materials, since in intact fuel rods a large part of the activity, except for the gaseous and halogen materials, remains confined in the fuel material (which looks like a ceramic material).
- On the other hand, low pressure can be maintained in the cold system, which is important since, even with the smallest leak being present in the primary system including the core of the reactor, the driving force of the leakage through the leak will depend on the difference between the outside and inside pressures. It is readily understood that this differential pressure should be kept as low as possible.
- The third reason is that the material of the tubes containing the fuel pellets is zirconium, which, if overheated to a temperature higher than 1200 ^{o}C, tends to oxidise by reacting with the water steam, which results in the generation of hydrogen. The presence of hydrogen as an explosive gas in the system involves a new hazard.

Therefore, hydrogen recombiners have now been installed in nuclear power plants, including Paks Nuclear Power Plant, to prevent the occurrence of such a situation, i.e. the formation of explosive hydrogen concentration.

Two things are inevitably required for the cooling of the reactor and for the operation of the cooling systems: a cooling medium, i.e. water for light-water cooled reactors, and electric power for the operation of the cooling system and the instruments used to supply essential information on the status of the power plant.

Thanks to the unstable nuclei with short half-lives, the decay heat generation, which is approximately 7 % of the operational power directly after shut down, decreases rapidly to some one per cent after a few hours and amounts to some fractions of one per cent of the operational power in a few days. The heat generation of the spent fuels removed from the reactor reduces to a level during a five-year period in general, which allows them to be loaded into interim store. During this five-year period, the spent fuel assemblies are stored and continuously cooled in pools beside the reactor.

The confinement of radioactive materials is guaranteed by several physical barriers: the fuel itself, the fuel clad, the reactor and the primary system structures, collectively as a pressure retaining system, and finally the containment structure.

How can a nuclear power plant be made safe?

The outlined above essential safety functions can be ensured and achieved at any time with high level of confidence via:

1. Adequate specification of the design bases: identification and characterisation of the design basis hazards and other events, as well as conditions affecting the plant safety.
2. Consideration of the effects of such hazards in the design, including the design of accident management and consequence mitigation features.
3. The use of products qualified for the potential impacts of the hazards.
4. Development and introduction of failure prevention, accident management and consequence mitigation procedures.
5. Assessment of the safety.
6. Periodic review of the safety, i.e. items 1 to 5 above, and taking the required safety enhancement measures.

Design bases

In order that a nuclear power plant is safely protected against the effects of external events, the hazards, which are typical to the site and are relevant for safety, will need to be identified and characterised in a way to ensure that these hazards be considered by the designer as a load, an effect or a condition that may affect the operation of the power plant. In addition, criteria will need to be established to verify the adequacy of the design with regard to the considered impacts, loads and conditions.

The hazards, to be considered as basis for the design, can be defined with the use of probabilistic or deterministic methods or, irrespective of any other conditions, by postulation.

The essence of the probability-based definition is that an event is considered a design basis event, a more severe one of which may occur only with a very low probability during the service life of the nuclear power plant. For instance, if the entire service life is fifty years, the natural phenomenon, e.g. an earthquake is considered as design basis earthquake, a more severe one of which may occur with a probability of 0.005 during the 50 years period. Expressed in annual frequency, this is the event, the occurrence frequency of which is 10^{-4}/year, i.e. has a recurrence interval of 10,000 years. The identification of the design basis in such a way requires that the hazards to be included in the design bases will also need to be identified with the use of the probabilistic method, which takes account of both the inherent randomness of the natural processes and the uncertainty of our relevant knowledge, i.e. the aleatory and epistemic uncertainties.

The hazard to be included in the design bases can also be identified by the deterministic method. This method is based on the fact that events which occurred in the past clearly have a determining effect on what might occur during the service life of the nuclear power plant. Generally, it makes no sense to address the recurrence period or annual frequency even if, during the analysis of past events, the uncertainties are identified using statistical methods and, with regard to that, the characteristics of the design basis event are identified with some margin. It is rather obvious that this method can barely be used for making a statement about the potential of the occurrence of infrequent events, e.g. a severe earthquake in an area with moderate seismicity, or for considering singular phenomena in an appropriate manner. The New Madrid seismic zone in the USA can be mentioned as an example, where, in the absence of written historical records, there was no information until 1811 about the existence of a structure capable of producing a devastating earthquake.

