# Case Analysis of Seismic Evaluation of Existing Nuclear Facilities

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**Abstract.** Earthquake is one of the main external risk factors for nuclear power. Especially after the March 11 earthquake in Japan, the Fukushima nuclear power accident has attracted worldwide attention. The seismic margin of existing nuclear facilities in all countries has been evaluated. However, the seismic margin assessment is mainly aimed at the situation beyond the design basis. For some existing nuclear facilities, there are changes in the seismic fortification criterion. At this time, it is necessary to conduct seismic appraisal. For the seismic appraisal of civil buildings, countries all over the world have formed relatively perfect technical standards, but there is no mature and general method for the seismic appraisal of existing nuclear facilities. When seismic identification of existing nuclear facilities is carried out, simple calculations based solely on the original design method are unreasonable. There is a need to propose a reasonable specialized method for seismic identification. Through the seismic evaluation of an existing nuclear facility, this paper puts forward the key technical problems to be considered in the research of seismic evaluation method of existing nuclear facilities. It provides a reference for the establishment of seismic evaluation method of existing nuclear facilities.

**Keywords:** Existing nuclear facilities, Seismic appraisal, Seismic margin.

## 1 Introduction

At 14:46 (13:46 Beijing time) on March 11, 2011, a strong earthquake occurred in the Pacific Ocean in northeastern Japan, and the moment magnitude Mw of the earthquake reached 9.0 (U.S. geological The Bureau of Investigation data is Mw9.1). It is the fourth largest earthquake in history, after Valdivia, Chile (magnitude 9.5) in 1960, Prince William Sound, Alaska (magnitude 9.2) in 1964, and the Andreanoff Islands, Alaska (magnitude 9.1) in 1957. The epicenter was located in the Pacific Ocean east of Miyagi Prefecture, Japan, about 130 kilometers away from Sendai, with a focal depth of 20 kilometers. The huge tsunami triggered by the earthquake caused devastating damage to Iwate, Miyagi, and Fukushima prefectures in northeastern Japan, and triggered a nuclear leak at the Fukushima Daiichi Nuclear Power Plant.


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After the Fukushima nuclear accident in Japan, all countries have carried out seismic assessment of nuclear facilities. However, the seismic margin evaluation work is mainly aimed at the situation that exceeds the design basis ground motion[1]. For some existing nuclear facilities, there is a situation where the seismic fortification standard has changed. Currently, it is necessary to conduct seismic appraisal. However, there is no specific method for seismic appraisal of existing nuclear facilities.

Due to its particularity, the seismic calculation of nuclear power plants has been greatly improved compared with the standard of conventional civil buildings. According to the code for Seismic Design of civil buildings, the seismic design is summarized as three-level fortification goals and two-stage design.

Three-level seismic fortification:

(1)No destroy under minor earthquake (frequent earthquakes); the 50-year exceedance probability is 63% (that is, the probability of at least one occurrence in 50 years is 63%), which is equivalent to 1/50 of the annual probability of occurrence, which is equivalent to a return period of 50 years.

(2)Repairable under middle earthquake (fortified earthquakes); the 50-year exceedance probability is 10% (that is, the probability of at least one occurrence in 50 years is 10%), which is equivalent to 1/475 of the annual probability of occurrence, which is equivalent to a return period of 475 years.

(3)No collapse under major earthquake (rare earthquake); the 50-year exceedance probability is 2% to 3% (that is, the probability of at least one occurrence in 50 years is 2% to 3%), which is equivalent to 1/2400 to 1/1600 of the annual probability of occurrence, which is equivalent to a return period of 1600 to 2400 years.

Two-stage seismic design:

The first stage: Perform internal force and deformation analysis on most structures under the action of frequent earthquakes, assuming that the structure is in an elastic working state, and linear dynamic and static analysis methods can be used for internal force and deformation analysis.

The second stage: some structures (irregular and with obvious weak parts) specified by the code are subjected to elastoplastic deformation analysis under the action of rare earthquakes.

SSC in a nuclear power plant shall be divided into the following three categories according to their importance to nuclear safety:

Category I SSC: important SSC related to nuclear safety in nuclear power plants, including SSC that will directly or indirectly cause accidents after damage; SSC required to ensure the safe shutdown of the reactor and maintain the shutdown state and discharge waste heat; earthquakes SSC necessary to mitigate the consequences of nuclear accident damage during and after an earthquake, and other SSC that would jeopardize the aforementioned SSC if damaged or lost their function.

