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Technical guidelines for the seismic safety re-evaluation at eastern european NPPs

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ABSTRACT

The paper describes one of the outcomes of the Engineering Safety Review Services (ESRS) that the IAEA provides as an element of the Agency's national, regional and interregional technical assistance and co-operation programmes and other extrabudgetary programmes to assess the safety of nuclear facilities. This refers to the establishment of detailed guidelines for conducting the seismic safety re-evaluation of existing nuclear power plants in Eastern European countries in line with updated criteria and current international practice.

1 - INTRODUCTION

The main purpose of the ESRS is to provide assistance to Member States with respect to implementation of requirements and recommendations of IAEA Codes and Safety Guides and of good international practice to ensure consistent and uniform assessments of safety. Because very few nuclear power plants are currently under development, most recent ESRS review missions have addressed issues related to re-evaluation of operating nuclear facilities, particularly concerning their vulnerability to earthquakes. In this regard, evaluations of seismic safety of WWER-type nuclear power plants have been the primary focus of ESRS review missions undertaken during the past seven years, as described in [1] and [2].

Worldwide experience shows that the re-assessment of the seismic capacity of an existing operating facility is prompted for the following reasons: (a) evidence of a higher seismic hazard at the site than expected before, due to more data, new methods and new experience from real earthquakes; and (b) regulatory requirements to ensure that the plant has margins for seismic loads greater than the original design basis earthquake. These reasons lead to the definition of a post-construction safety evaluation earthquake, called *"review level earthquake" (RLE)*. This earthquake is usually larger than the one for which the facility was originally designed, as was shown by the results of the seismic hazard re-evaluation at those NPP sites in Eastern European countries [1]. Therefore, the main objective of a post-construction re-evaluation programme is to evaluate the plant's current capability (i.e. the plant "*as-is*") to withstand such an earthquake and identify any necessary upgrades or changes in operating procedures.

Special considerations arise when the nuclear power plant has already been constructed and is in operation. Seismic *qualification* is distinguished from seismic *re-evaluation* primarily in that seismic *qualification* is intended to be performed at the plant design stage, whereas seismic *re-evaluation* is intended to be conducted after the plant has been constructed.

For those purposes the following considerations are relevant:

(1) It is a known technical finding that industrial facilities, especially NPPs, which have been sited, designed and constructed using good engineering practice and internationally accepted regulations have an inherent capability to resist earthquakes larger than the earthquake used in their original design. This inherent capability is a direct consequence of the conservatism that exists in the seismic design and is usually described in terms of *"seismic design margin"*.

(2) At the design stage it may be easy to add certain seismic design margins in traditional ways because the associated costs are relatively low. Typically, seismic design criteria applicable to NPPs are specified in such a way that, although it is known that they introduce very large seismic design margins, their size is not usually quantified. Because of the ways that seismic design margin is introduced by design criteria, seismic margin typically varies greatly from one location in the plant to another, from one structure, system and component to another, and from one location to another in the same structure.

(3) After the plant is constructed, however, it may be very costly to add the same seismic design margin if it is done in the traditional ways used during the design stage. At the post-construction stage, an adequate margin can be ensured through the use of special safety evaluation procedures. These procedures are aimed in raising more efficiently only the lower and most safety significant margins than do traditional seismic design criteria and methods. Nevertheless, although there may be special difficulties in performing hardware modifications during the operation period of an existing plant, the significance of these difficulties cannot be judged until the plant's capability to withstand earthquakes is systematically determined.

(4) Neither the IAEA, nor any regulatory authority, has established definitive and comprehensive guidelines for the seismic re-evaluation of *existing operating* nuclear power plants. Although some guidelines do exist for the seismic re-evaluation of existing nuclear power plants built to earlier standards, these are not established at the level of a regulatory guide or its equivalent. Nevertheless, a number of existing nuclear power plants throughout the world have been and are being subjected to review of their seismic safety. Rational criteria for resolving the main issues were developed, particularly in the USA, which have been adapted for the specific conditions in Western and Eastern European countries.

(5) It is also recognized that re-evaluation programmes at existing operating plants are unique and, therefore, plant-specific or regulatory-specific. This means that specific requirements and guidelines have to be developed for each case. The fact that the plant is already constructed and the specific construction details and its 'as-is' conditions can be inspected are also important factors in deciding on the level of effort and methods that can be used in its seismic re-evaluation. In deciding this, it is important to determine whether the plant has (or has not) been *originally* designed for seismic loads. For instance, in the specific case of the Armenian NPP seismic re-evaluation, this plant presents a good 'reference basis' since it was explicitly designed against earthquakes according to the rules valid at that time in the former USSR.

