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Seismic Response Analysis of Isolated Nuclear Power Plants with Friction Damper Isolation System

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Abstract

In this paper, a new friction damper isolation system (FDIS) is suggested for isolated nuclear power plants (NPPs). Seismic responses of NPPs are accomplished by means of the finite element approach and setting up a representative multi-particle model of NPPs. Results in terms of time domain analysis show that response of structure supported by FDIS under small seismic are correspond to fixed structure, and perform similar properties as conventional isolated structure under large seismic. The yield force of friction damper is one of the important parameters which are related to responses and absorbing energy under seismic input energy in new isolated structures. Compared with cases of different yield level, responses of superstructures increase respectively with yield force, while displacements of isolation layer decrease effectively. The proposed new isolation system could be beneficial in enhancing the seismic safety of isolated NPPs.

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1. Introduction

Seismic isolation is a significant development in earthquake engineering that is gaining rapid worldwide acceptance [1]. As a mature technology, seismic isolation has been used widely in the world. More than

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10,000 applications protect not only civil buildings but also bridges and industrial constructions [2]. Isolation technology aims mainly at separating superstructure from the supporting ground, in order to reduce the transmission of the seismic motion to the superstructure. It can shift the fundamental frequency of a structure away from the dominant frequencies of earthquake ground motion, and also provide additional damping to dissipate seismic energy. A lot of test programs and simulation researches of isolation system and bearings to demonstrate their feasibility and effectiveness have been carried out.

As a kind of critical industrial buildings, any damage of Nuclear power plants structures will lead to severe disasters. Different from conventional NPPs design, seismic isolation is considered to be the most promising technology to protect nuclear reactors from violent earthquake. Several studies performed in Japan have shown that it would not be possible to design large plants which are economical in areas of high seismicity without incorporating seismic isolation [3]. In spite of this, only two of nuclear power plants in commercial operation are protected by isolation until now: 4 PWRs (Pressurized Water Reactors) at Cruas in France and 2 PWRs at Koeberg in South Africa [2].

Interest in seismic isolation has increased significantly in recent years. Researches and developments of isolation in nuclear structures are being carried out by major construction companies, several universities and government agencies. In isolated NPPs, the design and qualification of equipment and their supports become a simpler task than before and the impact of seismic design on preferred equipment layouts is minimized. Since the response of isolated NPPs is highly predictable, the risk of accidents due to uncertainties in the ground motions is reduced and inner equipments protection is enhanced [4]. Additionally, standardized design of NPPs with isolation system could be approached easier than before.

Although, significant relative movements under small seismic between the isolated superstructure and ground can easily destroy the crucial service networks and pipelines crossing isolation layer. It is an important problem limit the usage of seismic isolation into nuclear power plant. In this paper, the friction damper isolation system (FDIS) is suggested in reducing seismic response of superstructure. A representative multi-particle model of nuclear power plant is introduced to study effects of the FDIS in reducing seismic response.

2. Friction Damper isolation system

The friction damper isolation system is composed of friction damper and normal rubber bearing. Different from normal isolation system, superstructures supported by FDIS under small seismic are kept rigid connection as fixed by the friction damper with high yield force and large initial stiffness. In this case, the networks and pipelines work well under small seismic. With increase of loading level, friction damper start slide while the horizontal shear force of isolation layer reaches design yield force under violent seismic, and then dissipate earthquake energy. While friction damper sliding, the FDIS works as normal isolation system and seismic response of superstructure is reduced effectively. In this case, destroy of pipelines crossing isolation layer has become insignificant damage with the crucial nuclear reactor is protected by isolation system. The FDIS overcomes the limit of normal isolation system, and keeps superstructure rigid connection with ground under design earthquake, which prevents the damage of crucial pipelines caused by large isolation layer displacement under small seismic.

