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Research Article

Seismic Vulnerability Assessment of Site-Vicinity Infrastructure for Supporting the Accident Management of a Nuclear Power Plant

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Nuclear power plants shall be designed to resist the effects of large earthquakes. The design basis earthquake affects large area around the plant site and can cause serious consequences that will affect the logistical support of the emergency actions at the plant, influence the psychological condition of the plant personnel, and determine the workload of the country's disaster management personnel. In this paper the main qualitative findings of a study are presented that have been performed for the case of a hypothetical 10^{-4}/a probability design basis earthquake for the Paks Nuclear Power Plant, Hungary. The study covers the qualitative assessment of the postearthquake conditions at the settlements around the plant site including quantitative evaluation of the condition of dwellings. The main goal of the recent phase of the study was to identify public utility vulnerabilities that define the outside support conditions of the nuclear power plant accident management. The results of the study can be used for the planning of logistical support of the plant accident management staff. The study also contributes to better understanding of the working conditions of the disaster management services in the region around the nuclear power plant.

1. Introduction

Nuclear power plants (NPP) shall be designed to resist all foreseeable external hazards at the site that can adversely affect the safety of the plant. According to the international practice, the frequency of the core damage and the early large release of radioactive substances into the environment shall be limited to the values of 10^{-5}/a and 10^{-6}/a, respectively. Because of these limitations, criterion for damage parameters of the hazards to be accounted in the design is set to the level of $10^{-4} \div 10^{-5}$ probabilities per annum. Proper design of the plant ensures that the systems, structures, and components required to secure the safety of the plant remain functional both during and after the external event, avoiding melting of the reactor core. The structures and systems required for accident management should remain functional even in the case of events beyond design basis. The plant staff and the disaster management services of the country should be prepared to manage extreme events and mitigate their consequences. The very first publications on Fukushima disaster emphasized the deficiencies in severe accident management [1]. One consequence of the Fukushima accident is that nuclear power plants, especially the multiunit plats, should do a better planning of accident management for long-lasting station blackouts that occur simultaneously with destructions caused by a natural disaster. Generally, the inadequate emergency response can increase the number of losses and casualties by an order of magnitude [2].

In general, the plant design includes both the plant and the site layout. These are very important for safety in relation to external hazards. However, the emergency planning and response require evaluation of the consequences of external events beyond the scope of the plant design. An extreme disastrous and rare external event can generate catastrophic consequences in large area around the plant site. The postevent conditions around the site affect the logistical support of the emergency actions at the plant influence the psychological condition of the plant personnel and determine the workload of the country's disaster management personnel.

In this paper, the postearthquake situation outside of the Paks Nuclear Power Plant is assessed that if a 10^{-4} annual probability earthquake would happen, in this case, the plant can be brought into safe shutdown condition thanks to the seismic safety upgrading measures implemented and there is no need for off-site measures [3]. The plant is also protected from the in-plant and on-site secondary effects of the earthquake (fires, explosions). Nevertheless, the plant personnel will need a minimum degree of logistical support from and communication with the outside area. The replacement of duty personnel and the shift change can be smoothly managed only if the communication and transport are operable and the staff members living around the plant are available, since they could be injured and psychologically affected by the event. Consequently, the postearthquake housing and public utilities' conditions of the region around the plant should be assessed for proper planning and preparedness.

Although the recent study is very focused to a specific site and used for a very specific application, it is part of a more generic research environment: earthquake preparedness, prediction, and evaluation of damage scenarios for effective management of postearthquake situation. The importance of the assessment of postevent situation has been recognized by competent authorities in Hungary [4–6] and worldwide (see, e.g., [2, 7–11]).

There are a large number of studies related to the scenario development and loss estimation methodology. An overall guidance is given, for example, in [11–14]. For example, the FEMA-P58 methodology ([13, 14]) has been applied in [15]. The Risk-UE [11] has been applied in [16]. The ELER v3.1 method [17] is applied in [2]. Typological analyses and expert judgement have been combined in [8]. A GIS based application is used in [9]. A Modified Mercalli intensity-based damage matrices were used to estimate damage to structural and nonstructural components of buildings [10]. However, there are rather limited examples for detailed earthquake damage forecasts for low-to-moderate seismicity regions [18, 19].

