Seismic Margin Assessment for Nuclear Facilities of Kozloduy NPP

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ABSTRACT

In accordance with the decision of the European Commission and ENSREG Declaration of 13 May 2011, all nuclear power plants in the European Union were subjected to a stress test. The stress test is defined as a targeted reassessment of the safety margins of nuclear power plants in the light of the events which occurred at Fukushima: extreme natural events challenging the plant safety functions and leading to a severe accident.

Seismic margins assessment is based on the analysis of the seismic resistance of the equipment, which is important for safety and participates in mitigation of accident scenarios. Seismic margin is determined on the basis of the prescribed limits of seismic accelerations that any nuclear facility can withstand without severe fuel damage and radioactive release into the environment.

The determining of the weak points and boundary effects in case of seismic action is done based on the data from the seismic PSA Level 1. Based on the calculated median values of the probable seismic deviations, the ranges of probable seismic action have been determined for which the resistance of the different nuclear facilities is assessed.

The safety margins re-assessment should define the nuclear facility ultimate capacity, i.e. to determine the values of accelerations for which the SSC failures would result in non-availability of the safety functions, and fuel damage would be inevitable. The assessment of this acceleration value is done using the data of the seismic analyses as performed on design stage, accounting for the dynamic response and actual spatial dimensions of the civil structures and for the materials properties.

For the purpose of the KNPP nuclear facilities safety re-assessment, the seismic capacity is accepted to be determine by the value of seismic acceleration, for which it can be ascertained with 95% certainty that the safety factor obtained at the respective seismic acceleration is not lower than 1.

The purpose of this report is to present the approach, main results and conclusions of the seismic margin assessment for "Kozloduy" NPP.

1. APPROACH DESCRIPTION

In conformity with [2], the main purpose of the stress-test is to analyze the nuclear facilities behavior and the effectiveness of the preventive measures undertaken. Each potentially weak points and cliff-edge effect is to be identified for each of the extreme situations considered.

In conformity with [2], the margins' assessment should define the nuclear facility ultimate capacity, i.e. to determine the values of accelerations, for which the SSC failures would result in non-availability of the safety functions and fuel damage would be inevitable.

The determining of the weak points and cliff-edge effects in case of seismic is done based on the data from the seismic PSA Level 1.

Within the frames of [8] the seismic hazard has been studied, and as part of this study equipotential hazard spectra of the input action have been generated, divided by frequency of occurrence into 8 levels: from 1E-01 event/year to 1E-08 event/year. The obtained probabilistic parameters of the ground acceleration (average and median values, standard deviation) are presented in Table 1. Based on the calculated median values of the probable seismic deviations, the ranges of probable seismic action have been determined for which the resistance of the different nuclear facilities is assessed. For Units 3&4 and 5&6 the first considered interval is between the value of ISPS (Industrial seismic protection system) actuation and seismic acceleration with probability of occurrence 1E-03 event/year; the second interval is between the accelerations with probability of occurrence 1E-03 and 1E-04; the third one is between probabilities 1E-04 and 1E-05, and so forth. Within the frames of [8] dynamic analyses of the structures have been conducted, with accounting for the “soil-structure” interaction as specific for the site, and probabilistic floor response spectra have been generated by acceleration values, as well as the peak accelerations have been determined for the different buildings elevations.

The safety related equipment which participates in the accident sequences has been analyzed on seismic stability, and the parameters of the functions describing the conditional probability of failure thereof (fragility curves) have been determined. The curve of the failure conditional probability determines the probability of destruction of the examined component, in case of seismic action definite occurrence (probability of latter’s occurrence equal to 1.0).

According to [8], the margins re-assessment must define the nuclear facility ultimate capacity, i.e. to determine the values of accelerations for which the SSC failures would result in non-availability of the safety functions, and fuel damage would be inevitable.

For the purpose of the safety margins reassessment, a review has been done of the conditional probability values on destruction of the different SSC, as obtained in [8]. Herein below are presented the basic terms related to determination of the parameters of conditional probability of the equipment and structures failure. This presentation is made in order to illustrate the approach adopted for determination of the seismic capacity of the facilities.

The curves of the conditional probability of component failure (a component being civil structure element, certain equipment, or certain element of the facility) are defined by the values of probability of latter’s failure at different values of the seismic response reference parameter. The purpose of the seismic vulnerability analyzing is to determine the PGA at which the seismically induced stresses in the analyzed component located in certain point of the civil structure would exceed its capacity.