2 - TECHNICAL GUIDELINES

For defining and implementing those seismic re-evaluation programmes, the IAEA has assisted Member States to develop case-specific guidelines to fill the gap mentioned in (4) above. In 1992, technical Terms of Reference were prepared for the seismic upgrading design of Units 1 and 2 of Kozloduy NPP (Bulgaria) within the framework of WANO (World

Association of Nuclear Operators) assistance for the safety enhancement of that plant. That experience was followed by the preparation of the Unified Criteria Document used in the seismic and fixes design for Paks NPP (Hungary), in 1994, and which contributed substantially to rationalize the programme started by the plant operator. Later, it followed the Technical Guidelines for the Seismic Re-evaluation Programme of Mochovce NPP-Units 1-4 (Slovak Republic), issued in 1995. During 1996, similar guidelines were prepared for Bohunice NPP (Slovak Republic) and the Armenian NPP-Unit 2 (Armenia). For the latter the final document was issued in March 1997 and it is the latest development in the subject and upon which this paper is mainly based.

2.1 - Objectives of the Technical Guidelines

The purpose of the technical guidelines (TG) is to provide the general framework within which a seismic re-evaluation programme shall be carried out in a manner consistent with current criteria and internationally recognized practice. It is a key tool for regulatory authorities and responsible organizations for the execution of the programme, giving a clear definition to different parties, organizations and specialists involved in its implementation on:

(i) objectives of the seismic re-evaluation programme;

(ii) phases, tasks and priorities in accordance with specific plant conditions;

(iii) a common and integrated technical framework for acceptance criteria, capacity evaluation and upgrade design methods.

Thus, considering that several organizations or specialists may perform different tasks of the programme, the TG provide a unified framework for an integrated input/output of each participant according to the final objective of the programme and, as shown by the results in Kozloduy and Paks NPPs, this was one of the most significant achievements of these TG.

2.2 - Structure of the TG document

The TG has been divided into 3 sections as follows:

(1) - Introduction and plant specific characteristics: This section introduces the plant itself, its original seismic design bases, the purposes and scope of the TG, and the reasons and objectives of the seismic re-evaluation programme, answering the question *why* the programme is required.

(2) - Work plan - phases, tasks and priorities: This section sets out a detailed description of the phases and tasks required for the execution of the programme. This section answers the question *what* to do for fulfilling programme's necessities.

(3) - Technical criteria and requirements: This section provides guidelines on requirements, methods for capacity evaluation and design of upgrades, acceptance criteria for determining and evaluating the seismic response and behaviour of systems, structures and components. Thus, this section answers the question on *how* to perform the activities required by the programme.

2.3 - Work plan - Objectives, phases, tasks and priorities

A detailed work plan shall be drawn up for the implementation of the seismic re-evaluation and upgrading programme of the plant, keeping in mind its long term characteristics. Due to funding constraints, the programme may be broken into smaller basic tasks, maintaining the logical technical sequence. The timing is not included in the TG because that matter should be defined by the responsible organization according to the project necessities, available resources and general milestone schedule. An important point for the successful completion of the programme is the existence of an organization with clear responsibility for its development and with the required technical capabilities to carry it out. This organization, with the role of project manager, should be constituted from the beginning of the programme formulation including the establishment of a design engineering group at the plant, in case such a group does not already exist. If additional non-seismic safety upgrades must be performed, verification of compatibility with the seismic upgrades is recommended. In particular, if a leak-before-break assessment were to be done, the seismic upgrades and analyses performed should be properly co-ordinated.

Two phases are usually defined as follows:

Phase I: *Walkdowns, evaluations and conceptual design of upgrades,*
with the objectives to document (as much as practicable) the original design bases (design criteria, methods of analysis, load combinations and so forth) of the plant; to define the RLE for the specific seismic hazard at the plant site; to identify all candidate plant upgrades (if any) needed to reach the safety level defined according to the criteria established in the TG; to prioritize candidate plant upgrades according to safety added versus cost, economic, and schedule considerations; and to elaborate the conceptual design of upgrades. Upgrades can be classified into two categories (higher and lower priority) using the criterion of obtaining a higher degree of seismic safety with optimal investments.