The method applicable in recent study for the assessment of losses of function of the infrastructure and casualties should be selected accounting for the peculiarities of the application. In Hungary, earthquakes with $5.8 \leq M < 6.0$ comparable with the plant design basis are extremely rare (Érmellék 1834, Komárom, 1763). Nevertheless, a 10^{-4}/a design basis earthquake can cause rather complex situation in the affected area: structural damage and fires in dwellings, kindergartens, hospitals, different community centres. Damage and limitation of electrical supply, potable water system, waste water system, and natural gas supply will affect habitability and the function of dwellings, community centres and medical services. The loss of water supply in settlements limits the fire-fighting capability, which is overloaded due to possible large number of fire events and transportation difficulties. The communication in the area would be hindered by road and bridge damage, landslides, and traffic accidents. Loss of electricity supply is one of the most common causes of failure that impede the availability of other systems, even if they are not damaged. When there are domestic power plants, or import capacities feeding into the system, the power lines and substations and the distribution system are functional; then electrical supply is available. Therefore, the main task of the assessment is the characterisation of the postevent condition of the electrical supply. Obviously, the loss of functions of majority of the mentioned systems is strictly interrelated, since these systems are connected which requires integrated approach (see, e.g., [20]).

In Hungary, neither the inhabitants nor the disaster management capabilities have thorough experience regarding large earthquakes. The disaster management system in Hungary has been proven to be well trained and experienced in managing large area river floods. However, the complexity of a postearthquake situation is rather differing from the case of situation caused by floods and cannot be easily simulated for training. The behaviour of the inhabitants in the region around the plant is difficult to forecast. Panic and confusion can be expected, since people in the region have never experienced even a minor shaking.

The results of the study can be used for planning of the logistical support of the plant accident management staff. The study also contributes to better understanding of the working conditions of the disaster management services in the region around the nuclear power plant. The study can help to emphasize the importance of the seismic safety of a plant by demonstrating the disastrous conditions that may occur in case of design basis earthquake, while the plant remains safe.

2. Case-Study Initial Conditions

2.1. Case-Study Earthquake and Soil Conditions. The parameters (magnitude, focal depth, and possible distance from the site) of the case-study earthquake have been selected in accordance with the design basis of the Paks Nuclear Power Plant. Probabilistic Seismic Hazard Assessment (PSHA) has been performed for the Paks NPP site. Deaggregation of the hazard is shown in Figure 1 for 10^{-4}/a level of exceedance.

According to this, an earthquake of moment magnitude 5.8–6.2 at an epicentral distance of ~10 km from the plant site is dominating in the hazard. The free-field ground motion has been obtained by nonlinear site response analysis. The design basis peak ground acceleration (PGA) is equal to 0.25 g. For comparison, a PGA of 0.08 g had to be accounted for the Paks site, if the EUROCODE 8 would be applied for an average structure with 50 years of service life.

Based on the seismic hazard assessment of Paks NPP site, two scenarios have been chosen for the study as follows:

(1) An earthquake of $M = 6.2$ is assumed to occur at ~10 km epicentral distance North-East from the NPP site.

(2) The same size earthquake as defined above happens just below the plant.

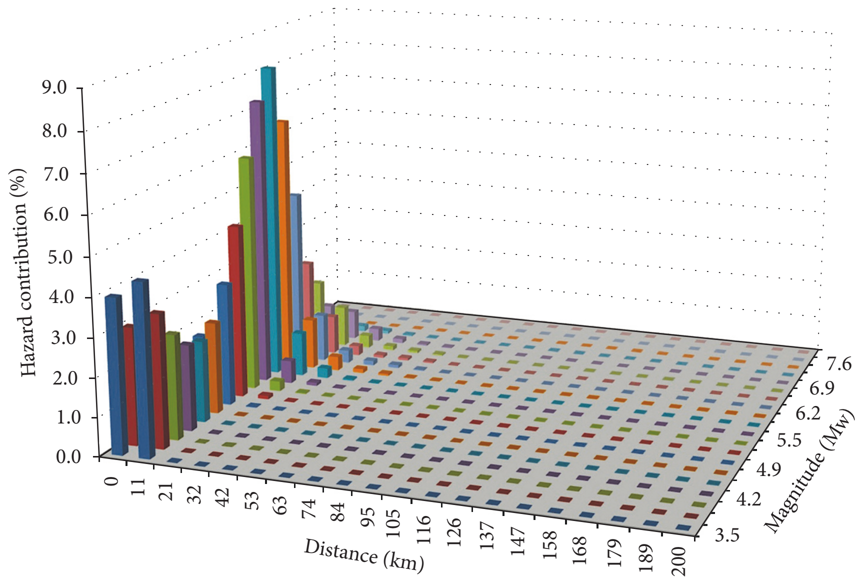

Figure 1: Magnitude-distance deaggregation for 10^{-4}/a level peak ground acceleration.

