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# APPLICATION PECULIARITIES OF THE SMA METHOD IN THE ESTIMATION OF NPP STRUCTURES, SYSTEMS AND ELEMENTS BY MEANS OF COMPUTATIONAL COMPLEXES

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*Within the framework of the implementation of Measure 18101 "Seismic Resistance of Systems and Building Structures" of the "Complex (Consolidated) Safety Upgrade Program" for NPP Power Units of the SE NNEGC Energoatom, a number of report documents were developed with the results of calculations of seismic resistance according to the approaches in NP 306.2.208-2016 "Requirements for seismic design and safety assessment of nuclear power plant units", PNAE G-7-002-86 "Standards for Calculating the Strength of Equipment and Pipelines of Nuclear Power Plants" and the HCLPF (High Confidence Low Probability of Failure) seismic margin value according to the approaches in the "Methods of the Design Calculation of the Seismic Resistance of Components of Operating NPPs within the seismic margin assessment (SMA) method MT-T.0.03.326-13". In accordance with the basic requirements of the SMA method, the determination of the HCLPF value was made on the basis of the stress-strain state (SSS) analysis for the zone with the maximum value of the seismic stress component ($\sigma_S$). However, in the framework of the state nuclear and radiation safety examinations of report documents of the SE NNEGC Energoatom, a number of calculation cases were detected where the above SMA method approach yielded insufficiently conservative HCLPF calculation results. It is currently relevant to determine the representative cross-sections of the design model of the elements for which the HCLPF value should be specified. This paper considers the example-based design case that demonstrated the insufficient conservatism of HCLPF calculation results in choosing a non-representative cross-section. Also considered are aspects of performing the analysis of the seismic margin resistance of NPP systems and elements with using specialized tools of modern computational complexes to eliminate errors in determining representative cross-sections.*

***Keywords:*** *seismic resistance, seismic margin resistance, seismic margin factor, stresses, representative cross-section.*

## Introduction

The HCLPF parameter is a characteristic of the seismic margin resistance of a structure, pipeline, or equipment related to the peak value of earthquake acceleration at the ground level. In the probabilistic sense, the HCLPF value is defined as the 95% confidence that the element failure will occur in less than 5% of cases. The determination of the integral HCLPF value of systems and elements is primarily caused by the necessity to further use this parameter in performing the probabilistic seismic hazard analysis (PSHA) of Ukrainian NPPs.

In the general case, the assessment of the seismic margin resistance of NPP systems and elements by calculation methods is performed in the following sequence:

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– a finite element model is developed;

– a modal analysis is performed;

– the seismic strength is determined in accordance with the requirements of NP 306.2.208-2016 [1];

– HCLPF parameter is determined in accordance with the requirements of the SMA method [2].

To calculate the seismic response of the element under study, depending on the results of modal analysis, the SMA method [2] regulates the choice of the calculation method. In this case, the vast majority of computational cases for NPP systems and elements (the first natural vibrational frequency in the range up to 20 Hz) are analyzed on the basis of the linear spectral method (LSM), which is based on the assumption that the elements under analysis work in the linear-elastic domain. In order to reduce some conservatism in the above approach (failure to consider the elastic-plastic model of structural behavior), it is customary that an additional dimensionless coefficient of inelastic energy absorption $F_\mu$ be used in the SMA method [2].

In practical calculations, to determine the HCLPF value, the factor of safety (FS) is used, which reflects how many times the intensity of the seismic impact on the ground must be increased in order to reach the acceptable value of the parameter being evaluated

$$FS = \frac{C - D_{NS}}{\left(D_S^2 + D_{SAM}^2\right)^{\frac{1}{2}} + \delta C_S}, \tag{1}$$

where $C$ are values of the admissible parameter (for example, admissible stresses for the calculated case of seismic effects according to PNAE G-7-002-86 [3], which are taken to be 1.8[σ], MPa); $D_{NS}$ is the component of all non-seismic loads that is included in the parameter which is being evaluated for the combination of loads under consideration (for example, this value may be $\sigma_2$ – the calculated stress from the NO mode (normal operation mode), MPa); $D_S$ is the component of seismic inertial loads (during calculations according to the PNAE G-7-002-86 approaches [3] this value is $\sigma_s$ – the calculated stress from the action of the maximum design earthquake (MDE)), MPa); $D_{SAM}$ is the component of seismic displacement of supports (not applied in most cases); $\delta C_S$ is the admissible parameter reduction due to seismic loading (not applied in most cases).

