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DEVELOPMENT AND EXPECTATION OF SEISMIC ISOLATION OF NUCLEAR POWER PLANT STRUCTURE

Hou Nannan[1], Dong Jianling* [1,2]

[1]Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing, China
(hnn18@mails.tsinghua.edu.cn)
[2]Collaborative Innovation Center of Advanced Nuclear Energy Technology, Tsinghua University, Beijing, China

ABSTRACT

Seismic isolation has been widely applied in the architecture field including normal buildings and bridges worldwide, but it is still immature in the field of nuclear power plants especially nuclear structure. Since the environment and functions of nuclear power plants are more complex than normal architecture and nuclear power plants require much higher safety and reliability than other projects, seismic isolation of nuclear power plants needs particular designs. The base isolation can not only bear the vertical load of the structure, but also reduce the response of seismic on the upper structure due to the low lateral stiffness of isolation devices so as to improve the safety of the nuclear structure in the earthquake. In addition, base isolation can make the seismic isolation design of the main structure and equipment of nuclear power plants achieve standardization unrestricted by the magnitude of design ground motion. This paper summarizes the development of the seismic isolation of nuclear power plant structure up to now, especially since 2018, and the research and implementation in China, and also describes the challenges and adverse effect of base isolation applied in the field of nuclear power plants. Finally, this paper gives the expectation for the future research on the basis above.

Keywords: seismic isolation, three-dimension isolation, nuclear power plant

INTRODUCTION

Nuclear energy has the advantages of high efficiency, safety, stability and little impact on the environment. The Fukushima incident warns us that the safety of nuclear power plants under earthquakes must be considered. The following measures can be taken to reduce earthquake hazards: 1) reasonable site selection; 2) seismic fortification requirements and standard of nuclear power plant; 3) isolation technology.

Base isolation technology can make the seismic design of nuclear power plants not stick to the level of design ground motion and implement standardized operation, so as to improve the overall reliability and safety of nuclear power plant. At present, base isolation technology can be adopted for nuclear island with the SSE design seismic standard of more than 0.3g, so that the actual seismic acceleration of the nuclear island can be controlled within 0.3g. This paper summarizes the research results of seismic isolation in the field of nuclear power plants and tries to give the development direction in the future.

BASE ISOLATION

Applications in Nuclear Power Plants Worldwide

∗ Corresponding author. Tel.: 8610-62785907; E-mail addresses: dongjl@mail.tsinghua.edu.cn.

Base isolation is widely used in the United States, Japan, France and other countries. The application of isolation technology in nuclear power plants can be divided into three types: whole building (foundation) isolation, floor isolation and equipment isolation.

Two liquid metal reactors in the United States have adopted isolation technology, namely PRISM and sodium cooled fast reactor SAFR. PRISM adopts 20 high damping synthetic rubber bearings for horizontal isolation of reactor vessel, which have sufficient stiffness under low strain and can resist wind and small earthquake. The test results show that the peak spectral acceleration is reduced from 16.5g to 0.25g by seismic isolation, and the horizontal spectral peak above 2Hz is eliminated. SAFR adopts 100 high damping thick rubber bearings for isolation in both horizontal and vertical directions. The test results show that the horizontal and vertical isolation frequencies are lower than 1Hz and 4Hz respectively, which effectively avoids the natural frequencies of most equipment.

France applied the base isolation to Koeberg nuclear power plant in South Africa and Cruas nuclear power plant in France in 1977 and 1984 respectively. The former adopts laminated rubber bearings and sliding friction plates, and the latter adopts only laminated rubber bearings. The synthetic neoprene seismic isolation bearings used in Cruas was aging with the increase of service life, which affects the performance under earthquake; The isolators with bimetallic interface used in Koeberg was prohibited because of poor mechanical properties. ITER under construction in France has designed a seismic isolation scheme for Tokamak device, which uses a square laminated elastic isolator made of 6 layers of elastomer and embedded steel plate and has formulated a new specification. The Heysham nuclear power plant and Torness nuclear power plant were built in the UK in 1983 and 1988 respectively, in which base isolation was also adopted in factory buildings. Italy launched a research and development (R&D) program in 1988 to support the development of isolation guidelines and qualification procedures for isolation systems.