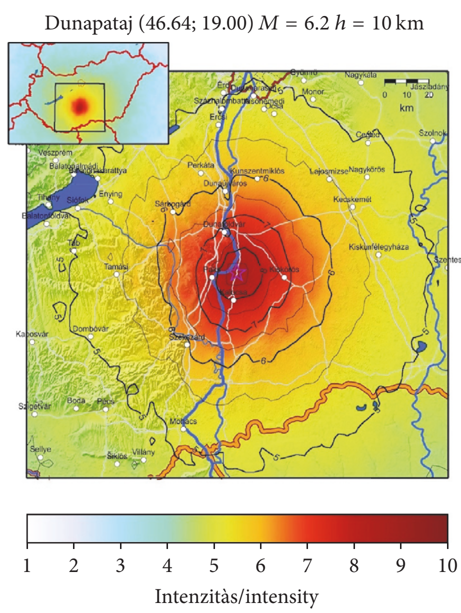

Figure 2: Instrumental intensity map of the Scenario 1 earthquake.

For evaluation of the damage of the built environment instrumental intensity map (shake-map) has been developed for the earthquake that is dominating the site seismic hazard. The intensity map of the first scenario is plotted in Figure 2. Analysis of the first scenario provides an insight into how devastating an earthquake could be comparable to the plant design basis earthquake for the area nearby the site.

The intensity map of the second scenario looks practically identical to the intensity map plotted in Figure 2. Analysis of the second case provides an impression on what would happen in the settlements where dwellings of the plant personnel are located. The second case analysis also demonstrates the logistical hurdles in supporting the work of plant emergency services personnel.

The plant site is located at the contact area of aerial loess sediments of Transdanubia and very thick fluvial sediments of Great Hungarian Plain. At the flood-plain of the Danube the surface is covered by Pleistocene fluvial gravel, gravelly sand (7–10 m), sand, fine grained sand (10–15 m) and Holocene fluvial fine grained sand, gravel, and eolic sand. Under relatively thin Quaternary sediments there are several hundred meters of Pannonian and underlying, variable Miocene layers. The West side of the area is covered by mainly wind-blown Quaternary sediments, mainly loess. Under these 20–100 m thick Quaternary layers lie the upper Pannonian layers on the whole territory. At the flood-plain continuous shallow groundwater regime is in place that is influenced by the Danube level. The upper soils at the flood-plain can be classified as C or D according to EUROCODE 8 while the soil at West side belongs mainly to classes B and C.

The loose, saturated, and noncohesive sandy soils susceptible to liquefaction appear as an additional hazard to an earthquake and may cause some further damage. Earthquake sites with similar soil conditions show the evidences of liquefaction [21].

The loess cover in the investigated area forms quite steep slopes typically alongside the roads. The loess bluff formation is unstable. There are several cases reported, when the loess bluff slid (see, e.g., [22]).

2.2. Population and Built Environment of the Plant. The distribution of population and data on the housing and infrastructure used in the study have been obtained by population census held in 2011 and published by the Hungarian Central Statistical Office [23]. The basic information on the electrical transmission network can be found in [24].

2.3. Methodology of Assessments. The assessments in the recent paper are rather qualitative. The expected damages have been assessed in accordance with European Macroseismic Intensity Scale, identifying the Vulnerability Class of the structure and assessing the expected damage in correlation with EMS intensity scale [25] and the corresponding phenomenological definition of damage. This methodology can be considered as a simplification of the methods given in [18, 19, 26]. The evaluations in this paper are simplified and qualitative; therefore, the guidance given in [27] has also been considered. Results of generic studies on vulnerability of built environment (e.g., in [28]) and some studies (e.g. [29]) have also been accounted for. A large number of specific studies on earthquake experiences and on the vulnerability of elements of the infrastructure have also been considered; see the references from [30–37].

3. Assessment of the Condition of General Building Stock

The earthquake effects on the building stock in the region around the plant have been assessed in [38] with focus on the dwelling conditions that affect the plant staff living in the settlements.

Except for two cities, Paks and Kalocsa, the plant site is surrounded by rural region, where the essential part of inhabitants is living in villages in one-family houses. Big part of the houses here are made of adobe or relatively poor masonry and built before 1945. According to [38] the earthquake consequences are rather catastrophic. In Bács-Kiskun County in the effected zone ~80% of the buildings suffered significant damage or collapsed. 5.000 to 7.000 people live in the area that was impacted by the earthquake effects.