Design for safety

The implementation of the essential safety functions is possible with the use of three construction principles as follows:

- By multiplication of the system installed for implementation of a given function, i.e. with the use of double, triple, or even quadruple redundancy. For example, three diesel generators, each with a capacity sufficient for the supply of the total electric power demand in emergency conditions, are used for each unit at Paks Nuclear Power Plant to provide for emergency electric power supply. In addition, they are each complemented with a safety battery plant, too.

- By construction of the systems of identical functions from components of different manufacturing, different design and different operational principle, i.e. by providing diversity of the systems to minimise the potential of simultaneous loss of the redundant systems, because identical components tend to fail in the same way and same time.

– The spatial separation of the redundant systems is used to ensure that a fire or another effect causing a failure could not affect the availability of more systems at a time.

Features of the design for external hazards

Extremely rare natural phenomena, external effects and circumstances, also the hazards of human origin, and even the potential of coincident occurrence of various correlated or independent hazards are considered in the design basis of a nuclear power plant. For example, it is quite an obvious assumption that an extreme snow load and windstorm can occur simultaneously. In the case of an earthquake, in addition to the vibrating effects, fires or flooding of areas, as consequential hazards caused by the earthquake, may prevent the fulfilment of the safety functions.

The earthquakes and most of the hazards of natural or human origin are specific in respect to the fact that the use of redundancy, which is one of the safety design principles, will not essentially improve the situation, since all redundant safety trains composed of identical components will be equally damaged, as an earthquake hits the entire plant site. The diverse construction of redundant systems of identical function is considered rather effective, since there is a chance that the components of diverse make or, by chance, of different operation principle will not all fail at the same time.

Spatial separation has a very significant role in guaranteeing safety vis-à-vis external hazards. Spatially separated safety systems, being installed in different locations of the plant site, may be equally affected by an earthquake, but the conditions will not be identical during and after the earthquake, especially with regard to the exposure to possible fire, flooding or falling of a nearby object onto the safety related systems, structures and components. Thus, there is a chance that some of the safety trains remain operable during and after an earthquake and their operation will not be jeopardized even by other damage, fires and floods. Spatial separation is particularly important in the case of an air crash, external hazard of human origin or explosion occurring as a consequence of a road accident. Such events have a more concentrated effect than an earthquake, but in a certain way they may affect the entire plant site; though an aircraft falling down onto a building will cause maximum damage in the targeted building, fires or other damage, caused for example by missiles, may also occur at several other points of the plant site.

Since external events have the potential to simultaneously affect all the emergency cooling systems of a reactor, and the integrity and operability thereof, as well as the electric power supply required for the operation of the cooling systems, design solutions not requiring the use of any external power supply, such as gravitational cooling water supply, cooling with natural circulation or heat removal from the containment by natural draught, have steadily gained ground.

There is a design principle, which, if obligatorily applied, may balance the uncertainty of the identification and characterisation of the external hazards and their effects on the plant safety. With the use of design solutions and appropriate engineering margins, it should be ensured that a sudden loss of function cannot come about if slightly higher and more severe loads occur than those considered in the design. This is the principle for avoiding cliff-edge effects. It is not stipulated how large such an engineering margin should be. In one approach, a nuclear power plant shall be capable of withstanding far higher acceleration values, e.g. as much as 40 % “overshoot”, than the design basis earthquake. According to another approach, it has to be ensured by sufficient conservatism that the unacceptable performance of safety functions will be less than about a 10 % probability for a ground motion equal to 150 % of the site-specific ground motion. Increasing this margin above and beyond a certain level is not practical and, on the other hand, will not even result in absolute safety, which is not achievable theoretically either.

For the case when an event with fatal consequences occurs and the safety systems are not capable of fulfilling their essential function, accident management and consequence mitigation tools and procedures should be developed and implemented, and the personnel trained and exercised for the use of such procedures, just like the use of the other accident prevention tools and procedures. The essence of accident management and consequence mitigation is nothing else but controlling the essential functions, the reactivity, the cooling and the confinement of radioactive materials with the use of any tools that can be deployed for this purpose. Deployable tools can be items of equipment prepared beforehand, such as a mobile background diesel generator on the site, hydrogen recombining units installed for use in accident conditions for the prevention of spontaneous explosion of hydrogen and for the protection of the containment, outside cooling of the reactor vessel in accident conditions to ensure the retention of core corium, long-term control of the containment pressure by containment cooling and filtered blow down, etc.