Category II SSC: SSC related to nuclear safety other than Category I SSC in a nuclear power plant, and SSC unrelated to nuclear safety that will endanger the above SSC after damage or loss of function.

Category III SSC: SSC in nuclear power plant that are not related to nuclear safety.

The operational safety seismic vibration used in nuclear power designed to refer to the seismic vibration with an annual exceedance probability of 2‰ in the design reference period, and its peak acceleration is not less than 0.075g. Usually it is the earthquake vibration that the nuclear power plant can operate normally.

The ultimate safety ground motion refers to the ground motion with an annual exceedance probability of 0.1‰ in the design reference period, and its peak acceleration is not less than 0.15g. It is usually the largest earthquake shaking that the nuclear power plant area may encounter, which is equivalent to a 50-year exceedance probability of 0.5%. Operational safety ground motion refers to the ground motion with an annual exceedance probability of 2‰ in the design reference period. In order to facilitate the comparison of building seismic design specifications, the exceedance probability is 9.5% in 50 years (the nuclear power design reference period is generally 40 years).

The "first stage" of the nuclear power plant seismic standard can be approximately equivalent to the first stage of the building seismic standard, but the exceedance probability is less than 1/6 of the building standard. The "second stage" of nuclear power plants has higher requirements than the third stage of building standards, which is not only the reduction of probability, but also the requirement of ensuring the integrity of pressure boundary.

Due to the high requirements of nuclear power equipment against earthquakes, in the initial design, it has brought great difficulties to the design and implementation with the increase of design ground motion. especially for existing nuclear facilities, new solutions must be explored.

In 1975, the US Nuclear Regulatory Commission's WASH-1400 research report was the world's first research report on exceeding benchmark events in nuclear power plants, and it was the earliest seismic margin assessment method (NRC-SMA). In 1988, the Electric Power Research Institute proposed the Conservative Deterministic Seismic Margin Assessment Method (EPRI-SMA) as an option for the U.S. Nuclear Regulatory Commission's Seismic Margin Program. In 1993, the US Nuclear Regulatory Commission proposed a combination of probabilistic risk assessment and seismic margin assessment (PRA-Based SMA). The research on the seismic margin of nuclear power plants in China started late and is still in the stage of digestion and absorption. Few scholars or nuclear management departments have conducted comprehensive and systematic research on the seismic margin assessment of active nuclear power plants, and most of their published papers focus on assessing the seismic margin of different systems or components of nuclear power plants using existing methods in the United States.

The seismic margin evaluation method is aimed at the evaluation in the case of exceeding the design basis. For the seismic identification under the design basis, there is currently no mature method in the world, and it is usually carried out according to the design method. However, this method has obvious shortcomings and cannot meet the special circumstances of seismic identification of existing nuclear facilities. Through the seismic analysis of existing nuclear facilities, the key links and elements of seismic identification can be identified, and the potential that can be tapped in each link can be found, which will help to establish a reasonable and feasible seismic identification method for existing nuclear facilities.

## 2 Project Overview

A nuclear facility plant was built in 2011 and completed structural construction in 2013.Its factory building is a frame shear wall structure, with two underground floors, the basement floor top elevation is -9.400 m, and the local area is -10.600 m; the roof elevation of the above-ground structure is 16.200 m at the highest.

The factory building is a seismic class I SSC. According to the "Code for Seismic Design of Nuclear Power Plants" (GB 50267-97), seismic analysis and design are carried out according to the ultimate safety ground motion SL-2 and operational safety ground motion SL-1. The horizontal acceleration peak values of SL-2 and SL-1 on the design basis ground were 0.209g and 0.105g respectively, and the vertical design acceleration peak value was 2/3 of the horizontal design acceleration peak value.

After the Fukushima nuclear accident in Japan, China conducted a major safety inspection of its existing nuclear facilities. The Institute of Geology of China Earthquake Administration recheck the seismic safety evaluation of the nuclear facility site. According to the new evaluation results, the SL-2 horizontal peak acceleration of the bedrock at the site was revised to 0.309g, and the peak acceleration of vertical design is the same as that of horizontal design. The seismic design level of the factory building has undergone great changes, and it is necessary to carry out seismic appraisal to it.

