ON THE SCOPE OF COMPUTATIONAL-AND-EXPERIMENTAL EVALUATION OF THE SEISMIC ADEQUACY OF NPP EQUIPMENT

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Translated from *Élektricheskie Stantsii*, No. 1, January 2014, pp. 21 – 26.

Relevant regulations require computational-and-experimental evaluation of the seismic adequacy of systems and equipment of each NPP unit, including the experimental study of the dynamic behavior of several thousand items of equipment in actual condition. Possible options for reducing the scope of equipment subject to visual checks, dynamic testing, and computational seismic adequacy analysis are examined. Procedures for optimizing the scope of the computational-and-experimental analysis of seismic adequacy are proposed.

Keywords: seismic adequacy; NPP equipment; dynamic response characteristics; resonances; natural frequencies; damping decrements.

The linear spectral method is required in [1] to be used for the computational analysis of the seismic adequacy of systems and components (equipment) of nuclear power plants (NPPs). If the first natural frequency of vibration is higher than 20 Hz, it is allowed to use a simpler static method that employs empirical coefficients to reduce seismic loads to a static load. The accelerations determined from the response spectrum with the static method are multiplied by a coefficient of 1.3 for frequencies of 20 – 33 Hz and by a coefficient of 1.0 for frequencies higher than 33 Hz [1]. The statistics collected at numerous NPP units indicates that the fundamental natural frequency of about 54% of the equipment is lower than 20 Hz (Fig. 1). Its seismic adequacy should be analyzed with the linear spectral method.

The linear spectral method represents the seismic load on equipment as an acceleration-frequency curve (floor response spectrum of a building, given a ground accelerogram). The seismic load on equipment is also described indicating the floor elevation of equipment in NPP buildings and damping ratio (decrement). Thus, the estimated seismic load on equipment directly depends on its dynamic response determined by installation, anchorage, and piping and other factors.

Purely computational methods (where no additional experimental data are used) allow for the effect of installation, anchorage, and piping on the dynamic behavior and seismic resistance of an item of equipment by prescribing boundary conditions based on available design data. However, installation operations inevitably cause design deviations associated with tolerances (routing deviations, plays in support structures, replacements of support members, etc.) and performance standards. Therefore, the design modeling of NPP systems and components is not highly reliable, which often leads to significant, including intolerable errors in the computed dynamic response and seismic adequacy of equipment, even with very detailed boundary conditions for the design models.

Numerous full-scale seismic studies of safety significant systems and equipment performed with our computational-and-experiments method [2 – 4] in actual installation, anchorage, and piping conditions have discovered significant differences between experimental dynamic responses of absolutely identical items of equipment (even located at the

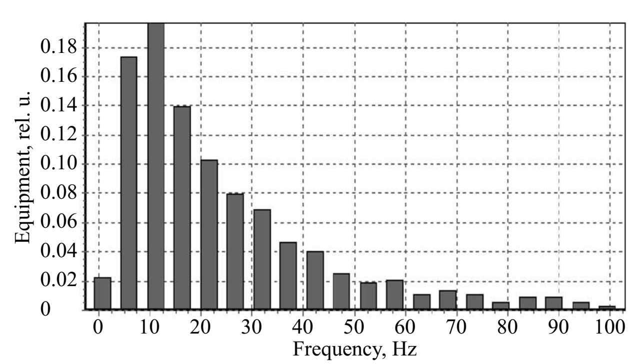

Fig. 1. Distribution of natural frequencies over all directions in the range from 0 to 100 Hz: the ordinate axis indicates the ratio of the number of equipment items with given natural frequency to the total number of inspected equipment items in relative units.

[1] JSC "Atomtehenergo," Russia.