The operational personnel may be extremely challenged by external events, whether of natural or human origin, since, as a consequence of such events, a variety of failures may occur simultaneously, which may result in an emergency situation in the entire power plant, even for all units in a different way in each unit of a power plant.

What happened at Fukuhsima Daiichi nuclear power plant?

On 11 March 2011, a severe earthquake with a magnitude of 9 occurred at a distance of 150 km from the east coast of Japan. This earthquake far exceeded the earthquakes detected in the 20th century along the Japan Trench, which were all around or below the magnitude 8. A devastating earthquake similar to the recent one occurred in 869, and was followed by a tsunami wave, which destroyed the city of Sendai. The earthquake that occurred on 11 March 2011 was one of the Earth’s largest ones of the past hundred years.

Five nuclear sites with a total number of 15 units are situated in the area affected by the earthquake, with three of them, Onagawa, Fukushima Daiichi and Fukushima Daini, altogether with 13 units, on the part of the coast which was most affected by the tsunami. Following the earthquake, all operating reactors were automatically shut down, which was followed by the start of cooling down operations. Considering the case of the Onagawa and Fukushima Daini power plants, it seems to be confirmed that no damage impairing safety occurred upon the effect of the earthquake. The situation was presumably similar in the Fukushima Daiichi power plant where six units were installed with three of them in operation, the other three being under maintenance. The Fukushima Daiichi plant also lost connection to external power supply, since the grid was heavily damaged. The tsunami reached the site of Fukushima Daiichi power plant approximately 34 minutes after the earthquake and destroyed the diesel generators which were used to supply electric power. From this point, batteries of limited capacity were available only for a limited time for controlling the reactors. The reinstatement of the electric power supply would have been required or mobile diesel generators should have been transported to the site from the hinterland, where critical circumstances existed due to the earthquake and the subsequent tsunami. A state of emergency was announced in the nuclear power plant after the loss of cooling and the evacuation of the population living near the power plant was commenced. The following series of events began at all units: the temperature and the pressure increased in the reactor due to loss of cooling. To prevent damage to the reactor, the reactors were blown down into the space of the steel containment. Note that, as results from the design principle of “design for safety” there was a double containment in the units, which is composed of an inside steel containment and an outside reinforced concrete building. However, some time later, hazardous overpressure developed within the inside containments, which were subsequently blown down to avoid any containment damage. The escaping hydrogen generated by oxidation of the overheated fuel clad exploded and destroyed the hall above the reactor. This sequence of events occurred for all the three units, with a difference in the location of the hydrogen blast and in the condition of the containment. In this situation, the emergency cooling of the reactors was possible with the use of special tools, e.g. by injection of seawater after addition of boron to provide for the control of reactivity. The blow down operations and the leaks caused by the damage resulted in release of gaseous radioactive materials, iodine and caesium into the environment.

The loss of cooling and the overheating of the fuel assemblies in the decay pools were the other problems which had to be dealt with. The overheating resulted in some discharges from these fuels, too.

The situation was aggravated by fires caused by the bursting into flames of cables and other combustible materials within the units.

The three damaged reactors are no longer available as production capacity; they are unrecoverable and will be isolated from the environment. The radioactivity released into the environment is moderate compared to the dimensions of the disaster and to the extent of discharges that occurred during the Chernobyl catastrophe. Thanks to the evacuation, the population is safe. Although radiation arising from the Japan nuclear release can be detected in the near environment and even at large distances, this detectable level does not involve any hazard to human health yet, not even in our country.

However, the situation is still serious. Reinstatement of the safety systems and thus, cooling of the reactor and the decay pools, and isolation of the discharged radioactive materials and isolation of the entire power plant, plus decontamination of the area to the maximum extent is a very complicated and represents work outstanding. New complications are still expected every day during the recovery work, but it is certain that the process is progressing well towards resuming total control over the reactors and the decay pools.

As can be seen from the above, the loss of one of the safety functions, i.e. the loss of cooling of the reactor and the spent nuclear fuel assemblies leads to serious consequences as result of the simultaneous loss of the emergency power supply, and also involves the failure of the other safety function, which is the confinement of the radioactive media. Actually, the world's biggest earthquake was not sufficient for causing this serious scenario, but a tsunami wave, which was far larger than considered in the design basis, had to occur to produce these effects.