In the 1980s, Japan studied and tested the feasibility of base isolation of nuclear island. Influenced by the beyond design basis accident of Koshwazaki Kariwa nuclear power plant under M6.8 earthquake in 2007 Niigata, the Japan Electric Industry Association announced to start the development of the next generation light water reactor and carried out a new round of experimental research on nuclear island base isolation in 2008. The project entitled "safety enhancement of light water reactor" supported by the Japanese government considers two kinds of reactor: pressurized water reactor and boiling water reactor. The sodium cooled fast reactor JSFR, one of the six fourth generation reactor types proposed by the International Forum, adopts base isolation.

The fourth generation reactor KALIMER designed by South Korea also adopts the base isolation. And a new type of three-dimensional base isolation bearing is developed for a transportable self-supporting reactor STAR-LM. Yoo B et al. tested the performance of the laminated rubber bearing used in KALIMER and provided real test data for the practical application of isolation design. Hong Pyo Lee et al. studied and established the scale model of APR 1400 reactor nuclear structure in Korea, and carried out the analysis and experiment of dynamic load response on the structure by using the sliding isolation structure EQS support (EradiQuake system).

Research of Seismic Isolation in China

At present, Tianwan nuclear power plant and ALSTOM Taishan nuclear power plant have adopted spring isolators in conventional island. And AP1000 steam turbines of Sanmen and Haiyang and the megawatt half speed nuclear power steam turbine units designed and produced by Shanghai steam turbine plant including Siemens and Alstom models of CPR1000 Nuclear Power Plant have also adopted spring isolators. Yangjiang units 1, 2 and 3 and Fangchenggang unit 1 have been successfully put into operation, and the units are still in good operation. The megawatt half speed nuclear power steam turbine units designed and produced by Dongfang Electric, especially the ARABELLE steam turbine generator units, are all spring supported.

In terms of nuclear islands, there has not yet been mature achievements published and applied in China. Shenzhen CGN Engineering Design Co., Ltd. has cooperated with France to implement the seismic isolation design research of CPR1000. And Shanghai Institute of Nuclear Engineering began to plan the seismic isolation design of AP1000 in 2008 to increase the actual seismic design capacity from 0.3g to 0.6g on the premise that the original standard design of the imported AP1000 units remains unchanged. Shanghai Institute of Nuclear Engineering first proposed the isolation scheme of using the base isolation bearings in nuclear island and configuring the locking device released according to a certain threshold value. About 282 sets of supporting isolation devices are fully distributed under the bottom plate of the nuclear island of the whole AP1000, directly taking 0.9g as the working condition beyond the design basis, so as to keep the nuclear island within the original seismic margin of 0.5g.

STANDARD

Many countries including Japan, the United States and France have made relevant specifications for seismic isolation design of nuclear power plants, among which the specifications of Japan and the United States have developed for a long time and are mature.

Codes for Seismic Isolation of Nuclear Power Plants in Japan

Since Japan is a country with many earthquakes, the seismic isolation related policies are more comprehensive. In 2000, Japan Electric Power Association issued the world's first seismic isolation design code for nuclear power plant structures, “Technical Guide for Seismic Isolation Structure Design Of Nuclear Power Plants” (JEAG 4614-2000), and Japan Nuclear Safety Agency issued guidelines for seismic isolation structure review rules (JNES-SS-1001) in 2009.

JEAG 4614-2000 describes the following aspects: 1) classifying the nuclear facilities using seismic isolation; 2) Isolation design and evaluation method; 3) Load combination and necessary safety margin; 4) Performance requirements of isolation bearing and energy dissipation device; 5) Design requirements of auxiliary system (such as machinery, pipeline, etc.); 6) Quality control and maintenance requirements of isolation bearing.