## 3 Analysis and check

Since there is no seismic appraisal method that can be based on, the seismic appraisal of this nuclear facility is completely carried out according to the new design method.

### 3.1 Synthesize the Benchmark Ground Motion of Bedrock

When synthesizing the ground motion time history of the bedrock of the project site, the probability of transcendence is 1% in 100 years (probability theory SL-2, 0.309g) and 2% in 100 years (the spectrum used in the calculation of the maximum withstand able seismic action) The target acceleration peaked value and response spectrum corresponding to 10% in 50 years (probability theory SL-1, 0.139g) are synthesized into three independent ground motion time histories.

According to the "Code for Seismic Design of Nuclear Power Plants" (GB 50267-97), the value of the acceleration peak value of the operational safety ground motion shall not be less than 1/2 of the corresponding peak value of the corresponding ultimate safety ground motion acceleration. Therefore, the acceleration peak value of SL-1 with a probability of exceeding 10% in 50 years is adjusted to 0.155g, and the spectral shape still adopts the original spectral shape.

In order to ensure the accuracy of the fitting target response spectrum when synthesizing ground motions, 60 target response spectrum control points were selected within 0.04s-6s. In the synthesis process, the method of approximating the target spectrum step by step is adopted, so that the synthesized acceleration time history accurately meets the bedrock acceleration peaked value and approximately meets the bedrock acceleration response spectrum. In this work, the relative error of fitting the target acceleration response spectrum is taken to be less than 5%. To make the time step of the synthetic time history is 0.02s, the number of discrete time points of small, medium and large earthquakes is 2048, 4096 and 4096 respectively. Three sets of acceleration time-history samples are provided for different probability levels of exceedance, a total of 9 time-history curves, 9 sets of target spectrum and synthetic ground motion spectrum comparison and error curves, and the fitting accuracy all meet the requirements of the specification (as a representative, only one set of drawings showing the synthetic accuracy is given, and the other two sets are omitted)m, as shown in Fig. 1.

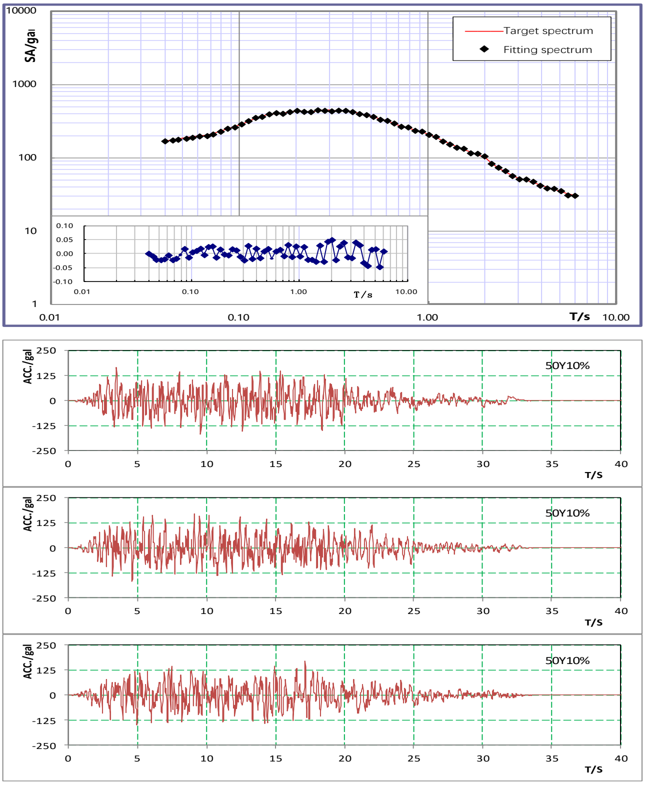


**Fig. 1.** Synthetic acceleration time history of bedrock (exceeding probability 10% in 50 years) and fitting result of target spectrum

### 3.2 Calculate Response Spectrum on the Base Elevation

According to the requirements of seismic response analysis of building structures and equipment, the horizontal and vertical seismic waves are reduced by half according to their amplitudes as the base incident waves for one-dimensional soil seismic response analysis, and the seismic responses of the site soil layer under earthquakes with different transcendence probability are calculated respectively. The response spectrum value of the free field reaction acceleration at the -11m elevation of the high-level radioactive waste liquid treatment facility project in the pilot plant is given, and the peak value of the reaction acceleration is shown in Table 1.