Considering the above, when using the PNAE G-7-002-86 [3] approaches to calculate the FS for equipment and pipelines under pressure, formula (1) of the SMA method [2] takes the form

$$FS = \frac{\left(1.8\,[\sigma] - \sigma_2\right)}{\left(\sigma_S\right)}. \tag{2}$$

The final HCLPF value is determined by taking into account the inelastic energy absorption coefficient ($F_\mu$) by the formula

$$HCLPF = FS \cdot F_\mu \cdot PGA_{MP3}, \tag{3}$$

where $PGA_{MP3}$ is the peak acceleration of the soil, or so called acceleration of the zero period on the soil at the MDE, g.

As a rule, calculations of the seismic resistance of systems and elements of Ukrainian NPPs are performed using the following structural analysis software: ANSYS; ASTRA-NPP, LIRA, dPipe, APM WinMachine. All of them are included in the list [6] of the calculation codes authorized by the SE NNEGC "Energoatom" to substantiate the safety of nuclear installations.

## Problem Formulation

Based on the need for a sustainable and systematic improvement of the quality of calculations in the field of nuclear and radiation safety, as well as the rapid development of the capacity of structural platforms for structural engineering analysis and geometric editors of 3D simulation, the vast majority of works presented in the assessment of the seismic resistance of computational models of complex-geometry systems and systems of NPPs (piping systems, valves, filters, heat exchangers, air ducts, cable structures, etc.) are simulated combinations of 3D, rod, solid, or plate elements.

In accordance with the main SMA method requirements [2], the determination of the HCLPF value is made on the basis of the SSS analysis for the zone with the maximum contribution value of the seismic stress component ($\sigma_S$). However, on the basis of many years of experience in carrying out expert verification calculations of the seismic resistance of NPP systems and components within the framework of state nuclear and radiation safety (NRS) examinations, there have been identified a number of calculation cases where the above-mentioned SMA method [2] to determine FS (see formula (2)) did not provide a sufficient level of conservatism.

In view of the above, the problem of the correct selection of the representative cross-sections of the calculation models for determining the HCLPF value with using formulas (2)–(3) becomes an actual subject to be analyzed.

## Development of a Finite Element Model

As an example, consider the design justification for the seismic resistance of U 26362-032 shut-off valves (SOV) (see Fig. 1), which is given in the SS KhNPP report [5]. The report [5] underwent the state NRS examination at the SSTC NRS [6] and was updated by the SS KhNPP with taking into account the identified shortcomings regarding the correct determination of the HCLPF value.

The U 26362-032 SOVs understudy are the same type of equipment manufactured at one factory with the only difference being in the tracing of connected pipelines. Therefore, according to the analysis results of the calculations of the pipeline systems with U 26362-032 SOVs, a type representative (operational marking 1TQ30S05) was selected for further seismic resistance assessment. To correctly take into account the operation of the pipeline-actuator system, the design model is built according to a combined approach: pipelines are simulated as rod elements, valves are taken into account by the connected masses, and the subject of the analysis, the 1TQ30S05 SOV, is modeled as a 3D model. The investigated finite element (FE) model is simulated from 58,582 elements, and has 74,109 grid nodes with sizes from 10 to 300 mm. The density of the FE grid for combined 3D models, as evidenced by the practice of performing expert verification calculations of Ukrainian NPP pipelines, allows us to determine the stress extrema for further analysis fairly accurately.

