Russian Standards and Design Practice of Ensuring NPP Reliability under Severe External Loading Conditions

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Russian Standards and design practice of ensuring NPP reliability under severe external loading conditions are described. The main attention is paid to the seismic design requirements. Explosions, aircraft impact, and tornado are briefly examined too.

1. INTRODUCTION

This report deals with the brief survey of Russian Standards and practice of NPP design under severe external loading conditions. Loadings that shall be taken into account are listed in the Standard [1]: maximum design earthquake; extreme snow, wind and climatic temperatures; hurricane; tornado; tzunami waves (occurance time interval of all these events is taken to be equal to 10000 years); aircraft impact; explosions. The main attention in this report will be paid to the seismic design requirements. Explosions, aircraft impact, and tornado will be briefly examined too.

2. NPP SEISMIC DESIGN

NPP seismic design requirements are provided by the Standard [2] approved in 1987. Before that (since 1979) the Temporal Standard [3] was used. It was based on the same general principles as the present-day Standard.

2.1. Seismic Site Suitability Criteria

Below-mentioned limitations are imposed on the choice of construction site for NPP.

NPP can not be built on the site if maximum design earthquake intensity is more than 8 of MSK-64 Scale. Sites that include capable faults are not suitable too.

There are some peculiarities characterizing a site as unfavourable one, and NPP may be built there only if appropriate measures are undertaken to ensure its safety.These peculiarities are: landslide and mud flow danger; mountaine workings; coast or bank erosion; coast slow sinking (with the sinking rate more than 10 mm per year); ground strength under foundations less than 0,2 MPa; tzunami waves induced flood.

2.2. Seismic Input Data

Several stages of seismic and geologic investigations shall be carried out to provide seismic input data. Previous earthquake intensity is established by use of the USSR Territory Seismic Map. It is presented in the Standard [4] regulating seismic design of usual (non-nuclear) structures. Then the data shall be made more precise on the basis of the region seismic investigstions, and finally - by carrying out of investigations on the site.

Design input data shall comprise following information.

2.2.1. Earthquake intensity I of MSK-64 Skale.

Design horisontal peak ground acceleration A used for NPP seismic analyses, depends on earthquake intensity. Two levels of seismic hazard shall be taken into account:

(a) Design Earthquake (DE) whose occurance time interval is taken to be equal to 100 years. This earthquake corresponds to S1 level of IEAE Recommendations [5].

(b) Maximum Design Earthquake (MDE) whose occurance time interval is taken to be equal to 10000 years. This earthquake corresponds to S2 level of the same Recommendations.

2.2.2. Design Response Spectra.

Standard acceleration response spectra (dynamic factors $\beta(T)$) specified by the Standard [4] are used. They correspond to horisontal peak ground acceleration value A=1. There are three spectra in the Standard depending on ground stiffness (stiff, middle or soft). They are represented in fig.1. One may note their following specific features.

(a) The same spectra are used both for horisontal and for vertical ground motions.
(b) The spectra are not dependent on system damping.
(c) The spectra do not have any phisical sense both in shortand in long-period ranges, because their zero-period accelerations are not equal to 1, and they do not become less than 0.8 for any large period T values.

For the purpose of comparison response spestra specified by US AEC Regulatory Guide 1.60 [7] are plotted in fig.1 too. It may be seen that in period range $0.4 \leq T \leq 1.5$ s Russian Spectra for stiff and middle grounds are close enough to American ones, and out of this range Russian Spectra provide larger accelerations.

2.2.3. Ground Motion Time Histories

Set of recorded, modified, or syntetic earthquake ground motions shall be specified. The Standard [2] does not apply any requere–

ments on them (e.g., on their compatibility with response spectra, on number of components and their mutual statistical independanse, etc). Time histories compatibility with response spectra can not be achieved by phisical reason bearing in mind abovementioned peculiarities of spectra (see 2.2.2.c)

2.3. NPP Seismic Criteria

The safety of NPP must be ensured during and after any earthquake including MDE. Safety conditions are established by the Standard [7].

Requirement to maintain capacity to produce electric power and/ /or heat after DE may be applied too at NPP Customer's request.

2.4. Seismic Design Classification

NPP components (structures, equipment, pipes, instruments, etc.) shall be divided into three Seismic Categories depending on their importance to safety. Classification criteria and seismic resistance requirements for them are presented in the Tab. 1 (see the next page). Some comments are given below.