Phase II: *Final design and execution of upgrades,*
with the objectives to elaborate the final design of upgrades and to execute them in accordance with the priorities established.

The TG include a detailed description of the following tasks:

- Task 1: Determination of the Review Level Earthquake (RLE)
- Task 2: Compilation of available seismic related information
- Task 3: Geotechnical data
- Task 4: Classification and identification of functions, systems, structures and components
- Task 5: Evaluation of seismic response of buildings and structures
- Task 6: Adequacy of foundation material
- Task 7: Evaluation of seismic capacity of buildings and structures
- Task 8: Evaluation of seismic capacity of distribution systems
- Task 9: Evaluation of seismic capacity of equipment (components)
- Task 10: Modifications: prioritization, design and implementation
- Task 11: Quality assurance and configuration control
- Task 12: Seismic instrumentation

The sequence, relationship and interdependence recommended between the different tasks are indicated in the flow chart of Figure 1. This flow chart has proved to be very useful in the division of responsibilities and coordination of assistance between different organizations performing the seismic re-evaluation programme for the Armenian NPP.

2.4 - Methods to be used for seismic re-evaluation

Several methods can be used to carry out the seismic re-evaluation programme. Three of them are described below:

(1) *Current criteria and comprehensive seismic design procedures:*
Current design criteria and comprehensive seismic design procedures, as applied for design of new facilities but using the re-evaluated seismic input, may be applied. It is noted that this would be a conservative and usually relatively expensive approach for re-evaluation of an existing operating facility.

(2) *A seismic margin assessment (SMA):*
The seismic margin assessment method, spelled out in [3], has been used by the international community for the seismic re-evaluation of existing operating facilities for beyond design basis earthquake events. The methodology is deterministic and follows the same pattern as design procedures, but is more liberal than criteria for new designs and permits a determination of whether the capacity of the as-built plant exceeds the target earthquake input which was selected for review. Still, it has a probabilistic basis which assures a high reliability of the plant to shut down safely in the event of an RLE. The objectives are to identify seismic vulnerabilities, if any, which, if remedied, will result in the plant being able to shut down safely in case of such event.
(3) *Probabilistic Safety Assessment :*
This method models the plant response to initiating events using fault trees and event trees. The conditional probability of failure of essential structures and components is represented by fragility curves. Using the event tree/fault tree models, fragility curves and the probabilistic seismic hazard curve, the frequency of core damage can be computed.

For the specific cases of the NPPs mentioned in Section 2 above, the Seismic Margin Assessment method was recommended with the details provided in the TG prepared.

2.5 - Classification of items to be re-evaluated and screening out procedures

The identification of systems, components and structures required to properly function during and after an RLE event is a key initial task of the re-evaluation programme as indicated in the flow chart of Figure 1. In that regard the main criteria, assumptions and procedures were mentioned in [1]. Particularly, only those structures, systems and components needed to bring the plant to a safe shutdown condition during and after an earthquake and to maintain it in that safe shutdown condition for a certain defined period need to be re-evaluated. The Safe Shutdown Equipment List and the screening out of those components and structures having seismic capacities higher than the postulated RLE are the main results of this first task.

2.6 - Evaluation of seismic margin capacity

The concept of High Confidence Low Probability Failure (HCLPF) capacity is used in the SMA reviews to quantify the seismic margins [1]. Two candidate procedures to determine the HCLPF seismic capacities for NPP structures and components have been developed: (i) the Fragility Analysis, and (ii) the Conservative Deterministic Failure Margin method. The latter (CDFM) is the procedure recommended in the TG.

The first step in estimating the seismic capacity is to define the failure mode for each of the items being evaluated. Several modes of seismic failure (each with a different consequence) have to be considered. The failure mode which is most likely or the most dominant to cause either loss of functionality, or loss of leak tightness, or loss of structural integrity or collapse, should be identified.