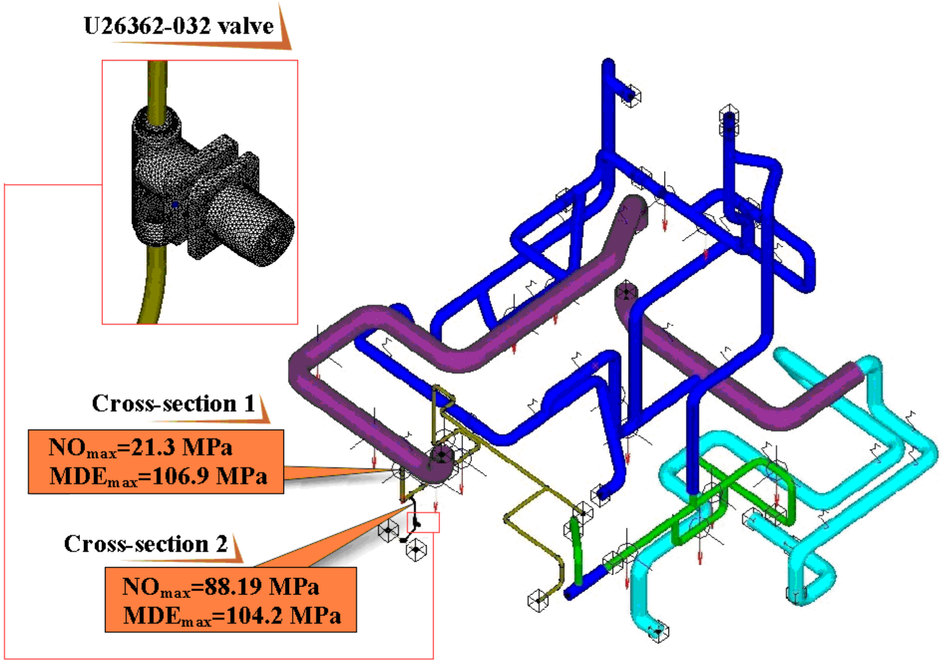

*Fig. 1. The design model from report [5] for the estimation of the seismic margin resistance of the U 26362-032 (1TQ30S05) SOV and the pipelines where it is installed*

The boundary conditions of anchorages are modeled according to design drawings:

– fixed supports are modeled with a rigid pinching of pipeline ends;

– guide supports are modeled with the prohibition of movements in the plane of the pipeline cross-section and permission of movements along the pipeline;

– sliding supports are modeled with the prohibition of movements in the vertical plane and permission of movements in the horizontal plane.

Limiting loading conditions are the following:

– internal pressure;

– pipeline load due to the weight of the environment, taken into account through the combined specific gravity of the pipeline, which includes both the pipeline's own weight and the weight of the internal environment.

The calculations were made by the SS KhNPP with using the APM WinMachine software.

According to the SSTC NRS recommendations and in order to adhere to the conservative approach, which is to determine the minimum value of the minimum seismic margin resistance of the structure as a whole (for the most loaded area without taking into account the approach to differentiating stress extrema during the formation of combinations of loads from dead weight effects), during the determination of the HCLPF value, in addition to the standard approach of the SMA method [2], the SS KhNPP additionally verified the condition

$$FS = \min\left\{\frac{\left(1.8\,[\sigma]-\sigma_2^{*}\right)}{\left(\sigma_S^{\max}\right)};\quad \frac{\left(1.8\,[\sigma]-\sigma_2^{\max}\right)}{\left(\sigma_S^{**}\right)}\right\}, \tag{4}$$

where $\sigma_2^{*}$ is the stress from the NO mode, defined in the same cross-section where the extremum of stresses from seismic loads of the MDE is localized; $\sigma_s^{**}$ is the stress from the MDE mode, defined in the same cross-section where the extremum of stresses from the MDE mode is localized.

In the case where the seismic resistance of the valves in the pipeline-valves system is analyzed, the FS according to the SMA method requirements [2] for the system can be set according to the weakest link principle as the minimum value obtained for all the elements of the system.

## Analysis of Numerical Calculation Results

The results of the assessment of seismic margin resistance are shown in the table below, and the location of representative cross-sections is shown in Fig. 1.

***The results of the assessment of the seismic margin resistance of a U 26362-032 SOV with a pipeline attached in accordance with the report [5]***

| Cross-section under study | $\sigma_2$, MPa | $\sigma_s$, MPa | Admissible stress 1.8[σ], MPa | Seismic safety factor, FS | $F_\mu$ | HCLPF |
|---|---|---|---|---|---|---|
| Pipeline. Cross-section 1 | 21.30 | 106.9 | 235.26 | 2.00 | 1.5 | 0.30 |
| Pipeline. Cross-section 2 | 88.19 | 104.2 | 235.26 | 1.41 | 1.5 | 0.21 |
| Valve body | 5.70 | 6.2 | 223.20 | 35.08 | 2.0 | 7.01 |

The calculation case considered demonstrates a 30% difference in HCLPF values for those cases where formulas (2) and (4) are used for determining FS. Thus, in some cases, the use of formula (2) leads to insufficiently conservative results. This is primarily due to the fact that the seismic component as the denominator of formula (2) has a significant effect on the HCLPF result.

An additional verification according to formula (4) is recommended to be performed if the following situations are observed in the analysis results of the SSS received:

– there is a significant difference in the numerical values of the obtained extrema in the NO and MDE modes (for example, $NO_{max}$=170 MPa, $MDE_{max}$=3 MPa.);

– there is homogeneity in the nature of the picture of stress distribution in the regions where the extrema of the NO and MDE modes are localized (see the example above).