First of all Category of a component depends on potential radioactive dose load on the public and NPP staff in the case of the component failure. Then it depends on its functions related to reactor safe shut down and maintaining it in safe shutdown conditions, to prevention of Maximum Design Accident and to localisation of released radioactive products. But if requirement to maintain capacity to produce electric power and/or heat after DE is to be satisfied then all requisite NPP components (i.e. almost all its non-nuclear part) shall be included in Category II too. Besides the last Category is divided into two subcategories: IIa is located in reactor building tight room, and IIb - out of it.

Components of the same system may be classified into different Categories, provided their separation is ensured. Separating elements are classified into higher Category.

If failure of lower Category component can lead to failure of higher Category components then Category of the former shall be classified into higher Category.

2.5. Seismic Design and Analysis of Safety-Related Structures

In general safety-related NPP structures design shall be carried out acciording to non-nuclear Standard [4], which was supplemented by some additional requirements increasing seismic inertia forces on Categories I and II.

There are some general design recommendations and rules in the Standard, which shall be taken into account for NPP structures too (naturally, if they are not in contradiction with techology and safety requirements). For example, building shall be divided into units by anti-seismic cuts (their width is to be enough to prevent mutual impacts of the next units); prefabricated reinforced concrete floors and roof shall be made stiff by joining plates togeth-

Table 1. Seismic Design Classification and Requirements

Seismic Categ.	NPP components classified into the Category	Seismic Requirements	
		DE	MDE
I	Normal operation systems or portions of systems whose failure can lead to release of radioactive products in amounts which can cause dose loads on the public exceeding the limits for Maximum Design Accident conditions established by the Standard [8]. Systems and components requisite for maintaining the reactor core in subcritical state, emergency heat removing and localisation of raleased radioactive products. Buildings, constructions, equipment, etc., whose failure can cause the failure of the abovementioned systems	To maintain the capability to work during and after the earthquake	To perform the safety related functions during and after the earthquake
II	Components not included in Category I whose failure can lead to radioactive products release in amounts which can cause dose loads on the public exceeding the annual limits for Normal Operating Conditions established by the Standard [8]. and/or Components requisite for electric power and heat production. Divided into two Subcategories: IIa - components located in the reactor building tight room IIb - other Category II components	To maintain the capability to work after the earthquake	
III	NPP components not included in Categories I and II.	According to non-nuclear Standards	

er and concreting their butts; floors and roof shall be joined with walls; for masonry walls requirements on brick and mortar strength dependent on earthquake intensity are established; steel reinforcement of masonry walls shall be made, etc.

2.5.1. Seismic Inertia Forces Calculation

Seismic loads on building shall be calculated by means of the response-spectrum method. Column vector $\{S_j\}$ of seismic inertia forces for j^{th} mode of the system is the following:

$$\{S_j\} = A\ g\ \beta_j\ [M]\ \{\eta_j\}\ k_2\ k_\psi\ k_\theta. \qquad (1)$$

where:

A = design peak ground acceleration dependent on earthquake intensity I:

Earthquake intensity I	5	6	7	8
A (1/g)	0.025	0.05	0.1	0.2

g = acceleration of gravity;
β_j = spectral acceleration corresponding to j^{th} mode period T_j (i.e. $\beta_j = \beta(T_j)$);
$[M]$ = mass matrix;
$\{\eta_j\}$ = normalized j^{th} mode shape:

$$\{\eta_j\} = \{\Phi_j\}\ \Gamma_j, \qquad (2)$$

where:

$\{\Phi_j\}$ = j^{th} mode shape;
Γ_j = modal participation factor for j^{th} mode:

$$\Gamma_j = \frac{\{\Phi_j\}[M]\{\cos\}}{\{\Phi_j\}^T[M]\{\Phi_j\}}, \qquad (3)$$

where:

$\{\cos\}$ = column vector of cosines of the angles between directions of degrees of freedom and seismic excitation;
$\{\}^T$ = means transpose of a vector.

Seismic inertia forces values are corrected by following factors:

k_2 = factor depending on building hight (usually value of k_2=1 is taken for NPP);
k_ψ = damping dependent factor; it varies in range from 1 to 1.5

being larger for tall and flexible constructions (masts, towers, frame structures with columns of small cross sections, etc.).

k_e = factor depending on Seismic Category:

Seismic Category	I	II	
		Related with radioactive products	Not related with radioactive products
k_e	0.625	0.5	0.3

As one may see, factor k_e decreases design seismic inertia forces. It is used to take into consideration the effect of possible unelastic structure deformations. The last can not be taken directly into account if construction is depicted as a linear system, but only on that condition its modes and frequencies can be calculated and consequently response-spectrum method can be used.