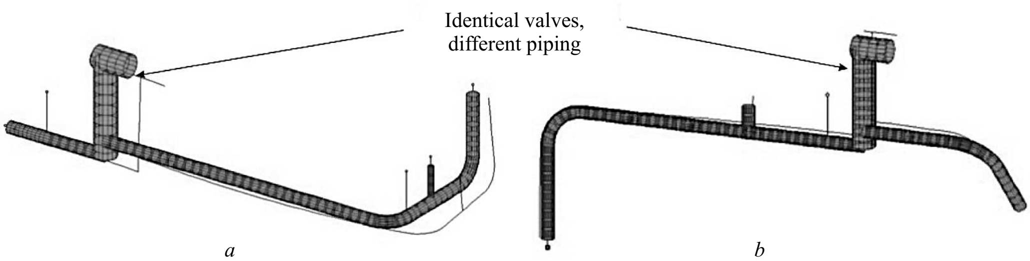

Fig. 2. Design models of identical, but differently connected valves: *a*, first vibration mode at 4.8 Hz; *b*, first vibration mode at 7.5 Hz.

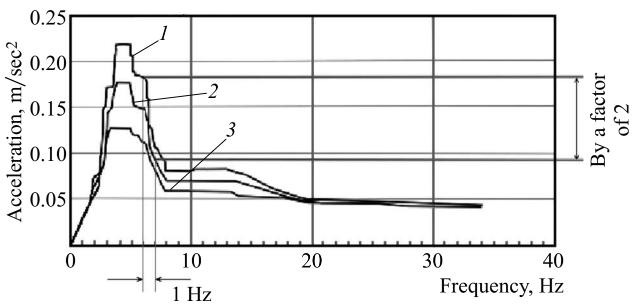

Fig. 3. Floor response spectrum for the standby diesel power plant building at –4.2 m elevation: *1*, *2*, *3* — damping decrements 2, 3, 5%.

same elevation of the same NPP unit) and, consequently, differences between their seismic adequacy [5].

For example, the fundamental frequencies of two absolutely identical, but differently connected bellows-operated check valves of the bypass primary water treatment system determined during a computational-and-experimental evaluation of their seismic adequacy at Unit 4 of the Kalininskaya NPP are 4.8 and 7.5 Hz (Fig. 2).

Since seismic loads exhibit strongly pronounced resonant behavior, design loads on equipment may differ by one to two orders of magnitude, depending on its dynamic response. Figure 3 shows a floor response spectrum of equipment. It can be seen that as the frequency of the seismic load changes by as little as 1.0 Hz, the load on equipment may double.

Moreover, even absolutely identical equipment with identical dynamic response characteristics installed at units of the same series designed for different NPP sites may take up different seismic loads. Figure 4 shows two floor response spectra for VVER-1000 units of two different NPPs (Unit 4 of Kalininskaya NPP and Unit 2 of Rostov NPP) at the elevation of the fuel storage tank of the standby diesel power plant (SDPP) for the same damping decrement. As is seen, for the same natural frequency of the tank (7.2 Hz), the seismic load at the Rostov NPP is higher by a factor of 2.5 than at the Kalininskaya NPP. It should be noted that, despite the differences between response spectra, the design solutions regarding the anchorage and piping of the fuel storage tank are absolutely identical for both NPPs.

In design evaluation of seismic adequacy, the seismic loads on NPP systems and equipment are often derived from conservative generalized response spectra resulting from an analysis of numerous response spectra for various NPP units. However, the response spectra proposed in [1] in 1986 and other generalized response spectra used in equipment design have currently become irrelevant due to the accumulation of a great amount of new data for new NPP units and the intensive development of instrumental and software capabilities of structural design. There is evidence that the accelerations in response spectra calculated for a real NPP with allowance for the site location are much (by 20 – 30%) higher than the accelerations in widely used generalized spectra.

However, the design evaluation of seismic adequacy is necessary to avoid basic errors at the stages of design and manufacture of new equipment, process systems and pipelines, and their support structures.

All the foregoing discussion confirms the need for the experimental study of the dynamic response of safety significant equipment followed by computational analysis of its seismic adequacy, as required by the regulations NP-064–05 [6] and MT 1.2.2.04.0069–2012 [7] formulated by Atomtehenergo and put into effect by Rosenergoatom [4, 8]. The analysis should be based on data (response spectra) on seismic loads on equipment of each NPP unit.