**Table 1.** Peak acceleration of response spectrum at -11.0 elevation

| SN | Exceeding Probability | Horizontal Peak (g) |
|---|---|---|
| 1 | 10% in 50 years (adjusted) | 0.152 |
| 2 | 2% in 100 years | 0.265 |
| 3 | 1% in 100 years | 0.300 |

Considering the possible errors caused by the simplification of the soil seismic response analysis calculation model and the ground motion input method, as well as the ease of use in engineering design, from a conservative point of view, in the double logarithmic coordinate, the calculated acceleration response at different positions spectral curve is straightened and smoothed, and the design response spectra of SL-2 and SL-1, which are biased towards safety, are obtained at each position.

### 3.3 3D Finite Element Modeling

The finite element software ANSYS 16.0 is used to establish a three-dimensional finite element model, as shown in Fig. 2, and the model is established according to the actual size drawings of the project., including the upper plant structure, the underground plant structure, and springs simulating soil constraints. The position coordinates of the walls and slabs of the finite element model are taken according to half the thickness of the actual structural walls and slabs (that is, the center position of the walls and slabs), which is achieved by adjusting the density of the material.

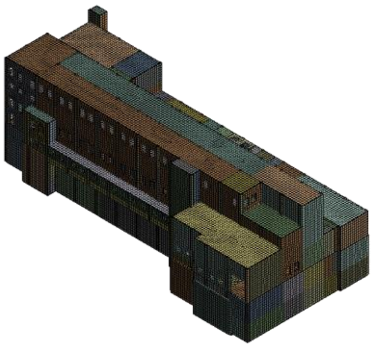

**Fig. 2.** The finite element model of the factory building

### 3.4 Load Combination

The following types of loads are considered in this seismic recheck:

(1)Standard value effect of permanent load(G): including self-weight, hydrostatic pressure and fixed equipment load.

(2)Standard value effect of live load(L): including any movable equipment load and temporary construction load.

(3)Standard value effect of temperature action($T_0$): considering the influence of temperature change on the structure, ignoring the hydration heat release during the construction process, the calculated positive and negative temperature difference is 35°C.

(4)Standard value effect of lateral earth pressure (He): the earth pressure on each wall unit is calculated by the formula $\sigma_a = \gamma z K_0$. The $K_0$ soil pressure coefficient is calculated by Rankine soil pressure theory, z is the unit buried depth, $\gamma$ is the soil weight.

(5)Basic wind pressure: 1.68 kN/m$^2$.

(6)Basic snow pressure: 1.01 kN/m$^2$.

(7)Earthquake action: the results of the site soil response analysis are used as the SL-2 seismic input, and the vertical design acceleration peak value is the same as the horizontal design acceleration peak value. First, check whether the bearing capacity of the structure meets the requirements under the earthquake with a probability of exceeding 1% in 100 years. If not satisfied, calculate the maximum seismic action level that the structure can withstand. When the calculated seismic acceleration peak value is between 0.306g and 0.269g, the 0.306g spectral shape is selected; when the acceleration peak value is less than 0.269g, the 0.269g spectral shape is selected.

In this seismic recheck, only the effect combination involving the seismic action is considered. The high-level radioactive waste liquid treatment plant is a class I building, and the various action sub-coefficients of the action effect combination can be adopted according to the provisions of Appendix B of the "Code for Seismic Design of Nuclear Power Plants" (GB 50267-97):

(1)The action-effect combination of the normal operation action is $S_1$, and the severe environmental action is $S'_1$ when the temperature action $T_0$ is included in the action-effect combination.

(2)The combination of effects of normal operation and extreme environmental effects $S_4$.

## 3.5 Seismic Analysis and Check

According to the load action and effect combination mentioned above, the seismic calculation of the powerhouse is carried out, and the stress and deformation of the powerhouse structure under the new seismic action level are calculated, to obtain the calculation results of reinforcement in different parts of the powerhouse, which are compare with the original reinforcement. If the actual reinforcement is not less than 95% of the calculated reinforcement, it is considered that the bearing capacity of the component meets the requirements; otherwise, it does not meet the requirements.