It is recommended to take into consideration three-dimensional seismic motion for Category I structures. Besides three components of seismic load shall be simultaneously applied: two horisontal (each of them is to be calculated by formula (1)), and vertical which is taken to be equal to half of horisontal. Such load components applying is equivalent to the assumption that the resultant ground acceleration is equal to $A_{sum} = 0.938A$ and has approximately 20^{o} slope to horisontal plane. The most unfavourable directions of components shall be taken for structure analysis.

2.5.2. Load Combinations and Materials Strength Limits

Load combinations corresponding to the following NPP operating conditions and events shall be taken into account when structures are analysed.

Seismic Category		Load combinations
I		NOC+MDE; DNOC+MDE; NOC+MDA+DE
II	a	NOC+MDA+DE
	b	NOC+DE; DNOC+DE

Designations in the table mean:

NOC = Normal Operating Conditions;

DNOC = Deviation from Normal Operating Conditions; the following events are considered as DNOC: malfunction of the reactor control and monitoring system; deenerging of PCP; disconnection of turbogenerator and main heat consumers; complete loss of off-site power supply; primary circuit leakage which can be compensited by normal makeup systems;

MDA = Maximum Design Accident;

DE = Design Earthquake;

MDE = Maximum Design Earthquake.

Load combinations for above-mentioned operation conditions shall be formed in conformance with the Standard [9]. Depending on loads duration they are divided into four groups, namely: "permanent", "long-lived", "short-lived" and "extreme" ones. List of loads included into any group is presented in the Standard. For example, permanent loads include dead load, soil pressure on earthretaining walls, prestressing loads, etc; long-lived loads are weight of the equipment, stored materials, people, cranes, NOC thermal and live loads, etc.; short-lived loads include snow, wind and ice, climatic temperatures, cranes braking and equipment transient regimes loads, etc. Extreme loads are DE, MDE and MDA.

Two types of load combinations are considered, namely: "main" and "extreme" ones. The first consists of permanent, long-lived and short-lived loads. Any of the "extreme" combinations includes in addition one of the extreme loads (there is an exception of this ruie, which is discussed below). Loads of any group included in combination are multiplied by the same factor. These factors for seismic load combination are: 0.9 for permanent loads, 0.8 for longlived loads, 0.5 for short-lived loads, 1.0 for seismic loads (as for any other exstreme load).

The load combination of two extreme loads, namely MDA+DE is considered as an exception for NPP constructions. It is made by the following reason. Although NPP pipes and equipment shall be designed to withstand the effects of MDE and therefore they can not be failed by DE, nevertheless probability of DE and MDA occasional occurance at the same time is too large. Indeed, DE occurance probability is equal to 10^{-2} 1/year, for MDA it is estimated as 10^{-3}-10^{-4} 1/year, consiquently probability of their coincidence is more than limit value 10^{-7} 1/year. Proceed from the same probabilistic reason MDE+MDA load combination is not considered. Moreover load combinations of MDE with loads of short duration and rare occurance may be neglected too (if ratio of load duration to its occurance interval is less than 10^{-3}).

Materials strength limits for styress analyses of structures under seismic loads are established by the Standard [4]. According to them materials strength limits under static loadings multiplied by the factor $m_{кр}$ shall be used. The factor is used to take into account a short duration of earthquake. It varies from 0.9 (analyses of multi-storey building's reinforced concrete columns subjected to shear forces) to 1.4 (steel constructions).

2.6 Generation of In-Structure Response Spectra and Time Histories

According to the Standard [2] in-structure response spectra and time histories shall be generated, but any additional specific requirements on this subject are not applied.

In practical analyses different building models, from the simplest lumped-mass beam ones to the space finite-element models are used. Soil-structure interaction is usually taken into account by means of effective springs and dashpots whose ends are connected to foundation slab. The opponent ends are excited by seismic ground motion. Spring stiffness for rock bases was obtained by solving the problem of vibrations of stamp embedded on elastic half-space. In this case M.I. Gorbunov-Posadov's formulas [10] are often used which supply for square and circular foundations the same stiffness values as, for example, ASCE Standard [11]. But it is experimentally established that similar formulas provide too low stiffness values for soft soils. In this case O.A. Savinov's semi-experimental formulas or similar to them given in the Standard [13] are often used. To take into account the energy dissipation due to radiation into foundation, different damping properties of subsistems, etc., formulas published in different issues and similar to those established by the Standard [11] are used. A survey of used methodologies and formulas are presented in the book [14]. More complicated methodologies taking into account coupled structure/base motion are also used in current practice.