The earthquake and tsunami that occurred on 11 March 2011 caused a nuclear disaster due to a single root cause, which was the underestimation of the height of the tsunami wave. The professional competence and scrupulousness of the Japanese engineers cannot be questioned, and we even know that they reviewed the design basis for tsunami hazard in the recent past, but, unfortunately, the underestimation of the hazards have been confirmed by the facts today. There is an opinion of many experts that if the hazard of earthquake and tsunami wave were assessed with the use of the probabilistic method, the recent one could be considered an event with an occurrence frequency of $\geq 10^{-3}$/year and hence, it could not even be considered as an ultimate design basis event, i.e. an event of 10^{-4}/year or more infrequent occurrence.

The features of the design contributed to the events developing in the way they actually developed. According to the design, the diesel generators used to provide for emergency power supply had been installed on the lower floor of the turbine building, thus the integrity of the earthquake proof generators and presumably the electric cables and the safety cooling water pump were all jeopardized by flooding in addition to the earthquake. It is readily acknowledged that spatial separation, in addition to redundancy, is inevitable. A more favourable disposition of the diesel generators and the spatial separation of the items of equipment and cables would have helped a lot. It was very lucky that there were suitable provisory means for the supply of seawater for the purposes of cooling the reactors. As per design, the prevention of the formation of an explosive concentration of hydrogen generated under accident conditions was ensured with the use of a nitrogen atmosphere in the containment. This solution inhibits the formation of the explosive mixture in the containment, but does not reduce the amount of hydrogen there. Design features of the filtered blow down system also contributed to the explosions happening during the containment venting. Emergency hydrogen recombiners, which have been installed for accident management purposes in several nuclear power plants, and recently at Paks as well, perhaps could have helped prevent the hydrogen blast or could have reduced the extent thereof.

Several important questions have arisen in relation to the events which occurred at Fukushima Daiichi nuclear power plant, the answers to which could scarcely be found by an outsider. These questions focus on the bases, the content and the timing of the actions taken by the personnel and the persons responsible for the accident management in response to the accident and during the recovery work, and to the problems and effectiveness of the implementation of these actions. A final evaluation cannot be undertaken without knowing the answers to these questions, nor without finding the answers from direct or indirect indications to the questions concerning the condition of the power plant after the occurrence of the earthquake and before the arrival of the tsunami wave, and into what conditions it got directly after the tsunami wave, or later as a result of the response actions.

The seismic safety of Paks Nuclear Power Plant

It is appropriate to ask how safe Paks Nuclear Power Plant would be in the case of a severe natural disaster, e.g. an earthquake of a magnitude presumable for the Paks site. For an understanding of this issue, two aspects will need to be clarified:

1. How severe an earthquake can be expected at the Paks site, or for what earthquake effects/loads should Paks Nuclear Power Plant be designed?
2. In what way can the nuclear power plant be made earthquake resistant, and what should be done to achieve this earthquake resistance at Paks Nuclear Power Plant?

For what magnitude of earthquake should Paks Nuclear Power Plant be designed?

According to the Hungarian regulations, a nuclear power plant shall be designed to withstand the effect of the largest earthquake that may occur within a ten thousand years period, and to withstand the seismic acceleration generated by such an earthquake. Note that, for non-nuclear installations, the design shall be based on the maximum earthquake during a period of 475 years.

The Pannonian Basin is an area characterised by moderate seismicity and our knowledge of this seismicity is rather uncertain. Thus probabilistic method is used by us, too, for the identification of the seismic hazard, and this method is suitable for the appropriate consideration of the uncertainties. The application of this probabilistic method includes identification of the source zones of quakes, for the characterisation of which the magnitude distribution function of the quakes is used. Thus, the magnitude frequency distribution and the maximum credible, or cut-off magnitude of the given zone are important data in the analyses. However, local shaking is identified by considering all possible quakes on every identified structure in all possible source zones, rather than a single quake of a given magnitude occurring at a specific location. The seismic hazard and the maximum shaking, recurring with a frequency of ten thousand years, have been identified in this way for the Paks site, too.