The approach recommended may be summed up by the following steps :

Step 1: calculate elastic seismic demand in members and connections by elastic seismic response analysis, using the elastic response spectrum;

Step 2: calculate the inelastic seismic demand in specific members by dividing the elastic seismic demand from Step 1 by an amount, $F\mu$, representing the inelastic energy absorption factor. $F\mu$ values are provided for various types of structural systems;

Step 3: combine the inelastic seismic demand with the best estimate of concurrent non-seismic demand using unity load factors to determine the total demand. The TG give the load combinations recommended for reinforced concrete and steel structural elements, masonry walls, and components and their supports;

Step 4: estimate seismic capacity of members and connections by ultimate strength or limit strength provisions in accordance with codes for the appropriate materials (i.e. US-ACI or equivalent national or European codes for concrete, US-AISC or equivalent national or European codes for steel), including the appropriate strength reduction factors;

Step 5: evaluate total demand to capacity ratios for members and connections based on the results of Steps 3 and 4. The structural system and individual members and connections must comply with the structural evaluation criteria when these ratios are less than unity. When ratio values exceed unity, strengthening measures should be considered and, if corresponds, properly implemented

The seismic response analysis, including soil-structure interaction effects, may be best estimate or median-centred. Sufficient parameter variation should be considered to account for uncertainties in soil material properties and stiffness and mass characteristics of the structures and components.

The response analysis will be conducted with the values of damping ratios given, for instance, in the Table 1 which are based on median values as recommended in References [4], [5] and [6], and which are consistent with those provided in applicable international standards. These values are the recommended for the specific case of the Armenian NPP

Limited inelastic behaviour is permitted proving that adequate design details exist such that ductile response (non-brittle failure modes) is possible or for those facilities with redundant lateral load paths. This inelastic energy absorption capacity is accounted for by specifying the *inelastic energy absorption factor* $F\mu$ for each system, structure member or component. They are defined as a function of the ductility μ (i.e. the ratio of inelastic to yield deformation) [4], representing the permissible level of inelastic distortions specified at the failure probability level of 5% approximately. It is always preferable to perform a non-linear analysis of the structure or component being evaluated in order to estimate the $F\mu$ factor. However, because of this type of analysis is often expensive and controversial, a set of standard values is usually recommended. As an example, Table 2 shows the values — not higher than 2.0 — recommended for the most common structural systems for the seismic re-evaluation of the Armenian NPP.

As shown, the permissible damping values and inelastic energy absorption factors recommended are more liberal than in original nuclear power plant design which is limited to elastic behaviour, but they are considerably more conservative than those which would be permitted in conventional seismic design.

For estimating the seismic capacity of systems and components, the TG recommend the procedures outlined in [1] with emphasis in the use of experience gained from real strong motion seismic events (the so-called 'qualification by earthquake experience'). Thus, the methodology developed by the USA-Seismic Qualifications Utility Group (SQUG) for verification of seismic adequacy of existing NPPs, [7] and [8], is recommended. However, most building structures and some Russian supplied systems and components of the WWER-440 type plants are so specialized that they are not included in the earthquake experience database. For those SSC not available in the database, the seismic re-evaluation should be done on a case by case basis by more conventional analytical procedures usually by analysis in the case of structures, systems and mechanical components, and by tests or a combination of tests and analysis for electrical equipment.

CONCLUSIONS

Over the past seven years the IAEA has had an active role in the seismic re-evaluation and upgrading of existing NPPs in Eastern European countries, and the technical guidelines prepared as a result of this involvement have proved to be very useful in organizing the work of the responsible institutions, assuring consistency in the assessment and avoiding overlapping between different parties. The TG has been prepared with the participation of plant operators, original Russian designers and experts with broad experience in seismic re-evaluation in Western countries, reflecting the consensus between all parties involved and linking together the necessities for safety enhancement at specific plants, the particularities of the reactor type and the experience in similar processes worldwide. Thus, solid bases were set up for the preparation of internationally accepted guidance for the seismic re-evaluation of *existing operating* facilities, complementing the current IAEA Safety Guide 50-SG-D15. The IAEA NUSSAC (Nuclear Safety Standards Advisory Committee) has recently recommended the preparation of a Safety Report document in this regard, which could be used by NPP owners/operators as well as regulatory authorities in a licensing context. The document draft will be prepared by the end of 1997 based upon the TG briefly outlined in this paper.