The assessment of this acceleration value is done using the data of the seismic analyses as performed on design stage, accounting for the dynamic response and actual spatial dimensions of the civil structures and for the materials properties. There are many factors and uncertainties (accidental and modeled), affecting the seismic capacity, therefore the conditional probability of failure of certain element could be presented as a family of curves, each of them being attributed to certain confidence band, thereby accounting for the uncertainty. An example of fragility curves family is presented in Figure 1.

Table 1. Values of the hazard curves for maximal acceleration, used in [8]

Annual probability of exceeding	**15%**	**Median**	**Average**	**85%**	**Standard deviation**
1E-1	0.0308	0.0366	0.0372	0.0435	0.0062
1E-2	0.0674	0.0764	0.0769	0.0866	0.0094
1E-3	0.1043	0.1217	0.1231	0.1420	0.0184
1E-4	0.1515	0.1819	0.1847	0.2184	0.0328
1E-5	0.2091	0.2614	0.2676	0.3268	0.0583
1E-6	0.2773	0.3637	0.3763	0.4770	0.1002
1E-7	0.3554	0.4893	0.5131	0.6736	0.1622

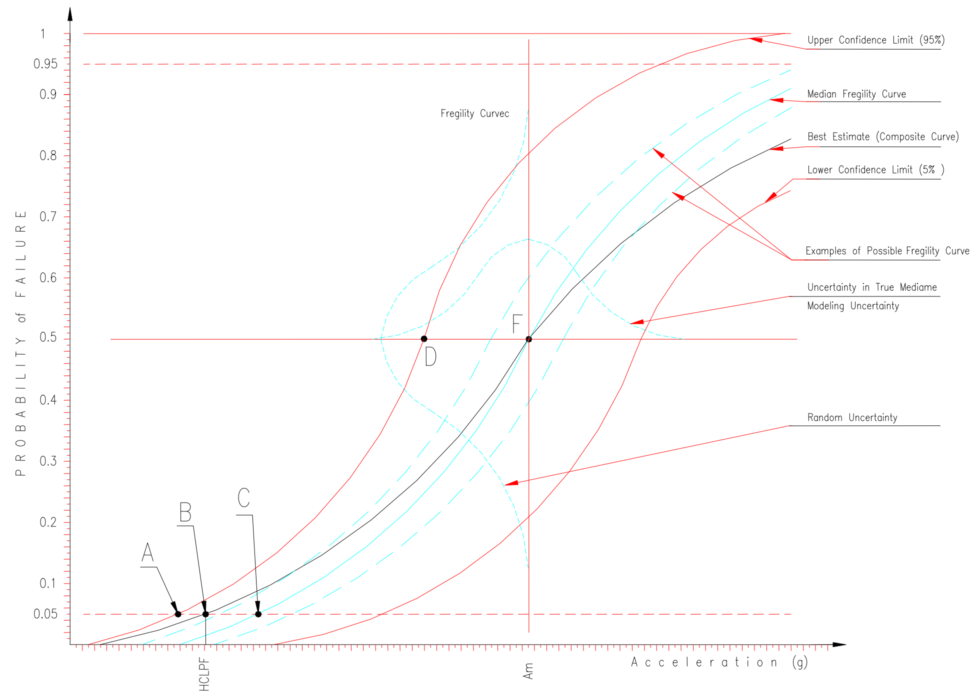

Figure 1. Fragility curves example

The different parameters of the curve of conditional probability of failure are as follows:

F = Am – point of the median presenting the acceleration at which the probability of failure is 50%.

The curve of the median values is a standard Gauss cumulative function with known βr and βu=0:

$$Pf(a) = \Phi\left(\frac{\lg(a / Am)}{\beta r}\right)$$ where:

- a - is the current FGA value along axis X;
- Am - is the acceleration value for which failure occurs with 50% probability (point F), or the seismic acceleration for which the safety factor of the analyzed element is equal to 1.
- βr - is random uncertainty

Out of parameters of the conditional probability of failure one could determine the point of the so-called High Confidence of Low Probability of Failure – HCLPF. This value may be used for assessments of the seismic safety of the elements, without to calculate the failures for the different levels of seismic action, with realistic (non-conservative) approach in parameters assessment.