For the superstructure supported by this friction damper isolation system under earthquake excitation $x_g(t)$, the governing equations of motion can be written as:

$$[M]\{\ddot{x}_s\} + [C]\{\dot{x}_s\} + [K]\{x_s\} = -(\ddot{x}_g + \mu\ddot{x}_b)[M]\{I\} \quad (1)$$

$$m_0(\ddot{x}_g + \ddot{x}_b) + \sum_{i=1}^n m_i(\ddot{x}_g + \ddot{x}_b + \ddot{x}_{si}) + C\dot{x}_b + Kx_b = 0 \quad (2)$$

where $[M]$, $[C]$, and $[K]$ are the superstructure's mass, damping, and stiffness matrices, respectively, $\{x_s\}$ is the relative displacement vector of building with respect to the isolation layer, $\{x_b\}$ is the relative displacement of isolation layer with respect to the ground, C and K are the stiffness and damping of the base isolation system, m_0 and m_i are the mass of the base isolation system and building's i^{th} story, $\{I\}$ is the unit vector with same dimension as $\{x_s\}$, μ is the control factor and can be expressed as the following:

$$\mu = \begin{cases} 0 & F < Q_d \\ 1 & F \geq Q_d \end{cases} \quad (3)$$

where F and Q_d are earthquake shear force and design yield force of FDIS.

Under small earthquake, shear force $F < Q_d$ and $\mu = 0$, the superstructure keeps rigid connected to ground. In this case, governing equation of isolated structure supported by FDIS is same as the fixed one, and can be expressed by Eq.1. With beyond design earthquakes input, friction damper starts slide for shear force $F \geq Q_d$ and starts to dissipate earthquake energy, in which governing equation should be written by Eq.1 and Eq.2.

3. Nuclear power plant analysis model

Fig.1 (a) presents the multi-particle model of a standardized Pressurized Water Reactor plant analyzed in this study. The model is composed of two sticks: the external containment structure and the internal structures. The two sticks are structurally independent and connected only at the base. Each model is composed of several rigid masses supported by link elements representing NPPs, which parameters are from Ref [5]. Seismic responses of isolated NPPs are investigated using this multi-particle model supported by FDIS. In this paper, SAP2000 Nonlinear is used to analysis seismic history responses of fixed and isolated NPPs.

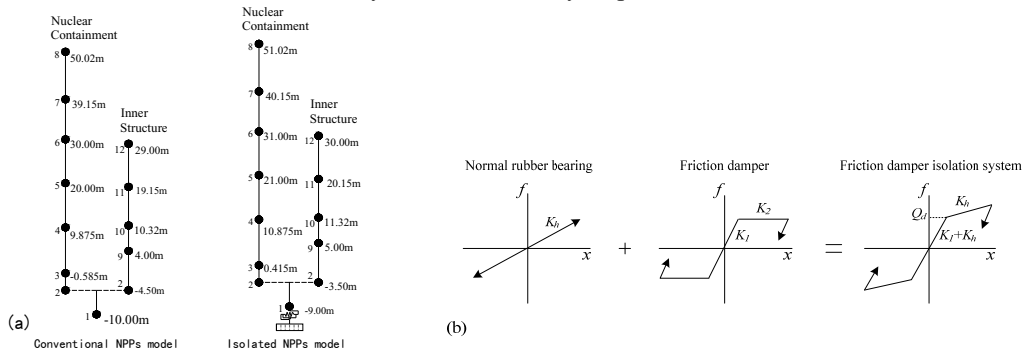


Fig1. Analysis model: (a) Fixed and isolated models of NPPs; (b) Simplify model of friction damper isolation system (FDIS)

Friction damper isolation system in this analysis is composed of 180 normal rubber bearings (GZP1000, which vertical stiffness $K_v = 4.649 \times 10^6 \text{ kN/m}$ and elastic stiffness is $1.815 \times 10^6 \text{ kN/m}$) and equal amounts friction dampers, its force-displacement characteristics for assembled FDIS provide an additional means of energy dissipation as shown in Fig.1 (b). Normal rubber bearing is modeled as linear elastic component in this analysis. For the friction damper, its first-slope stiffness K_1 is shown in Table 2 and second-slope (post-yield) stiffness $K_2 = 0$. The force-displacement characteristics for FDIS is a bilinear hysteretic model, which first-slope stiffness equal to $K_1 + K_h$ can provide essential rigid connection while shear force F is less than Q_d .