From the logistical support of the plant emergency personnel point of view, the situation of interest is in Paks and in the nearby villages. Practically two-thirds of the buildings in Paks will be significantly damaged and nearly 20,000 people will be affected by the consequences of an earthquake. There are much less damage to be expected in community centres and medical service infrastructures, since these facilities are relatively new-built and properly designed, constructed, and maintained.

4. Condition of the Public Utilities

4.1. Electric Power Supply. The Hungarian power transmission system is structured into 400/220 kV basic system, 120 kV main distribution system, 20/35 kV system with overhead lines, 10 kV cable distribution system for cities, 5/6 kV for feeding industrial consumers, and system with 400/230 V for direct supply of the consumer and public lighting. The national power system is connected to the cooperation systems by 750/400 kV lines [24]. The Hungarian power system can be qualified as reliable and well maintained.

Main elements of the transmission system are the power plants, transmission lines, and the substations.

Except for the nuclear power plant, there are not any power plants in the area affected by earthquake in our case study. It is assumed that the domestic generating capacities and the import capacities can feed the electric energy system and compensate the loss of the nuclear generating capacity. In this study, the direct earthquake damage is considered. The propagation of failures and unstable response and possible black-out of the system due to the instant shut-down of the nuclear power plant with total 2000 MW capacity is not investigated.

The substation at the nuclear power plant is upgraded and qualified for the design basis earthquake loads. The other 23 substations of the Hungarian transmission system are outside of the impacted area (the closest one at Pécs is 82 km from the plant). Consequently, the function of the transmission lines (towers and cables) defines the availability of the entire system.

The steel towers of the basic transmission grid (tower height 40–50 m) and main distribution grid (tower height 25–30 m) are designed in accordance with MSZ EN 50341 (MSZ 151 was applied before introduction of the EUROCODE). Wind load dominates the design of the towers. Design features of the towers are reported, for example, in [39, 40].

Assessment methodology of the vulnerabilities of transmission systems is given, for example, in [12, 28, 41].

Analysis of the towers of the Hungarian transmission system for earthquake loads corresponding to the plant design basis demonstrates sufficient capacity of towers, if the design wind load is not coinciding with earthquake. One of the four 400 kV lines is passing through the area with soil liquefaction hazards. Although the possible damage due to liquefaction could not been excluded on one of the transmission lines, the transmission system will not hinder the power supply into the impacted area thanks to the structure of the system (loop and radial) and the redundancies.

The medium and low voltage distribution system is very extended. It is composed by the 20 kV overhead lines, 10 kV cable distribution system for cities, 5/6 kV for feeding industrial consumers, and consumer and public lighting system with 400/230 V. The medium to low voltage system is built mainly on B10–B16 type concrete poles with mounted equipment (combined in some places with steel corner masts). The 400/230 overhead distribution lines in the villages are built on 8–12 m concrete (rarely wood) poles with tip loads 4 to 28 kN. At the consumer level, widely used H-shaped concrete poles are of type B8,5–B12 weighting ~800 to ~3000 kg and with tip load 2–13 kN and height of centre of mass at ~3.6 to ~4.5 m. The poles are designed for dead load, operational loads, and environmental loads (wind, ice).

Simplified calculation performed for the poles of type B12/28 and B8,5/2 shows that the base bending moment and base shear due to horizontal ground acceleration should not cause damage of the poles if the earthquake does not coincide with other exceptional (accidental) loads. The dominating failure modes are due to poor soil conditions and possible liquefaction. The anchorages of pole-mounted devices seem to be insufficient to withstand the inertial loads. However, that needs more rigorous evaluation. Failure modes and approximate failure probability for elements of low voltage distribution system are shown in Table 1.

Direct earthquake damage as well as the propagation of the failures is expected in this low voltage overhead system. The large amount of building damage in the villages especially

Table 1: Failure modes and approximate failure probability for elements of low voltage distribution system in the considered region.

	Failure modes	Probability
Poles	Shear	Low
	Flexural	Medium
	Foundation failure (due to insufficient bearing capacity of loose Holocene alluvium and liquefaction)	High
Overhead lines	Break	Low
	Short-cut	Low
Mounted on poles equipment (transformers)	Anchorage/fitting failures	High

(see [38]) will cause large number of local disturbances failures and damage in the consumer level system that can escalate to system failure. The building damage can cause fires at several places, especially when electrical failures coincide with the failures of natural gas connections into the houses. Propagation failures modes should be considered in the future.