JNES-SS-1001 is generally based on deterministic method. Although seismic probabilistic risk assessment method is required when considering residual risk, safety margin design method is used in the design of isolation system.

Codes for Seismic Isolation of Nuclear Power Plants in the United States

The United States issued “Seismic Design Criteria for Structures, Systems and Components in Nuclear Facilities” (ASCE 43-05) in 2005, which provides a set of design standards more stringent than ordinary buildings to ensure that nuclear facilities can maintain the expected performance under earthquake. However, the specification does not contain relevant contents of seismic isolation. “Seismic Analysis of Safety-Related Nuclear Structures” (ASCE SEI 4-16) adds a chapter on the design, analysis and testing of seismic isolation structures of nuclear power plants on the basis of ASCE-05.

Codes for Seismic Isolation of Nuclear Power Plants in China

The code for seismic design of nuclear power plants (GB 50267-1997) in China does not contain isolation related contents. But the standard for seismic isolation design of buildings (GB/T 51408-2021) was issued in April 2021, where Chapter 9 specifies the seismic isolation design standard of nuclear power plant buildings which is applicable to nuclear power plant buildings that use isolation bearings to achieve base isolation. The contents include: general provisions such as fortification objectives and site selection, seismic isolation design, floor response spectrum, requirements of isolation bearings, inspection rules of rubber isolation bearings, seismic monitoring and alarm, etc.

NEW TYPE SEISMIC ISOLATION

Common isolators include laminated rubber isolation bearings and sliding bearings such as friction pendulum, both of which can realize horizontal isolation but can't work well in vertical direction. In addition, they will increase the horizontal displacement response while reducing the horizontal acceleration response, which might cause the fracture of the connecting pipelines between the isolation parts and the non-isolation parts. Besides, the base isolation system may amplify some seismic wave responses under long-period ground motion, so it is very necessary to improve and innovate the traditional isolation system.

Three-dimensional seismic isolation

3-D seismic isolation can be achieved by one isolator acting in three directions, such as rubber bearings with low vertical stiffness, coil springs with separate dampers, or by two isolation systems in series.

Yoo B et al. applied the 3-D isolation structure shown in Figure 1 to STAR-LM reactor. The dynamic analysis shows that compared with the non-isolated structure, the 2-D and 3-D isolation system can reduce the acceleration response in the horizontal direction, and the 3-D isolation system can also reduce the floor acceleration by 2.4 times in the vertical direction.

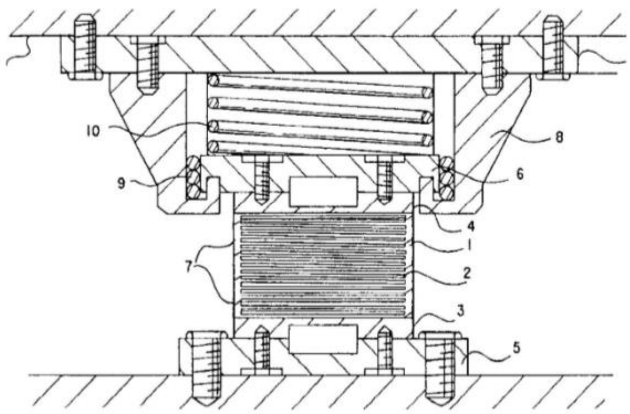

Figure 1. Schematic Drawing of 3-D Seismic Isolation Device.

In 2000, Japan carried out a large-scale research on the application of 3-D isolation technology to fast breeder reactor (FBR), and proposed three kinds of isolation devices: 1) rolling sealed air spring; 2) Steel wire reinforced air spring; 3) Hydraulic 3-D isolation device. The calculation and experimental results show that the isolation structure has significant anti shaking performance and vertical and horizontal isolation performance. Through the shaking table test of rolling sealed air spring and hydraulic swing suppression system, it is confirmed that the 3-D isolation device can be applied to nuclear power plant. Kageyama Mitsuru and others developed a 3-D isolation system composed of 3-D air spring, viscous damper and anti-sway device. Experiments show that the system is feasible in practical engineering. The 3-D isolation device is evaluated from performance, system reliability, easy maintenance and economy. It is concluded that the performance of the rolling sealed air spring shown in Figure 2 is better than the other two isolation devices, especially in terms of suitable performance for nuclear power plant.