It should be noted that such calculation cases are not common. The experience of performing state NRS examinations demonstrates that in almost all cases the SMA method requirements [2] yield correct and conservative results of calculating HCLPF values.

It should be noted that the toolkit of most modern computing platforms also includes means of graphical visualization of isopoles of any magnitude by users' creating their own result values. Consequently, in the post-processing calculation complex module, the user generates variables (operators) for which corresponding result values are assigned (in our case, the stress result matrices for each node of the von Mises FE model for the NO and MDE modes). Next, a variable is created that manages these calculation results according to a user-defined formula (for example, in the ANSYS software package such a tool is the "User defined result" function). Fig. 2 below shows an example of visualization of HCLPF parameter distribution isopoles.

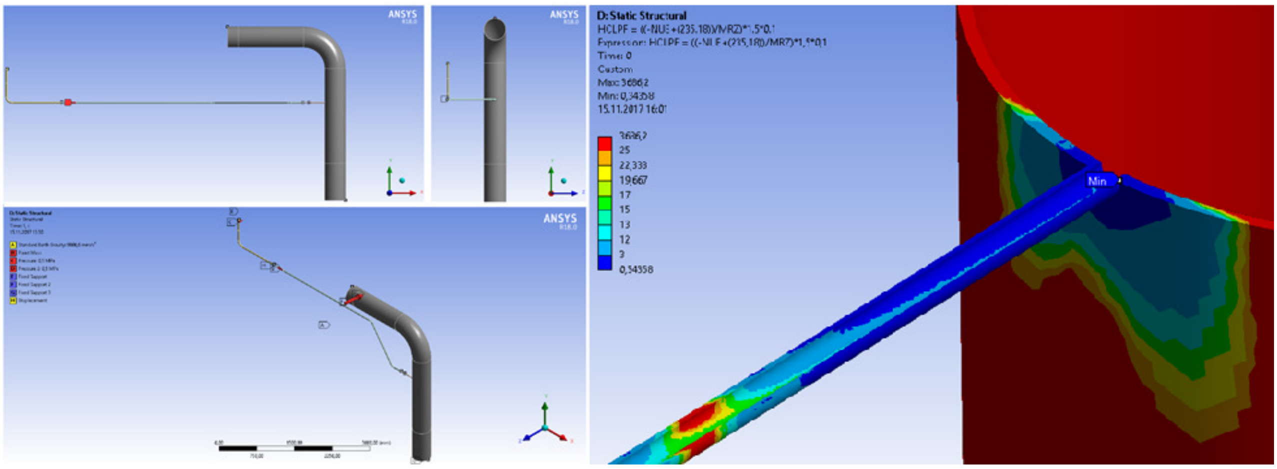

*Fig. 2. Pipeline models (from the SSTC NRS report [7]) of the TQ33B01 tank connection to the TQ33S27 SOV (incl.), overflow of the TQ33B01 tank of Unit 4 of SS RNPP, visualization of the HCLPF parameter distribution isopoles in the most loaded area*

The application of the above methods of using custom, user-created values in processing the obtained results of seismic strength is important precisely for the principle of adherence to the conservative approach. The biggest advantage of this approach is that the HCLPF value is calculated at the hardware level for each node of the FE model under study, which, in turn, makes it impossible for errors to be made in the selection of representative cross-sections in determining the HCLPF value (and does not require additional verification according to formula (4)).

## Conclusions

1. Many years of experience in conducting expert verification calculations make it possible to state that in some cases the SMA method requirements [2] do not provide a sufficient level of conservatism of HCLPF calculation results. However, such calculation cases are not common. It is advisable to perform additional verification according to formula (4) if the following conditions are met:

– there is a significant difference in the numerical values of the obtained extrema in the NO and MDE modes;

– there is homogeneity in the nature of the MDE stress distribution isopols in the regions where the extrema of the NO and MDE modes are localized.

Modern computational complexes allow us to avoid errors in selecting representative cross-sections, which is realized by the SSTC NRS in performing expert verification calculations of the seismic margin resistance.

2. The use of the approaches described in this article will increase the representativeness of PSHA results by more accurately determining the seismic margin resistance of elements.