The design basis earthquake or safe-shutdown-earthquake needs to be characterised for the design of a nuclear power plant. Various scales are used for characterisation of the size of the earthquakes. The most widespread scale is the Richter Scale, which gives the magnitude of the earthquake and is proportional to the energy released by the quake. The magnitude of the perceivable earthquakes is higher than 2. The magnitude of earthquakes in Hungary known from historical and instrumental records were all lower than 6.6. The biggest earthquake in Hungary occurred at Érmellék, while the magnitude of the earthquake experienced by many people at Berhida was ≈4.9. Intensity scales are also used, which include, in general, a 12-grade scale for the classification of earthquakes by the damage they cause. The grades on the intensity scale can be determined on the basis of phenomenological description of the damage, such as tilted chimneys or fissured brick walls.

However, an input parameter is required for the design work, which is applicable for the definition of the direct effects, i.e. the loads. Such earthquake parameters are the ground motion, the acceleration and velocity of the ground motion, and the ground displacement. In general, the ground acceleration (mostly the horizontal component of the acceleration) is used as input for the design, which is expressed as a fraction of the gravitational acceleration (g).

Since there is only a qualitative relation between the ground acceleration assumed for the site and the magnitude of an anywhere occurred earthquake, it is not appropriate to make a statement that a nuclear power plant is designed or, particularly, dimensioned to an earthquake of any magnitude, though these terms are used in everyday talk and in the media.

Proper design for the design base ground acceleration provides the assurance that the facility will not be damaged in the case of the design base earthquake. However, the ground motion acceleration is not an appropriate measure for assessing whether the facility will be damaged or not due to a particular earthquake exceeding the design basis one. The average horizontal acceleration caused in the coastal region of Honshu Island by the Tohoku earthquake of magnitude nine could be 0.3 to 0.35 g. For the 14 affected units, the earthquake caused a slightly higher shaking than for the safe shutdown earthquake considered in the design basis. Particularly at the Fukushima Daiichi plant, the acceleration was approximately ≤0.5 g. The Niigataken Chuetsu-Oki earthquake was as small as a magnitude of 6.6 - 6.8, but it caused a maximum horizontal acceleration of ≈0.68 g at the Kashiwazaki-Kariwa nuclear power plant. This was two times higher than the acceleration of the earthquake used as design basis. In the two cases above, the systems, structures and equipment designed as specified by the nuclear standards survived the loads generated by the ground motions without any damage. The damage is better characterised, for example, by the cumulative absolute velocity, the value of which depends not only on the amplitude of the acceleration-time function but also on the duration of a strong earthquake. This could be of a value of 10 g sec for the recent Big Tohaku earthquake, and at most 2 g sec for the Niigataken Chuetsu-Oki earthquake on the site of Kashiwazaki-Kariwa nuclear power plant.

Experience shows that designing for an effect of vibration character is a question of investment cost rather than a technical issue.

There is no reliable technical solution for cases in which an earthquake is capable of causing permanent dislocation on the surface. This raises the following question:

Is it allowable for a fault line to exist near a plant site?

The presence of a fault line cannot be considered as an exclusion criterion in the selection of a plant site, unless this fault line is capable of causing a permanent displacement on the surface. The minimum distance shall be at least 8 to 10 kms. The presence of a tectonic structure capable of causing permanent dislocation can be determined on the basis of the seismic activity during a period of some ten thousand years for high activity areas, and of some ≈2.5 million years (Quaternary) for low activity areas.

The question arises whether the faults near the Paks site are capable of causing permanent displacement or not. It is valid for all fault lines that ground motion may occur as the effect of an earthquake along the fault line. This effect was considered in the identification of the ground motion expected for the site of the nuclear power plant. The Pannonian Basin is fragmented but, in general, such a high elastic energy cannot accumulate under the given geological conditions which would be sufficient for causing a permanent displacement on the surface if this energy releases in the form of an earthquake. Therefore, such fault lines, including those near the Paks site, do not raise doubts the acceptability of the site.

A micro-seismic monitoring system has been installed at the nuclear power plant and in a 50 km region of the power plant in the framework of the Paks Seismic Safety Programme, which is used to monitor the seismic activity of the site and the entire region. However, no one should believe that the seismic monitors at the units or even the micro-seismic monitoring network could be capable of forecasting an earthquake.

What else could be caused by an earthquake?