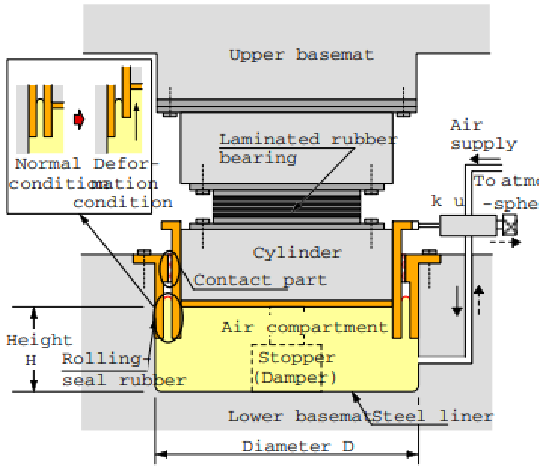

Figure 2. The 3-D base isolation device with rolling sealed air spring.

For laminated rubber bearings, increasing the thickness of single-layer rubber layer can reduce the vertical stiffness of the bearings. And if the total thickness remains unchanged, the horizon shear stiffness will be similar to that of ordinary rubber bearing. So, it is also a feasible way to realize 3-D isolation. However, the increase of the thickness of the rubber layer will reduce the first shape coefficient of the bearing, so the mechanical properties of the thick rubber bearing needs to be further studied. The SAFR reactor in the United States adopts 100 thick rubber isolation bearings with shape coefficient between 3 and 6. Kenji Kanazawa and others designed thick rubber bearings to avoid increasing the difficulty of vulcanization processing due to the thickening of the rubber layer.

Wang Tao and others designed a 3-D isolation system composed of thick rubber isolation bearings and oil dampers. The shaking table test of 1/15 scale model shows that it has the same isolation effect as the traditional isolation system in the horizontal direction. Although the response in the vertical direction is amplified, it can be used for vertical isolation of important equipment and pipelines in nuclear power plants.

In addition to the overall 3-D isolators mentioned above, vertical isolation can also be adopted for main equipment on the basis of overall horizontal isolation. The advantage is that the offset between the gravity center of superstructure and the position of the supporting structure can be very small, so the equipment will not have excessive swing response, and the characteristics of each isolation system will be simpler than the former.

S. Kitamura et al. designed a model that the reactor vessel and main components are suspended on a large public deck supported by an isolation device composed of large conical disk springs on the basis of overall horizontal isolation, as shown in Figure 3. The vertical isolation effect of the system is verified by the vibration test of the model.

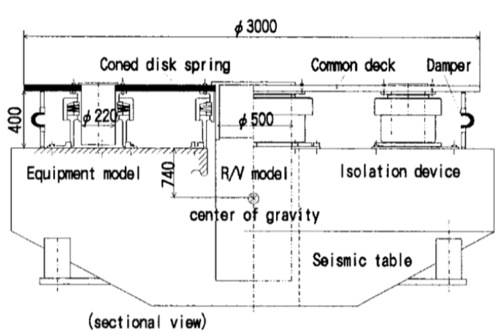

Figure 3. Vertical isolation system model.