This HCLPF means that it could be maintained with 95% certainty that the probability of failure is lower than 5 %.

The left and right boundaries of the confidence band are the finite points of distribution of the statistic variable, which depend on the assumed distribution (±1.65σ) with supposition of known βr and βu.

The left boundary of the normal distribution is presented by the curve of 95% certainty of non-exceeding, and it is of interest being the conservative boundary for the event occurrence.

In this case the calculation of the left boundary curve is done by the equation:

$$Pf(a) = \Phi\left(\frac{\lg(a/Am) - 1.65*\beta u}{\beta r}\right),$$

where:

a - is the current FGA value along axis X;

Am - is the median value of the acceleration for seismic failure occurrence, or 50% probability that with this acceleration the element will not fail for seismic cause.

βr - internal uncertainty

βu - modeled uncertainty

Φ - standard Gauss cumulative function

Point D presents 95% certainty of non-exceeding 50% probability of failure, and is calculated by the equation:

$$AD = Am*\exp(-1.65\beta u).$$

For the purpose of the KNPP nuclear facilities safety re-assessment, it is agreed that the seismic capacity should be determined using AD, since for this value of the seismic acceleration the safety factor (by force/capacity) is equal to 1. Each safety factor could be determined with different confidence interval. The assumption of the seismic acceleration value in point D being the limit ensures 95% certainty that the safety factor obtained with acceleration AD is not lower than 1.

If the value of AD, determined for certain structure, system or component (SSC), falls within the boundaries of some of the confidence bands as determined for the purpose of the re-assessment, then it is assumed that the respective SSC will fail, and the consequences of its loss should be considered. In order to determine the failures related to the structures and the buried facilities, the value of AD shall be compared with the absolute maximum free field accelerations for the ranges subject to this review. For the equipment arranged by height at different elevations in the structures, the AD value shall be compared to the maximum horizontal spectral acceleration at the respective elevation, recorded by the respective probabilistic floor response spectra.

The analysis includes consequent review of all seismic action bands, whereby for each band the safety related SSC which would fail are presented. The changes in the nuclear facility behavior are determined (the changes in the accident sequences process), as well as the changes in the performance of the safety functions.

The consequential review of each band allows determination of the nuclear facility capacity to sustain actions of different load degree. Such approach allows for systematic achievement of the main purpose of the safety re-assessment, namely, to determine the maximum acceleration values whereby the Unit would survive without severe fuel damage and radioactivity release into the environment.

2. MARGIN ASSESSMENT

The results obtained for Units 5&6 of Kozloduy NPP after application of the above described approach, are presented below.

The cliff-edge effects are shown in Table 2.

In case of earthquake with acceleration in the range $0.05 \leq PGA \leq 0.12$ g, based on the data from [8] it could be summarized that all safety functions are sufficiently assured, and there are no weak points or cliff-edge effects in the Units response related to the earthquake.

The only consequence of the earthquake is the reactor scram signal. In case of earthquake with acceleration PGA 0.05g, a reactor scram signal is generated by the Industrial seismic protection system (ISPS).

If, before of the earthquake occurrence, the reactor has been operated in some of the power modes, then after earthquake the emergency protection has been actuated, the reactor would go into transient towards its shutdown and stabilizing in hot state. For performing the actions to put the Unit into hot shutdown state, the personnel has available the whole technological resource in full scope, i.e. all safety systems and normal operation systems, which preserve entirely their functionality. If the reactor has been in cold condition before the earthquake occurrence, then the earthquake would not cause any changes in the operation mode, i.e. the train of residual heat removal system (TQn2) which has been in operation would continue as it is without interruption. All remaining systems and trains of system TQn2 which are in stand-by mode also maintain their functionality.

Earthquake with an acceleration in the range $0.12 < PGA \leq 0.18$ g reaches the loss of offside power condition (LOOP). The occurrence of LOOP does not represent significant risk for Units 5 and 6 of Kozloduy NPP, since this is a design accident, and all systems required to mitigate the situation would remain available after the earthquake.

The over-ground civil structures (prefabricated RC elements) of circulation pump stations CPS-3 and CPS-4 are classified as of 3rd seismic category, they have not been strengthened during the Modernization Program implementation, and so they are vulnerable to seismic actions. Based on the expert engineering assessment, it could be expected that towards the upper limit of the analyzed range severe damages and destructions would occur, thereby causing failure of the equipment installed therein.