The computational-and-experimental verification of the seismic adequacy of equipment includes:

— listing of items of equipment to be inspected;

— checking the equipment against the installation and design requirements;

— experimental determination of the dynamic response of the equipment in actual installation, anchorage, and piping conditions;

— determination of the seismic loads on the equipment from the available response spectra for buildings and structures of a specific NPP unit;

— analysis of the design-basis seismic loads on the equipment;

— selection of seismic adequacy criteria for the equipment;

— computational verification of the seismic adequacy of typical equipment representatives of its type (refinement of design) based on dynamic test data;

— formulation of recommendations on providing seismic adequacy of seismically unfit items of equipment.

The required input data for computations include dynamic test data, design drawings, and structural layout of equipment and response spectra for the buildings that house the equipment.

After the analysis of input data, equipment is modeled (or available models are improved) using beam or shell finite-elements with distributed mass. New models incorporate the actual installation, anchorage, and piping conditions for equipment. Prior to the computations, the models are refined using dynamic test data, which makes it possible to correct the magnitudes of seismic loads on equipment. After the computations, the seismic adequacy criteria are tested. The basic criteria are the strength of pipelines at critical points, the strength of the attachment of equipment to pipelines and supports, the strength of support structures, etc.

Accomplishing all the above tasks for all items of safety significant equipment of an NPP unit is a challenge. Each NPP unit commonly includes two to three thousand items of equipment of seismic category I that should be analyzed for seismic adequacy. This necessitates the optimization (minimization) of the list of equipment to be inspected and the scope of computational-and-experimental evaluation of seismic adequacy.

The computational-and-experimental analysis of the seismic adequacy of equipment of Russian NPPs may be restricted to the equipment of seismic category I, which must be verified to withstand a maximum credible earthquake (intensity 7 on the MSK-64 scale for all Russian NPPs, as per the standard [6]). The equipment of seismic category II of Russian NPPs must be verified to withstand a design-basis earthquake (intensity 6 on the MSK-64 scale). For Russian-design NPPs constructed in seismic areas abroad (India, Egypt, Iran, Bulgaria, etc.), it is necessary to verify the seismic adequacy of equipment of both seismic categories using the computational-and-experimental method.

Nowadays, lists of equipment for computational-and-experimental evaluation of seismic adequacy are compiled based on lists of objects, seismic categories, and safety groups provided by the design organization or NPP. The following is usually excluded from the lists:

— auxiliary small-sized equipment (manometers, transducers, etc.) that does not affect the dynamic behavior of analyzed systems because its dynamic response characteristics fall beyond the range of seismic resonances;

— auxiliary small-sized manually driven valves that do not affect the dynamic behavior of analyzed systems because of their light local weight (the center of mass is on the pipeline axis) and absence of projectings;

— large-sized equipment (reactor vessel, emergency core cooling system tanks, steam generators, etc.) whose seismic adequacy is analyzed at the design stage in combination with building structures because this equipment is included in design models of buildings and all possible loads are overestimated, to be on the safe side;

— autonomous electrical equipment (without external connections affecting its dynamic behavior) whose seismic adequacy was studied in vitro on shaking tables or with the computational-and-experimental method closely simulating the real installation and anchorage conditions.

A statistical analysis of the dynamic response of examined equipment does not allow identifying types of equipment that need not to be subjected to dynamic testing. This is because practically all types of equipment include items whose natural frequencies and damping decrements fall within the seismic resonance range; i.e., the currently available experimental data do not allow the reliable determination of the dynamic response of equipment without its testing.