For the reinforced concrete continuous beam, the analysis method considering the plastic internal force redistribution is adopted, and the appropriate bending moment amplitude modulation method is carried out for the internal force value.

(1)According to the comparison results, as shown in Fig. 3, due to the increase of seismic action, the bearing capacity of some components does not meet the requirements, and the distribution is as follows:

(2)Basement 2: some walls with thickness of ≤300mm which are mainly concentrated in the emergency pool area and the roof of individual rooms.

(3)Basement 1: transverse walls of some radioactive rooms in the C-D area; some walls with thickness of ≤300mm; the ceilings of individual rooms.

Aboveground part:

a, some walls with thickness ≤300mm.

b, C, D, E axis partial concrete column.

c, 8.5m height 11-15/A-C area roof frame beam; 11.1m height C-D area partial frame beam.

d,11.1m height C-D area part of the floor; some roof panels.

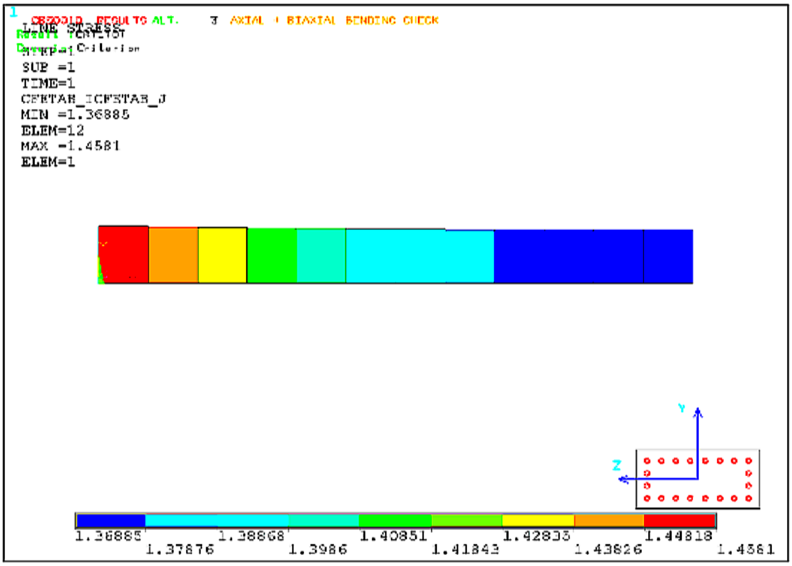


**Fig. 3.** Example of reinforcement comparison

## 3.6 Estimate the Ultimate Seismic Capacity

According to the spectral shape obtained by the analysis of the soil layer response under the 0.309g seismic action of the bedrock SL-2, with 0.005g as the step, the acceleration peak value is gradually lowered until 0.274g as the seismic input, and the bearing capacity of the powerhouse structure is calculated to meet the requirements. After calculation, when the acceleration peak value is reduced to 0.270g, the bearing capacity of some components still does not meet the requirements.

After that, according to the spectral shape obtained by the analysis of the soil layer response under the 0.269g seismic action of the bedrock SL-2, the acceleration peak value was gradually lowered for seismic recheck. The recheck shows that the maximum SL-2 bedrock peak acceleration that the structure can withstand is 0.224g. The maximum SL-2 bedrock peak acceleration that the main radioactive room components can withstand is 0.249g. The maximum SL-2 bedrock peak acceleration that the foundation can withstand is 0.239g.

The analysis and verification results show that although the nuclear facility has a certain safety margin, the improvement is limited compared to the original design basis, and it is far from meeting the new seismic design basis.

## 4 Basic Framework of Seismic Characterization Methods for Existing Nuclear Facilities

According to the original design method, the seismic calculation and analysis of the existing nuclear facilities whose design level has been improved obviously cannot meet the requirements. In fact, different methods are generally adopted and designed for the seismic identification of existing buildings, taking civil buildings as an example. At present, China has formed a relatively complete technical standard. In 1968, the Beijing-Tianjin Regional Earthquake Office issued the "Seismic Appraisal Standard for Newly built General Civil Buildings in Beijing-Tianjin Region (Draft)" and "Seismic Appraisal Standard for General Single-story Industrial Plants in Beijing Region (Draft). Draft)", "Beijing Old Building Seismic Appraisal Standards (Draft)", "Seismic Inspection Requirements for Rural Houses in Beijing-Tianjin Region and Key Points of Seismic Measures (Draft)" and "Seismic Appraisal Standards for Chimneys and Water Towers in Beijing-Tianjin Region (Draft)", a total of the above five drafts, and carry out seismic identification and reinforcement pilot work in the corresponding areas. Since then, the prelude to the seismic identification and reinforcement work in my country has been opened.