The CPS equipment is not involved in managing the emergency situation in case of LOOP; therefore, these earthquake consequences would not affect the safety functions thereof. In this sense, the loss of circulation pumps (VC) would not affect the development of the accident sequences and the safety functions performance.

Earthquake with an acceleration in the range $0.18 < PGA \leq 0.26$ g observe the first seismic failures of equipment and structures associated with the provision of safety function (SF). Destruction in the construction of turbine and electrical equipment buildings leads to an inability to use the normal operation system for mitigation of the process.

It can be summarized that failures caused by the earthquake will lead to the following cliff-edge effects on the safety functions performance:

- *Subcriticality* – normal operated boron injection system (TK) is lost due to failure of I&C panels OVATION in the reactor building.

  Failures of OVATION panels in the reactor building would not complicate the emergency situation, because, the emergency boron injection system (TQn3) remains operable after the earthquake.

  For Unit 5, however, are available only two channels of the emergency boron injection system (TQn3), due to the failure of the first channel of service water system (QF). The failure of first channel of QF system is occurred due to damage of the single-lens compensator of the head pipeline between diesel generator station and Unit 5 and all consumers of this train would fail, i.e. the redundancy degree of the safety systems and safety related systems, using essential consumers service water as cooling medium, would decrease - two trains of safety systems and safety related systems remain available – trains # 2 and # 3. It should be noted that, due to the induced failure of first diesel generator 1DG (GV), pressurized relieve valve may be used to perform the feed&bleed procedure only until exhaustion of the battery capacity (EA10), i.e. for about 10 hours, according to [7].

- *Residual heat removal* - seismically induced failure of a normal feed water system (RL), due to fall of the roof in the turbine hall would cause reduction of implementation level of this safety function to the emergency feed-water system (TX) and alternative feed-water system.

In view of seismic failure of first channel of service water system (QF) Unit 5 will have two channels of emergency feed-water system (TX) and Unit 6 emergency feed-water system (TX) will remain available in full.

It should be noted that in [8], as consequence of the Turbine hall roof fall, also break of pipeline connected with SG is assumed, i.e. the Unit would go into accident situation with secondary brake. It should be taken into consideration that these are localizable leaks from SG.

- *Core cooling* – For Unit 5 performance of the function will be limited to two channels of emergency core cooling system (TQn2). For Unit 6 block function will be implemented in accordance with the design, i.e. all channels of the system will be available, as they are not affected by the earthquake.

It should be noted that in case of earthquake of this range it is not unlikely that the movement of the mobile DG of the system for SG alternative make-up would be impeded. The mobile DG is mounted on a platform together with fuel oil tank, control board and a 140 m long high power cable rolled on a drum. This platform, with the equipment installed thereon, is stored in a special compartment located between DGS-1 and DGS-2. The transportation of the mobile DG platform is done by truck trailer crane. In order to use the mobile DG, safe and reliable routes are required to be constructed to allow movement between the different points of its connection to users. These routes must not be traced over the non-qualified bridges above the cold canal, because these bridges would probably be damaged is case of seismic action within the subject range. The routes also must not be traced near technological and pedestrian overpass trestles, which may be damaged as well and thus impede access to the mobile DG connection points.

Earthquake with an acceleration in the range 0.26 <PGA ≤ 0.36 g additionally to the previews range observed liquefaction of the sands beneath the spray ponds of service water system, as well as liquefaction of the sands beneath circulation pump stations CPS-3 and CPS-4, seismic induced failures of instrumentation equipment and steam damp to the atmosphere (BRU-A) as well as other devices.

The failure of BRU-A will influence on providing for the heat removal from primary through the secondary side. Only SG SV will remain available to perform the above function in that situation.

A conservative postulation can be made that the liquefaction of the sands beneath the spray ponds will lead to their destruction and therefrom to the complete loss of service water to essential consumers both in Unit 5 and in Unit 6. The loss of the system will lead to failure of all loads, which predetermines that in the conditions of loss of off-site power, the only available (operable) equipment for a limited period of time will be the equipment which is on battery supply.

If the reactor was in power mode, than the heat removal through the secondary side can be restored only for one of the two Units, since at the site there is only one Mobile Diesel Generator (MDG) which feeds the pump of the system for SG alternative make-up. There are certain conditions for moving the MDG to its final destination. The removal of the steam generated at the SG can only be done through the SG SV. System SG alternative makeup can provide heat removal from the primary circuit only during less than 24 hours. Then, if you do not provide additional amounts of feed water fuel damage cannot be prevented.