As an example, we have analyzed 180 items of equipment with experimentally determined fundamental natural frequencies of higher than 20 Hz at two VVÉR-1000 units of the same series (Rostov NPP Unit 2 and Kalininskaya NPP Unit 4). The following parameters have been analyzed: type of equipment, system, type of support structures, weight, dimensions, etc. The analysis shows that only items of equipment with absolutely identical parameters have close dynamic response characteristics (frequencies and decrements). This is usually equipment of the same type and manufacturer anchored in an identical manner and having slightly different weight and dimensions. Thus, tests may not be conducted only in those rare cases where absolutely identical (same type and manufacturer) equipment with the same anchorage was earlier tested at other NPP units. In this case, it is necessary to check whether the installation and anchorage comply with the design requirements.

The analysis has revealed the following items of identical equipment of the different units that has similar natural frequencies and damping decrements in a frequency range to higher than 20 Hz and may no longer be tested: spray pumps and emergency boron injection pumps, VDNA-nzh-15s fans, hermetically sealed valves of the ventilation system, ECCS intermediate circuit pumps, SDPP water, oil, and fuel pumps, fire water pumps, main steam isolation valves (MSIV), and plate heat exchangers installed directly on the concrete foundation without intermediate supports.

In addition to the optimization (minimization) of the full list of equipment subject to computational-and-experimental seismic verification, it is also necessary to compile a list of equipment (and to select equipment representatives) whose seismic adequacy should be verified based on dynamic test data and will guarantee the seismic adequacy of all the equipment on the full list.

In the case of identical equipment with similar anchorage and piping, selecting equipment representatives is not difficult. It is sufficient to choose an item of equipment that showed the worst response in dynamic testing and has the seismically worst position in NPP buildings. Such equipment may include in-line valves, pumps, fans, plate heat exchangers, self-contained air conditioners, tanks, etc.

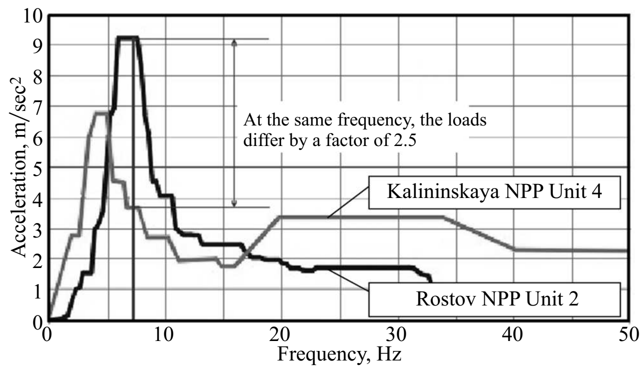

Fig. 4. Floor response spectra at the elevation of the SDPP fuel storage tank at NPP units of the same series at different NPP sites.

It is most difficult to select equipment representatives for the analysis of the seismic adequacy of equipment that is of the same type but is differently anchored and connected. For example, the dynamic response characteristics of in-line valves and, hence, the seismic loads on them depend primarily on the configuration and securing of the connected pipelines. The same is true of equipment on intermediate supporting metalwork, pipeline sections, heat exchangers mechanically coupled with auxiliary equipment and pipelines, etc. There were cases where the configuration and securing of connected pipelines were different for 30 and more items of absolutely identical equipment. Consequently, the spread of experimental fundamental natural frequencies of such equipment covered the entire seismic resonance range in the response spectra. Currently, equipment representatives are selected based on data of dynamic tests and the experience of computing engineers.

To simplify the selection of equipment representatives for seismic adequacy analysis based on dynamic tests data, it is necessary to develop objective mathematical criteria for selecting one or several representatives from a group of identical items of equipment with different anchorage and piping.

An analysis of numerous response spectra for various NPP units confirms that if the fundamental natural frequency of equipment is higher than 20 Hz, then the seismic load weakly depends on its dynamic response (Fig. 3).

Selecting representatives from a group of identical equipment is not necessary when:

— the fundamental natural frequency of all representatives in the group of identical items of equipment with different anchorage and piping is higher than 20 Hz, because the dynamic response has a weak effect on the seismic load;

— the fundamental frequency of only one item in the group is lower than 20 Hz, because this outlier should be analyzed with the linear spectral method.