To study a wide range of friction damper isolation system properties, three models were prepared with yield force Q_d equal to 3%, 6% and 12% of the supported total weight W (as shown in Table 1). Seismic responses of fixed NPPs (named as UNISO) are also analyzed to compare with isolated NPPs.

Table 1 Analysis sets and parameters of friction damper

Case	I	II	III
Yield ratio Q_d/W	3%	6%	12%
$Q_d/(kN)$	80	160	320
$K_f \times 10^6/(N/m)$	16	32	64

4. Seismic response analysis

4.1 Ground motions.

According to the Chinese Code for Seismic Design of nuclear power plants (GB 50267-97) [6], seven artificial earthquake waves are proposed based on standard response spectrum. Seven artificial waves are named from ART1 to ART7, and well-fitting of them with standard response spectrums are shown in Fig.2.

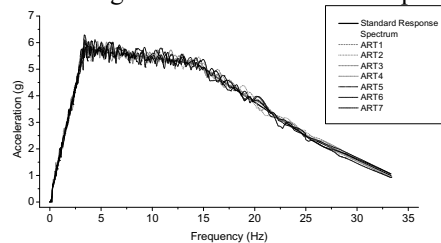


Fig.2 Artificial and standard response spectrums

In the code mentioned above, Operating Basis Earthquake (OBE) and Safe Shutdown Earthquake (SSE) are always required in NPPs seismic response analysis, and the maximum acceleration of SSE is no less than 0.15g. To study seismic responses of isolated models, earthquake simulations are performed at four intensity loading levels (acceleration amplitude is 0.05g, 0.10g, 0.20g, and 0.40g).

4.2 Acceleration analysis results.

Fig. 3 presents the average peak accelerations of node 8 and 12, which are the top of nuclear containment and internal structures, respectively. It's obviously that acceleration responses increase gradually with Q_d/W ratio of 3%, 6% and 12%. Also, acceleration responses of each case rise with increase of input seismic level, and the response of fixed NPPs is much larger than others'. Under 0.05g earthquake, average peak acceleration values of case 3%, 6% and 12% are only 14.0%, 22.4% and 37.0% of fixed case response. For 0.40g earthquake input, the ratios change to 6.5%, 8.0% and 14.5% respectively. The same trend can be seen from the response comparison in Fig.3 (b).

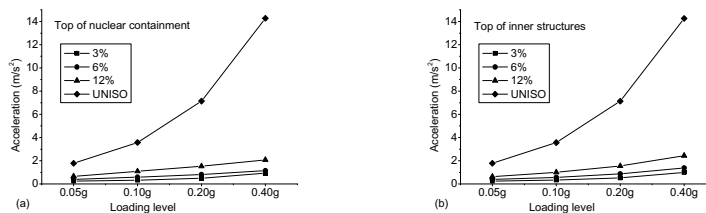


Fig.3 Average peak acceleration values under different earthquake levels of 0.05g, 0.10g, 0.20g and 0.40g: (a) peak acceleration of nuclear containment' top; (b) peak acceleration of internal structures' top

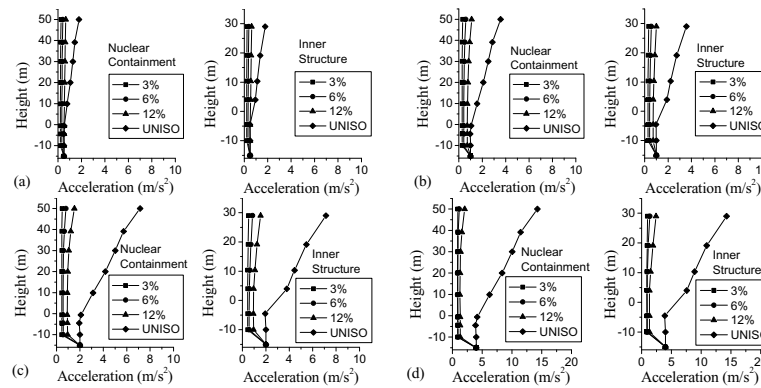


Fig.4 Acceleration response comparison of isolated and un-isolated NPPs: (a) 0.05g seismic input; (a) 0.10g seismic input; (a) 0.20g seismic input; (a) 0.40g seismic input;

Fig. 4 shows the average story accelerations of four cases under different earthquake levels. With 0.05g earthquake input, isolation displacement of case 12% is less than 5mm, and friction damper is still rigid. In such condition, peak accelerations of node 1, 2 and 3 are equal to the value of case UNISO. With increase of yield force from 80 to 320kN, ground motion imposed to superstructure arises correspondingly, and response of it is closer to fixed one. Friction damper slides under 0.40g severe earthquake input and dissipate earthquake energy. Fig. 4(d) presents the excellent isolation effects of FDIS for both containment and inner structures.