If the reactor was in shutdown mode, than heat removal cannot be restored due to the complete loss of service water system. The core cooling function cannot be realized and the core fuel damage cannot be prevented. The Unit’s reserves depend in this case on the time necessary to reach fuel damage.

From the analyses carried out is seen that at seismic accelerations higher than 0.34.g the heat removal cannot be assured and fuel damage may occur. Therefore, the determined seismic margin of Units 5&6 is 0.14 g (or 70%) above level RLE.

Table 2. Cliff-edge effects at assessment of the margins for Units 5&6 of Kozloduy NPP. Reactor

Acceleration, g	Direct consequences of the earthquake	Consequences on SF		Final state
		Effect on SF	Loss of SF	
0.05 ≤ PGA ≤ 0.12	There is no	There is no	There is no	***Safe:*** All facilities and systems keep fully their functionality after occurrence of earthquake of this range.
0,12 < PGA ≤ 0,18	• LOOP • severe damages and destructions of circulation pump stations CPS-3 and CPS-4	There is no	There is no	***Safe:*** In conformity with the project.
0,18 < PGA ≤ 0,26	• LOOP • Damage of the single-lens compensator of the head pipeline between DGS and Unit 5; • Fall of the Turbine hall roof, which is expected to occur on the boundary between this range and the next one; • Destruction of the columns of the electrical equipment building, in the middle of the range. • Destruction of the bearing structure of Auxiliary Building in the upper part of the range • I&C equipment elements, such as manometric thermometers, OVATION panels (in Reactor building and Turbine building)	• Subcriticality - намаляване на нивото на резервиране • residual heat removal - reducing the level of redundancy • core cooling - reducing the level of redundancy for Unit 5 • SFP cooling- reducing the level of redundancy for Unit 5	There is no	***Safe:*** In conformity with the project for Unit 6. Two channels of the safety systems keep their working capacity for Unit 5.
0,26 < PGA ≤ 0,36	In addition to the failures, described above the following seismic failures are expected: • Liquefaction of the sands beneath the spray ponds at the upper part of the reviewed seismic action range; • Liquefaction of the sands beneath the forebay of WCPS 3 and 4 at the lower part of the reviewed seismic action range. Loss of stability is expected, as well as horizontal slip of the verticall wall of the forebay of WCPS 3 and 4 at the upper part of the reviewed seismic action range • Failure of the Turbine Hall at the lower part of the reviewed seismic action range. • Failure of the Atmospheric steam dump valve (BRU-A) • Service Water Reserve Tank V=80m3; • Break of Pure Condensate Reservoir TQ01B01;	• Loss of service water system • Loss emergency DG	All connected with the fuel cooling.	***Fuel damage***

Acceleration, g	Direct consequences of the earthquake	Consequences on SF		Final state
		Effect on SF	Loss of SF	
	• I&C equipment elements - sensors, panels and other			
1,9			Loss of confinement integrity	***Fuel damage and releases***

3. CONCLUSIONS

It can be summarized that the fuel damage cannot be prevented in case of PGA above 0.33-0.35 g, i.e. in case of the accelerations at which liquefaction of the sands beneath the spray ponds is expected.

This result shows that in relative measurement units the margin of Kozloduy NPP Units 5&6 consists in 0.13g, or in 65% in relation to the RLE, which determines an SSE of 0.2g for the Kozloduy NPP site, i.e. the Units can resist without fuel damage to an earthquake which is 1.65 times stronger than the reevaluated SSE for NI valid as of 30.06.2011.

The margin of units 5 and 6 constitute 0.13 g or 65% compared to the review level earthquake RLE (PGA = 0.2 g).

In comparison to the initial design bases which define an safety SSE for NI of 0,1g, the margin consists in 0.23g or 230%, i.e. the Units can resist without fuel damage to an earthquake which is 3.3 times stronger than the SSE accepted in the initial design

The assessment of the margins regarding the seismic impacts, carried out in the framework of Kozloduy NPP stress test is significant conservative and gives confidence that seismically SSC of Kozloduy NPP are in condition to assure the safety of the plant at maximum possible for the site seismic impacts.

REFERENCE

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