An earthquake may have other consequences besides ground vibratory motion. Such a consequence was the tsunami in Japan. It makes no sense to speak about such a tsunami wave in Paks by the Danube. However, there is another phenomenon, soil liquefaction, which can occur as an effect of vibration, since the saturated loose soils lose their shear strength, i.e. behave like a liquid. This may cause a loss of stability and, after the event, the settlement of the building. For Paks Nuclear Power Plant Ltd, the soil liquefaction is a Beyond Design Basis event, with an occurrence probability less than 10^{-4}/year.

Seismic safety programme

The site of Paks Nuclear Power Plant was selected in the sixties in an area exposed to a very low level of the seismic hazard. The assessment of the hazard was based on the historical and instrumental records. The maximum credible earthquake for the design was defined in terms of intensity as the historical maximum with a certain margin (+ on intensity grade). The power plant was designed and constructed in consideration of the seismic safety regulations of the seventies. The loads caused by the ground motion of the maximum credible earthquake were assessed negligible compared with other extreme loads, like maximum wind load. The safety requirements related to the external hazards were radically modified in the eighties. They become more rigorous and thus a shaking value characterised by an exceedance probability of 10^{-4}/year has became the design basis, which is of much lower probability than the acceleration value linked to the intensity of the previously identified design basis earthquake. The serious consequences that may result from the new definition of the design basis were pointed out by geological and seismological investigations undertaken in the late eighties at the Paks site. It became obvious that the maximum horizontal acceleration value to be considered as design basis is at least ten times higher than that taken into account in the design. The assessment of the problem was included in the systematic safety assessment, which was carried out in 1993 by Paks Nuclear Power Plant with the use of state-of-the-art methods. Based on the preliminary assessment of the site seismicity and on the analysis of the safety issue, a comprehensive safety enhancement project was launched by the management of the nuclear power plant with the professional support of the International Atomic Energy Agency and under the supervision of the Hungarian Atomic Energy Authority, to upgrade the seismic safety of the facility.

The interpretation and fulfilment of the requirements indicated that:

– the earthquake hazard of the site had to be assessed and the features of the safe shutdown earthquake with an exceeding probability of 10^{-4}/y had to be identified; for the Paks site, this can be characterised by a maximum horizontal acceleration of 0.25 g;

– the plant seismic capacity had to be reviewed, and the design of the seismic reinforcements had to be performed for the new design basis earthquake;

– the comprehensive qualification/reinforcement of the power plant had to be carried out in a way to ensure that the reactor can be shut down, cooled down and kept cooled in the long term, and the radioactive materials can be confined even after an earthquake occurring once during a period of 10,000 years.

The programme was implemented in two phases. The most urgent and easy to implement reinforcements were carried out as early as 1994–1995 using the preliminary, overestimated earthquake input. This included the inspection of the anchoring of cable trays, electrical and I&C racks, electrical cabinets, and the stationary batteries, the inspection of the stability of the non-structural partition walls between various rooms of the main building, and the design and implementation of the reinforcements identified during the review. The design and implementation of the reinforcements requiring serious preparatory work commenced in 1998 and were finished by the end of 2002. The volume of upgrading measures can be characterised by a single figure: more than 2500 tons of structural steel were installed to reinforce the nuclear power plant.

The work was uniquely complex, since a nuclear power plant, which was practically not designed to withstand an earthquake, had to be reinforced and qualified to significant shaking.

Application of a graded approach allowed the implementation of this amount of work; the method of dynamic calculation of structures and systems, and the qualification procedure were differentiated by their safety and seismic safety classification. The standard methods prescribed for the design of nuclear power plants and the methodology developed for re-qualification of operating plants were combined. The selection of the methodology was substantiated by seismic blasting experiments, trial calculations and numerical experiments.

At the end of the programme, the probabilistic safety assessment demonstrated that, as a result of the actions taken, the “required and sufficient” level of safety had been achieved. The compliance of the earthquake safety with the relevant national and international standards was confirmed by a periodic safety review in 2007.

With its one and a half decade completion period, this project has been the largest project of Paks Nuclear Power Plant with a cost spent on the reinforcements amounting to more than USD 200 million.

Some examples of the reinforcements are presented in Figures 1 to 3. Figure 1 shows the viscous-dampers beneath the steam generators. Figure 2 shows the longitudinal fixing of the row of columns of the reactor hall, while Figure 3 shows the steel bridge for fixing the frame of the reactor hall laterally between the bubble condenser towers of neighbouring units.