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Figure 1: Flow chart of general work plan

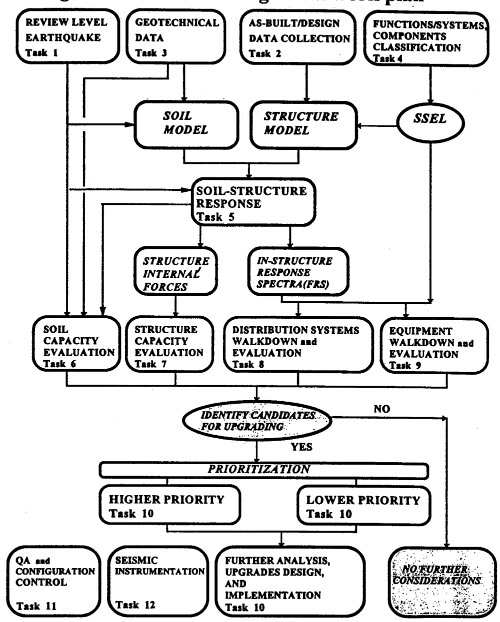

Table 1 - Damping values to be used for the seismic re-evaluation of the Armenian NPP

ITEMS	DAMPING (% of critical damping) with stress levels < yield	DAMPING (% of critical damping) with stress levels ≥ yield
(a) Structures:		
(1) Reinforced concrete structures :	7.0%	10.0%
(2) Welded steel structures :	5.0%	7.0%
(3) Bolted or riveted steel structures :	7.0%	10.0%
(4) Reinforced masonry walls :	7.0%	10.0%
(5) Unreinforced masonry walls :	5.0%	7.0%
(6) Steel structures with precast panels :	7.0%	7.0%
(b) Soil: For simplified soil-structure interaction analysis (SSI) radiation damping as a function of structural foundation geometry will not be limited but resultant composite modal damping should not exceed in principle, values in typical national standards. However, the use of higher values, if properly justified and determined would be permitted		
(c) Systems and Components : except the following:	5.0%	5.0%
(1) Tank liquid sloshing :	0.5%	0.5%
(2) Cable Raceway: if at least one quarter full of loose cable	10.0%	15.0%
(3) HVAC Duct :	7.0%	7.0%
(4) Vertical pumps : (deep well and emersion)	3.0%	3.0%
(5) Instrument racks :	3.0%	3.0%
(d) Generation of In-structure Spectra:		
(1)When generating floor in-structure or in component response spectra for relatively lightly loaded supporting structures, systems or components ($S \leq 0.50$ Sy):		
(a) steel:	2.0%	
(b) concrete:	4.0%	
(2) When generating floor, in-structure or in component response spectra for supporting structures (0.5 Sy < S < 1.0 Sy):		
(a) steel:	5.0%	
(b) concrete:	7.0%	
(3)When generating in-structure or in-component response spectra for supporting structure loaded beyond yield (S>= 1.0 Sy):		
(a) steel:	7.0%	
(b) concrete:	10.0%	

Table 2 : Inelastic Energy Absorption Factors Fμ to be used for the seismic re-evaluation of the Armenian NPP

Structural System	Fμ
(I)MOMENT RESISTING FRAME SYSTEMS	
Concrete:	
(1) Columns where flexure dominates :	1.25
(2) Columns where axial compression or shear dominates :	1.00
(3) Beams :	1.25
(4) Connections (any) :	1.00
Steel:	
(5) Columns where flexure dominates :	1.50
(6) Columns where axial compression or shear dominates :	1.00
(6) Beams :	1.50
(7) Connections (any) :	1.00
(II) SHEAR WALLS	
(1) Concrete and Reinforced Masonry Walls:	
(a) in plane bending :	1.75
(b) in plane shear :	1.50
(c) out-of-plane bending :	1.75
(d) out-of-plane shear :	1.00
(2) Unreinforced masonry out-of-plane shear :	1.00
(3) Concrete reactor confinement box (WWER/440)	0.90
(c)BRACED FRAMES:	
Concrete:	
(1) Columns where flexure dominates :	1.25
(2) Columns where axial compression or shear dominates :	1.00
(3) Beams :	1.50
(4) Bracing (Steel) :	1.50
(5) Connections (any) :	1.00
Steel:	
(6) Columns :	1.00
(7) Beams :	2.00
(8) Tension only bracing and tension ties or struts :	1.50
(9) Connections (any) :	1.00
(d)Adequately Anchored Passive Electrical and Mechanical Equipment:	
(1) Bent plate panels :	1.50
(2) Steel angles framing :	2.00
(3) Steel housings :	2.00
(4) Cast iron :	1.00
(e) Piping, Conduit, Instrument Tubing and HVAC Duct:	
(1) Butt joined grove welded steel pipe :	1.50
(2) Socket welded pipe :	1.50
(3) Threaded pipe:	1.00
(4) Conduit :	1.25
(5) Instrument tubing :	1.50
(6) Cable trays :	1.50
(7) HVAC duct :	1.50
(8) Distribution System Supports :	1.25