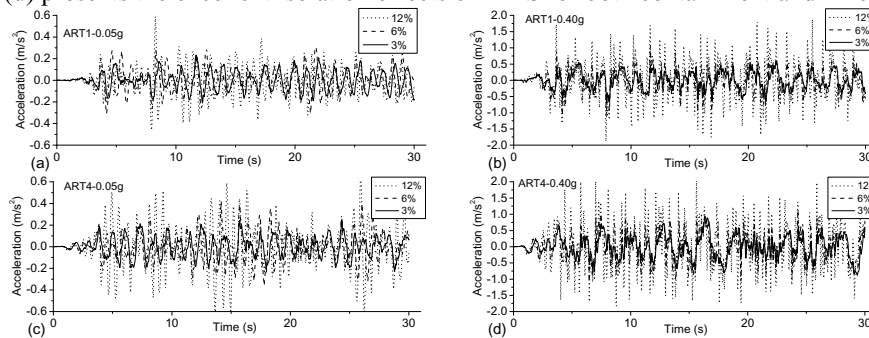


Fig.5 History of acceleration of top of nuclear containment: (a) 0.05g ART1 seismic input; (b) 0.40g ART1 seismic input; (c) 0.05g ART4 seismic input; (d) 0.40g ART4 seismic input;

Fig.5 presents the acceleration time histories of top nuclear containment under wave ART1 and ART4. It is observed that peak acceleration are increasing with arise of yield force generally, and amplification factor are 118% and 130% under ART1 and ART4 for case 12%. In this case, friction damper slides under 0.40g input. Acceleration responses reduce to 53% and 44.5% of input value, and the isolation effects are extraordinary.

Table 2 Average displacements of isolation layer (mm)

Q_d/W	0.05g	0.10g	0.20g	0.40g
3%	8.60	17.17	40.37	99.91
6%	6.54	11.89	27.25	67.39
12%	4.89	11.20	21.36	47.91

In the acceleration analysis above, with the friction damper keeps rigid, response of superstructure enlarger than small earthquake input value, and the vibration characteristic is similar to fixed structure. Under violent earthquake, friction damper slides during earthquake waves input, and the vibration characteristics of structure supported by FDIS are similar to normal isolated structure.

4.3 Isolation displacement analysis results.

The average isolation displacements under seven artificial waves are shown in Table 2. It is observed that the displacement is decreasing with increase of yield force. In the case 12%, friction damper isolation system keeps rigid under 0.05g earthquake input, while isolation layer displacement is less than 5mm (the yield displacement of friction damper). With the increase of input earthquake, friction damper slides and isolation layer displacement arises correspondingly. The maximum displacement is 99.91mm of case 3% under 0.40g earthquake input, which is still far less than the value of normal isolation structure.

5. Summary

In this paper, a new friction damper isolation system for NPPs is proposed. This novel isolation system effectively reduce large isolation displacement, which limits the use of isolation technology in NPPs. Results from FEM analysis are used to verify the effectiveness of this system and investigate the influence of friction damper on seismic responses of isolated NPPs. Some conclusions of significance can be drawn as follows:

1. Under different loading levels, accelerations of superstructure increase with arise of yield force. With 0.05g input, the vibration characteristics of superstructure with FDIS keeps rigid are close to fixed one.
2. The isolation layer displacement is well controlled by F. The maximum displacement value is, in general, decreasing with the increase in the yield force of FDIS. In case 12% with 0.05g earthquake input, isolation displacement is less than 5mm and the FDIS is still rigid.
3. Under different loading levels, friction dampers slide with the shear force of isolation layer reach the design yield force, and then become to dissipate input energy.

Acknowledgements

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