Figure 1: Viscous vibration dampers beneath the steam generators

Figure 2: Longitudinal reinforcements in the reactor hall

Figure 3: Bridge structure between the bubble towers for reinforcing the reactor building structures

What would happen in the nuclear power plant during an earthquake?

In the framework of the programme, an accident management procedure system was developed for the operational personnel, which specifies the actions to be taken in the case of an earthquake. The management of such situations forms part of the regular training of the staff similarly to all other accident events.

In the case of an earthquake, Paks Nuclear Power Plant will be shut down by its protection systems if any of the systems are damaged, but the reinforced systems remain available for bringing the nuclear power plant into a safe state. Special seismic instrumentation is installed to support the operations required upon the occurrence of such an event, the work of the operational staff and the assessment of the post-earthquake conditions at the nuclear power plant. The acceleration detectors are merely considered auxiliary instrumentation, since the units, just like a complicated nervous system, are meshed by measuring and protection systems, which actuate the appropriate protective actions if any of the safety related systems get damaged.

In the case of an earthquake, the seismic detectors installed onto the base mat transmit a signal to the control room and trigger the closing of the isolation valves if the horizontal acceleration exceeds the level of 0.05 g. This protective operation does not initiate the shutting down of the reactors, but will isolate the systems which have not been reinforced to withstand seismic events, because they have no safety function in such cases. The unit will be shut down by the I&C and protection systems used to monitor the operation and protect the plant. For example, the sloshing of the water in the bubble condenser or the sloshing of the water in a steam generator due to an earthquake will result in the reactor scram, even if no damage occurs. In the case of an earthquake, the unit is shut down or, if there is no disturbance or loss of function, it continues to operate. The decision whether or not the units should be shut down after a (minor) earthquake, if, otherwise, no protective intervention has been initiated, should be made upon processing the signals of the accelerometers installed in the free-field (in the courtyard). This decision process is regulated by dedicated procedures and criteria based on the cumulative absolute velocity and response spectrum criteria. If the plant is shut down due to protection system actuation or because of exceeding the criteria limits, operator actions and control of the post-earthquake conditions shall be organised and performed. Acceleration recorders are installed at critical locations of the units to allow assessment of the conditions. This conception is identical to those used in other parts of the world with moderate seismic activity.

Summary: The earthquake safety of Paks Nuclear Power Plant is ensured, as specified by the currently valid requirements, by reinforcements and qualification for the largest possible earthquake of ten thousand years occurrence frequency and via appropriate procedures to be followed in the case of an earthquake, and by the training of the personnel for such procedures.

The safety of the nuclear power plant is not static, but rather subject to continuous critique and renewal. The catastrophe at Fukushima Daiichi nuclear power plant will certainly provide several lessons, which, after appropriate analysis, can be used for improving the seismic safety of Paks Nuclear Power Plant.

Richter Scale

The Richter Scale is a measure of the intensity (the Richter magnitude, in other words, the dimension) of an earthquake, based on instrumental observations. The magnitude is proportional to the logarithm of the energy released at the source of the earthquake.

Initially, the Richter magnitude was derived with the use of a formula from the maximum displacement indicated by a seismograph of a specific type and the distance from the epicentre. (The value itself is the decimal logarithm of the maximum displacement measured in microns by a Wood-Anderson type seismograph at a distance of 100 km from the location of the earthquake.) Today, several other definitions of the magnitude are available, which are slightly different with regard to the intensity of a specific earthquake.

It obviously follows from the above that the scale is open at the top, i.e. has no formal maximum. Nevertheless, based on the mechanism of action of earthquakes and the mechanical properties of the Earth's crust, magnitudes over 10 practically do not occur. Another important feature of the scale is that approx. 32 times difference exists between two grades of the scale with regard to the released energy.

Large earthquakes

Date	Location	Magnitude
22 May 1960	Chile	9.5
28 March 1964	Prince William, South Alaska	9.2
26 December 2004	Sumatra, Andaman Islands	9.1
03 November 2011	Honshu, Japan	9.0
04 November 1952	Kamchatka, Russia	9.0
13 August 1868	Arica, Peru (now Chile)	9.0
26 January 1700	Cascadia-zone (USA, Canada)	9.0

(Source: U.S. Geological Survey web site)