After the Tonghai earthquake in Yunnan Province in 1970 and the Haicheng earthquake in Liaoning in 1975, on the basis of the original draft, the first identification standard in my country was formed, referred to as the 75 version of the identification standard. After going through the 1977 version and the 1995 version, it has been improved and supplemented. After the Wenchuan Earthquake in 2008, experiences of earthquake damage from previous major earthquakes at home and abroad are carefully summed up (especially the Wenchuan Earthquake), and suggestions from all sectors of society, including scientific research department, design department, and universities are extensively solicited. Finally, the current seismic appraisal standard of 09 edition is formed.

In order to meet the urgent needs of our country's current nuclear power development and the increasingly severe seismic situation, a targeted seismic identification method system should be established for existing nuclear facilities. Combined with the analysis results of the above examples, the identification method should include the following main contents:

(1)Build the Performance Target System for Seismic Appraisal of Nuclear Facilities

Based on a detailed comparison of the seismic classification standards for nuclear safety buildings in major nuclear power operating countries at home and abroad, considering the actual status of our country's nuclear power industry, based on safety functions and structural integrity, and according to the performance-based seismic identification method needs, adapting to the classification method of seismic SSC adapting to our country's nuclear power industry is putting forward. On the basis of analyzing and calibrating the seismic reliability of nuclear safety buildings[2,3], a limit state classification method is proposed, and a performance target system for seismic evaluation of nuclear safety buildings is established.

(2)Determine the Quantitative Performance Indicators for Seismic Identification of Typical Nuclear Facilities

According to the limit state levels corresponding to different performance levels, the contribution of different types of components to the structural safety redundancy is studied, and the reliability sensitivity index is used to quantitatively identify the importance of each level and key parts of the structural force transmission system; quantify the importance of various types of components. The influence of different damage states on the overall safety of the structure was established, and the correlation model between the component damage and the overall reliability of the structure was established. The corresponding relationship between performance level and component damage and structural damage index is established, and a quantitative division method is proposed.

(3)Determine the Earthquake Actions for Seismic Appraisal

Fully considering the characteristics of the existing structure, according to the concept of transcendence probability such as earthquake risk, based on the time-varying reliability law and the principle of consistent risk, study the value of earthquake action with different subsequent service years, and give the calculation of ground motion parameters method. At the same time, on the basis of analyzing and comparing the design response spectrum of mainstream nuclear power at home and abroad[4,5,6], according to the actual situation of the demonstration project location, the applicable seismic wave data is collected, and a specific identification response spectrum is established.

(4)Analysis of Coupling Influence of Buildings and Equipment under earthquake action

Considering that equipment is an important part of industrial buildings, there are great differences in damping between equipment and structure[7,8,9], and there is obvious dynamic coupling phenomenon under earthquake action, so it belongs to a typical non-classical damping system. Given this, the structural dynamics theory can be used to quantitatively analyze the error caused by the forced decoupling when the mode shape decomposition method is used for calculation[10,11,12,13]. On this basis, the refined seismic analysis of the existing nuclear facilities is realized to further tap the potential of existing structures[14,15,16,17,18,19].

## 5 Conclusion

At present, the earthquake situation is severe, which directly threatens the safety of nuclear facilities. During the whole life cycle of nuclear facilities, there is an actual situation that the seismic design level changes. Currently, it is necessary to conduct seismic appraisal. For the seismic appraisal of existing nuclear facilities, the original design method should not be simply adopted, but a specific method should be adopted. This study analyzes the example of seismic identification of an existing nuclear facility, identifies the key links affecting the seismic identification of nuclear facilities, and, on this basis, establishes the basic framework of the seismic identification method of nuclear facilities. However, in the future, in-depth research is still needed to improve the specific details of the implementation of the seismic identification of existing nuclear facilities and prepare the seismic identification standard of nuclear facilities, which guides the seismic identification of existing nuclear facilities.

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