To improve and optimize the computational-and-experimental evaluation of the seismic adequacy of NPP units, we have developed an electronic database intended for seismic qualification of identical equipment at uninspected and new NPP units. The database contains universal qualification cards of examined items of equipment, including the full set of parameters (type of equipment, geometry, type of supports, anchorage, dynamic test data, computed data, etc.).

The database will make it possible to reduce the scope of computational-and-experimental verification of seismic adequacy by screening out the earlier qualified identical equipment included in the database at various stages.

This is by no means about establishing similarity to tested and qualified equipment, as proposed in foreign seismic qualification procedures based on the generic implementation procedure (GIP) because this approach does not seem to be justified.

Dynamic testing of all items of equipment of seismic category I on the full list (about two to three thousand items) usually lasts approximately eight weeks, plus three to four weeks to process and interpret the test data (determine the natural frequencies and damping decrements). The necessary seismic analysis of usually chosen 200 to 300 equipment representatives is carried out for six to eight months. Thus, the complete computational-and-experimental seismic evaluation of systems and equipment of one NPP unit requires about a year.

CONCLUSIONS

To considerably reduce the scope and duration (to six to eight months per one NPP unit) of seismic evaluation, it is proposed to

— compile full lists of equipment of seismic category I for Russian NPPs and equipment of categories I and II for Russian-design NPPs constructed abroad;

— perform walkdowns and visual checks of equipment on the full list to verify its compliance to the installation and anchorage design requirements;

— based on these walkdowns and visual checks, compile lists of equipment to be tested in real anchorage and piping conditions (at this stage, it is possible to screen out earlier tested and seismically qualified identical equipment included in the electronic database);

— based on the test data, compile lists of equipment for the final verification analysis (at this stage, it is also possible to screen out equipment that is designed for higher seismic loads and included in the electronic database).

REFERENCES

1. *PNAÉ G-7-002–86. Regulations for Strength Analysis of Equipment and Pipings of Nuclear Power Plants* [in Russian], Énergoatomizdat, Moscow (1989).
2. A. N. Anan’ev, P. S. Kaznovsky, S. P. Kaznovsky, V. I. Lebedev, and Kh. D. Chechenov, *Seismic Safety of Nuclear Power Plants* [in Russian], Izd. MGTU im N. E. Baumana, Moscow (2011).
3. RF Patent No. 2284553, S. P. Kaznovsky, P. S. Kaznovsky, V. F. Mishchenkov, and V. V. Piskarev, “A method for verification of the seismic adequacy of a multicomponent system,” *Byull. Izobret.*, No. 27 (2006).

4. A. P. Kaznovsky, P. S. Kaznovsky, S. I. Ryasnyj, and E. S. Saakov, "Confirmation of the seismic resistance of nuclear power plant equipment after assembly," *Power Tech. Eng.*, **47**(1), 42 – 46 (2013).
5. A. P. Kaznovsky, P. S. Kaznovsky, K. G. Kas'yanov, and S. I. Ryasnyi, "Verification of the seismic adequacy of the process equipment of Kalininskaya NPPs Unit 4 by dynamic testing," in: *Abstrs. of 2nd Int. Sci.-Tech. Conf. on NPP Commissioning* [in Russian], Izd. Atomtehenergo, Moscow (2012).
6. "NP-064–05. Allowing for natural and man-made impacts on nuclear facilities," *Yadern. Radiats. Bezopasn.*, No. 3(40), 47 – 87 (2006).
7. *MT 1.2.2.04.0069–2012. A Method for Verification of the Dynamic Response Characteristics of Systems and Components of Safety-Significant NPP Units* [in Russian], Izd. Rosenergoatom, Moscow (2012).
8. A. P. Kaznovsky, P. S. Kaznovsky, S. I. Ryasnyi, and E. S. Saakov, "Seismic regulations for safety-significant systems and components of NPP units," *Élektr. Stantsii*, No. 9 (2012).