2.7. Seismic Qualification of the Equipment

Requirements on the seismic qualification of the equipment and pipes concerned with radioactive products are established by the Standard [15]. But as a special lecture devoted to that subject is presented at this seminar, this problem will not be examined in this paper.

General requirements on the seismic qualification of Category I and II electric, automatic and communication equipment are provided by the Standard [2]. Their strength and maintaining capacity to work shall be checked. Both analytic methods and tests are permitted. If shaking-table tests are carried out the device shall be switched on and its work regime shall be imitated. General requirements to electric devices are established by the Standard [16], and shaking-table test regimes for their seismic qualification are given in the Standard [17].

2.8. Earthquake Instrumentation

According to the Standard [2] the seismic control and signalling system shall be installed to provide automatic safe shutdown of reactor in the case of earthquake occurence. Seismic instrumentation for any other purposes is not required.

3. EXPLOSIONS

"Explosion overpressure-time" curve established by the Standard [1] is shown in fig. 2. Its duration is equal to 1 s.

According to the Standard [18] for Nuclear Heating Plants peak overpressure shall be taken Δp=50 kPa.

For NPP of other type Δp values depend on the place of a potential explosion which can occurs either inside or outside its territiry. In the first case a possibility of explosions of such objects as hydrogen receivers, acetylene production installations, etc., is considered. Design value Δp=10 kPa shall be taken. Placing of any objects whose explosion can cause higher peak overpressure is forbidden in the NPP territory during all its life. If potential explosive objects exist or are planned to be placed nearer than 5 km of reactor building (e.g., oil distilleries, stores of petrol and explosives, main gas-pipes, heat accumulators, navigable river, railways, etc.) then peak overpressure Δp shall be established by means of analysis or be taken equal to Δp=30 kPa.

At least one train of protection systems and one barrier of the accident localisation system shall remain operation after explosion. Methods of structures analyses under explosions are regulated by the Standard [19]. The increased strength limits of the materials are used in order to take into account an influence of the loading rate.

4. AIRCRAFT IMPACT

According to the Standard [18] aircraft impact shall be taken without fail into consideration for Nuclear Heating Plants. For NPP of other types this event shall be taken into account in dependence on the aircraft situation in the site neighbourhood or on Customer requirements.

Aircraft of 20000kg mass and 200 m/s velocity is considered. Used "force-time" and "impact area-time" diagramms are plotted in fig. 3. The most unfavourable impact angle in the range from 10° to 45° to horisontal plane shall be used.

At least one train of protection systems and one barrier of the accident localisation system shall remain operation after aircraft impact. Nonlinear behaviour of reinforced concrete is admitted; the width of the cracks is not limited (provided they can not lead to the release of the radioactive products); spalling of concrete inside of structure is not admitted; any requerement concerning the maintain of a tight of the inside layer is not applied. Strength limits of concrete and reinforcement materials are taken according to the Standard [18], i.e. they are increased as for explosions.

Dynamic analysis of structure shall be carried out to generate in-structure response spectra.

5. TORNADO

Except requirement of Standart [1] to take tornado into account there are no other regulations concerning this subject. Analysis methodologies published in technical literature (e.g., [20]) are used nowadays.

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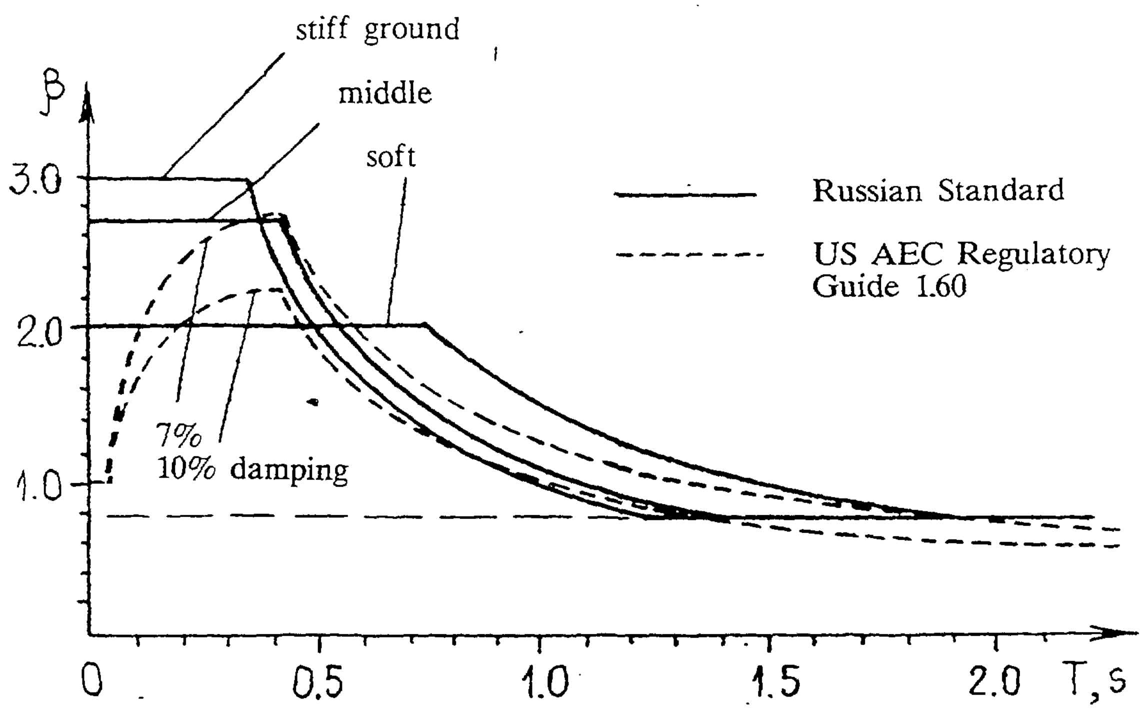