4.2. Natural Gas Distribution System. There is a high-pressure buried gas pipeline (≤D300) passing through the area but bypassing the settlements.

The settlements in the area are supplied by natural gas that have a rather complex distribution network (buried ductile PE distribution pipelines, steel-pipes for consumer part). Dominating failure modes are the local failures and damage of the gas system caused by the interaction with building damage (see [38]) that can also cause fires at several places simultaneously. The gas and electrical supply systems as well as their failure modes are interconnected; see [42].

4.3. Potable Water Systems. The potable water system of the settlements in the region is rather complex. It consists of wells, chemical preparation stations, distribution pipelines, elevated water tanks/water towers, and consumer system. Weak links in the system are as follows:

(i) The nonductile buried pipelines in some places that can be broken due to soil failures and differential movement (most of the piping is ductile)

(ii) Hg or Ak type spherical-shaped, top-heavy, elevated water tanks that are either guyed (Hg) or fixed-base (Ak) structures usually with 50 to 100 m^3 volume and 18 to 3 m high, probability of falling due to break of guy-line or flexural damage in case of fixed base

(iii) Large number of local connection and in-building damage due to building damage [38]

(iv) Loss of electrical supply.

It is rather possible that the potable water system would be lost in most of the villages of the affected area.

The failure modes of the waste water systems are rather similar to those typical for the water system.

Figure 3: Sliding of the loess bluff to the road No. 6 (photo made by the authors).

4.4. Transportation Facilities. The road network in the region is well developed. The settlements as well as the plant site are connected to the main road No. 6 and highway by redundant connections. Although local road failures can be expected at flood-plain due to liquefaction, the villages and cities in region can be accessed. Part of the main road No. 6 is passing beside the rectilinear loess bluff North of the city of Paks susceptible to cracking-sliding failure. The loess bluff is unstable and can slide as it happened in 1976, 1977, 1993, and 2008 [22, 43] and very recently (see Figure 3). These events have been triggered by weather conditions.

Simple calculation applying sliding block model indicates that the nuclear power plant design basis earthquake can trigger the sliding of the loess bluff. Consequently, one of the main roads for accessing the plant site from North can be temporarily blocked.

4.5. Secondary Hazards due to Transportation and Industrial/Agriculture Activities. The hazards due to residential, industrial, military activities, and transportation are mapped and characterised in the 30 km area around the plant (type of activity, type/chemical composition and amount of hazardous material used or stored, distance to the plant, distance to the settlements, etc.). Considering the effects on the plant, these anthropogenic hazards effects can be screened out by distance except for the hazards due to road transportation of fuel, PB-gas, hydrochloric acid, and ammonia. The amount of transportation of these hazardous materials on the main road No. 6 and highway No. 6 is rather infrequent ($\sim 10^{-4}$/a amount of all goods). Those, the annual frequency of coincidence of a 10^{-4}/a design basis earthquake and transportation of the mentioned above chemicals passing by the vicinity of the plant is $<10^{-7}$/a. Consequently, these "earthquake + transportation" hazards are negligible for the plant and for the nearby settlements, too.

According to the mapping and characterisation of the residential and industrial/agriculture activities in the settlements around the plant, damage of the facilities containing hazardous chemicals can aggravate the postearthquake situation due to release of toxic materials, fire, and explosions. Considering the amount of used/stored hazardous materials these effects are rather local. Nevertheless, these secondary hazards affect the situation in the settlements around the plant. These aspects of the postearthquake situation are subject of future study.

4.6. Critical Facilities. Compared to the dwellings in the rural area there are much less damage to be expected in community centres, kindergarten, schools, medical service infrastructures, and fire-fighting facilities since these facilities are relatively new-built and properly designed, constructed, and maintained. That is even more valid in the cities affected by an earthquake. Loss or limitation of function of these facilities and services can be caused by loss of electrical and water supply.

5. Conclusions

Most critical element of the infrastructure in rural area is the consumer level overhead electrical distribution system. Potable water supply and natural gas supply can fail due to structural damage and loss of electrical supply. The habitability of dwellings, as well as the availability of specific utilities and services and community centres, is limited due to the loss of electrical, water, and gas supply. Although it has not been investigated, it is obvious that the restoration of the utilities will be hindered by logistical burden due to high number of events and possible casualties/injuries. Defining the weakest elements of the infrastructure in affected area of the nuclear power plant by design basis earthquake helps the planning of emergency measures. Identification of the weak elements of the infrastructure helps to focus further studies.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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