3. Among the prospects for further research in the direction of a more accurate determination of the HCLPF value, we should single out the following topical issues:

– correct simplification of large-scale models of pipelines with a small number of fixed supports (among the SMA method requirements is the need to construct the pipeline segment under study to the nearest fixed support);

– displacement of the center of mass of valve actuators in the context of its influence on the response of the general design;

– study of the dependence of the SSS of tanks on seismic effects.

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# Особливості застосування методу граничної сейсмостійкості при оцінці конструкцій, систем та елементів атомних електростанцій за допомогою розрахункових комплексів

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*У межах виконання заходу 18101 «Забезпечення сейсмостійкості систем та будівельних конструкцій» «Комплексної (зведеної) програми підвищення рівня безпеки енергоблоків атомних електростанцій» для енергоблоків АЕС України ДП НАЕК «Енергоатом» було розроблено низку звітних документів з результатами розрахунків сейсмостійкості згідно з підходами НП 306.2.208-2016 «Вимоги до сейсмостійкого проектування та оцінки сейсмічної безпеки енергоблоків атомних станцій», «ПНАЭ Г-7-002-86. Нормы расчета на прочность оборудования и трубопроводов атомных энергетических установок» та граничної сейсмостійкості (HCLPF) згідно з підходами «Методики расчетного анализа сейсмостойкости элементов действующих АЭС в рамках метода граничной сейсмостойкости. МТ-Т.0.03.326-13» (надалі – Методика МГС). Відповідно до основних положень Методики МГС визначення показника граничної сейсмостійкості HCLPF (High Confidence Low Probability of Failure – висока достовірність низької імовірності відмови) прийнято виконувати на основі аналізу напружено-деформованого стану елемента для зони з максимальним значенням сейсмічної складової напружень ($\sigma_S$). Проте в рамках виконання державних експертиз з ядерної та радіаційної безпеки звітних документів ДП НАЕК «Енергоатом» було виявлено низку розрахункових випадків, коли вищезазначений підхід Методики МГС давав недостатньо консервативні результати розрахунків HCLPF. На цей час актуальним є визначення репрезентативних перерізів розрахункової моделі елементів, для яких має бути встановлений показник HCLPF. В статті на відповідному прикладі розглянутий розрахунковий випадок, який продемонстрував недостатній консерватизм результатів розрахунків HCLPF в разі обрання нерепрезентативного перерізу. Також розглянуті аспекти проведення аналізу граничної сейсмостійкості систем та елементів АЕС з використанням спеціалізованих інструментів сучасних розрахункових комплексів для уникнення помилок при визначенні репрезентативних перерізів.*

***Ключові слова**: сейсмостійкість, гранична сейсмостійкість, коефіцієнт сейсмічного запасу, напруження, репрезентативний переріз.*

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# USE OF IN-HOUSE DESIGN MODULES WHEN CHOOSING BEARING ASSEMBLIES FOR PUMPS BEING DESIGNED

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*Among the main components that largely affect the operational reliability of centrifugal pumps are bearing assemblies. Based both on the generalization of theoretical data and practical skills in selecting bearings, specialists of JSC VNIIAEN developed basic design modules, in which a general approach to the selection and analysis of the performance of bearing assemblies is laid. These design modules can work either as separate units or as part of an integrated module that allows us to calculate the thermal balance of the bearing assembly system with taking into account a number of factors, such as lubrication conditions, cooling methods, mandatory verification of the recommended design features of both individual system elements and basic critical performance indicators of a bearing. Functional cause-effect relationships of the module can help better understand the problems that arise during the operation of bearings. This paper discusses JSC VNIIAEN's in-house design modules for selecting pump bearing assemblies, and proposes a new method for designing bearing assemblies, with the method based on the integrated use of individual modules represented as an integrated module in the form of a computer-aided design (CAD) system. The flexibility of the methodology used allows us to supplement and improve the developed design modules included in the integrated module in the form of a CAD system by using the results of scientific research, feedback from operational locations, and constant monitoring of various information sources.*

***Keywords:*** *rolling bearings, sliding bearings, design modules, lubrication, cooling, performance, thermal balance of the system.*

## Introduction

For more than 50 years, JSC VNIIAEN has been creating high-quality pumping equipment (almost 800 types of pumps). This equipment is successfully used in many large nuclear and thermal energy complexes; oil, chemical, sugar and food industry facilities; water supply and irrigation facilities; construction and mining works; metro systems; agloblast-furnace and steel production; livestock complexes; public infrastructure, etc.

The durability and efficiency of a pump depends to a large extent on the correctly selected and well-elaborated design of bearing assemblies.

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