Fig.1

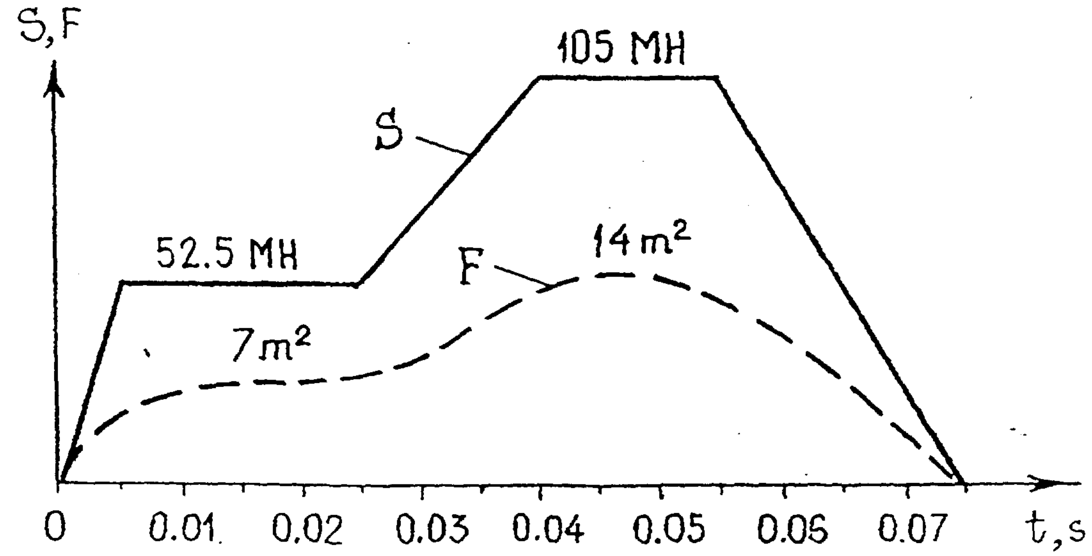

Fig.2

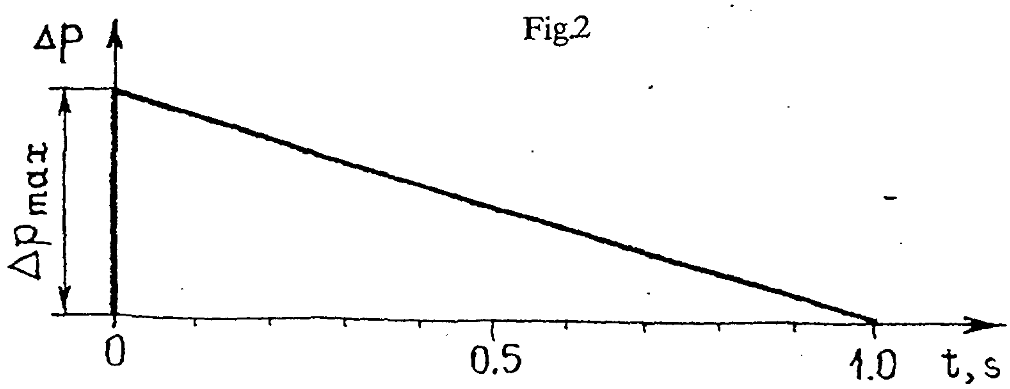

Fig.3