Several new isolation devices

The research shows that the isolators may have large deformation under low frequency and high energy earthquake. Tuned mass damper composed of spring, mass and damper has been widely used in buildings, machinery, transportation and other fields. Zhou Fulin and others studied the application of TMD technology in heavy structures and verified its effectiveness in seismic isolation, and found that the lower the isolation layer is, the more obvious the damping effect is. Iuliis designed a new structure combining friction pendulum and TMD based on an ordinary building model. The dynamic analysis shows that it has good isolation effect. Mikayel also designed a base isolation structure combined with TMD and determined the best parameters. Hou Gangling compared the isolation effect of TMD and ordinary base isolation based on the containment model of AP1000 nuclear power plant. The results show that the base isolation can make TMD part have better effect and TMD can reduce the influence of the change of BIS bearings' stiffness and damping ratio. The BIS-TMD system has good isolation effect and high stability.

Because of the heavy self-weight, high cost and complex installation process of traditional laminated rubber bearings, Kelly used fiber reinforced materials to replace the steel plate in the laminated rubber bearings. The results show that its performance is similar to that of steel, which greatly reduces the self-weight of the bearings and makes the process simpler.

For sliding isolation bearings, some researchers introduced shape memory alloy (SMA) into sliding isolation system to improve their performance. Large size SMA spring can not only generate large displacement, but also carry heavy load, and has good reset and damping performance. Cardone et al. designed and manufactured two SMA sliding isolation devices and carried out shaking table test. The results show that the structure can be reliably used for isolation. Ozbulut et al. designed an isolation system composed of a sliding bearing and SMA and made time history analysis and optimization design of bridge structures. However, the application of SMA in the field of nuclear power plants has not been published.

Due to the rapid development of material science, various new materials, such as piezoelectric materials and shape memory materials, make the prospect of seismic isolation devices broader. For example, the polymer material composed of natural rubber and special filler developed in China has large damping and low cost.

PROBLEMS AND FUTURE DEVELOPMENT DIRECTION

Comparing the response results of isolated model with that of non-isolated model, it is concluded that the seismic response can be greatly reduced by isolation. But at present, the isolation technology also has the following problems:

(1) Either rubber bearing or sliding bearing will increase the displacement of the structure in the horizontal direction, which may rupture the connecting pipelines;

(2) The friction pendulum bearing is composed of multiple curved metal parts, which is difficult to manufacture, and when the superstructure slides to the height of concave curved surface, the vertical vibration of the structure will increase. Rubber bearing relies on polyurethane spring to provide reset ability, which may fail in harsh environment;

(3) If the isolation bearing is located in the radioactive area, it is required that the bearing has good radiation protection and heat resistance, and it is difficult to check the performance;

(4) The isolation system using only rubber bearings can only achieve horizontal isolation and the vertical response actually increases under the combined action of horizontal and vertical ground motion;

(5) Due to the complex internal structure of nuclear power plants, the isolation devices may cause stress concentration and damage to some equipment and pipelines. However, there is few research on the seismic performance of local equipment and pipelines;

(6) As the sliding support needs to be provided with a stopper, it may cause the superstructure to collide with the stopper and cause damage.

The future research on seismic isolation of nuclear power plants can be carried out from the following aspects:

(1) In view of the Fukushima incident, it is also worth studying how to deal with the tsunami caused by the earthquake and the impact of frequent typhoons in coastal areas on the isolated nuclear power plants;

(2) 3-D isolation must be realized. Especially for the whole structure with 3-D isolation, the bearing stiffness is small, so how to ensure its stability and safety needs further research;

(3) Based on the research on the isolation performance of the overall structure, it is necessary to study the isolation performance of local structures such as internal equipment and pipelines;

(4) Whether the isolation devices and materials can work continuously under the action of multiple main earthquakes and aftershocks to ensure the safety of the nuclear power plant is worthy of further study.

(5) New isolation materials could be studied and applied.

CONCLUSION

At this stage, the research on anti-seismic technology of nuclear power plants has been relatively mature, but anti-seismic technology cannot completely solve the harm caused by earthquake to nuclear power plants. Seismic isolation is undoubtedly an important development direction in seismic safety. However, due to the particularity and complex structure of nuclear power plants, there are few practical application examples of seismic isolation technology in nuclear power plants and many problems are still to be solved. Therefore, the research on nuclear power plant isolation technology is of great significance.

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