

Pseudo Dynamic Test Of Spring Vibration Isolation Foundation Of Steam-turbine Generator Considering Gravity Effect

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Abstract. A 1:8 foundation model was designed and fabricated based on a spring vibration isolation steam-turbine generator foundation. The gravity was simulated through the hydraulic servo loading system, and the pseudo dynamic tests were carried out under the action of two different 7th intensity medium earthquakes and a 8th intensity rare earthquake. The results indicate that, under the action of different earthquakes, the acceleration amplification factors are all smaller, the inter-story drift angles of each story are in accordance with the specification requirements. Cracks appeared under the action of 8th intensity rare earthquake, but no penetrating cracks. Springs have played a good role in vibration isolation, and no relative slippages between the spring vibration isolator and the capital of columns.

Introduction

The application of spring vibration isolation system on the foundation of steam-turbine generator is playing an extremely important role whether in seismic isolation, noise reduction, eliminating the adverse effects to the generator caused by uneven settlement of the foundation, or in space-saving, reducing the cost and other aspects[1]. This study is based on a practical project, a 1:8 spring vibration isolation foundation model was designed and fabricated. The similarity ratio of acceleration of gravity is 8:1 according the similarity theory. For large buildings, the simulation of gravity could not be realized by artificial mass, and other gravity simulation technologies are less studied both at home and abroad. The anti-seismic behavior of the steam-turbine generator foundation is studied by pseudo dynamic test in the literatures[2-5], but the gravity effect is not considered. It is simulated by applying the pre tightening force through the means of manual screw in the literatures[6,7], however, it is not safe and reliable, and difficult to apply the load evenly and accurately, the pretightening force could not reach the expected value, especially for large buildings. Therefore, it is necessary to make a more accurate simulation of gravity by the special device, getting a more objective result by pseudo dynamic test.

Test model

Materials and dimensions of the model. The model is a 9.2m×2.5m×3.5m six spans frame structure. There are four independent columns in the third and the fourth span, connected with the spring isolator respectively, no beams. Keeping the materials and reinforcement ratio of the model same with the prototype, using C45 concrete, and HRB400 steel bar. The quality of generator concentrated on the foundation roof, accounted for about forty percent of the total mass of the generator and the foundation. According to the similarity ratio of the quality, simulated the quality of the generator with cast iron in accordance with the quality distribution of the equipment on the prototype. As shown in Fig 1 is the finished model.



Fig 1 Test model

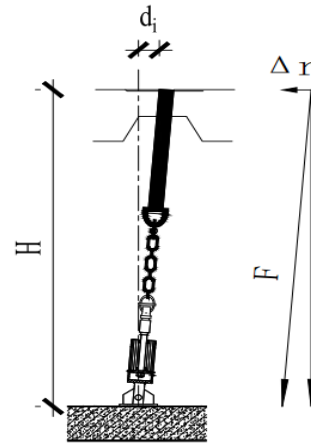


Fig 2 Horizontal component of hydraulic loading system

Gravity simulation. The gravity effect can be neglected in the ordinary dynamic characteristics test, but in the pseudo dynamic test, the vertical pressure of the spring and the columns will be reduced if the gravity effect is neglected, which will impact on the following aspects: 1. Reducing the maximum level of static friction force provided by the anti-skid pads located above and below the spring isolators. 2. The axial compression ratio of the spring and the column will change, which will affect their mechanical properties[8]. In this experiment, the hydraulic pressure servo system was first used to simulate the gravity by applying the pretightening force. According to the mass distribution of the prototype structure, foundation roof and the bottom plate are connected with actuators in 14 different positions. The pressure of each actuator is applied evenly which is controlled by the pressure gauge until the required preload is reached.

Testing program

Earthquake Accelerogram Selection. The seismic precautionary intensity of the site where project located is 7 degree; the design basic acceleration of ground motion is 0.1g; the 1st group of grouping of design earthquake; construction site for the Class 2 category. Peak accelerations of fortification earthquake and rarely earthquake action are 0.408g and 0.1g respectively.

A strong earthquake record-Imperial Valley (USA, 1979) was selected from Strong Motion Database PEER for pseudo-dynamic test. In addition, using seismic design response spectrum as the target response spectrum to synthesize the time history curve of earthquake acceleration for fortification earthquake and rarely earthquake, as shown in Fig.3-Fig.5.

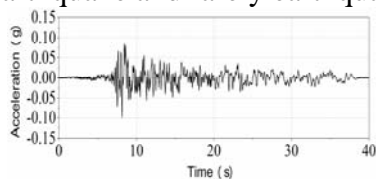


Fig.3 Acceleration time history
Imperial Valley

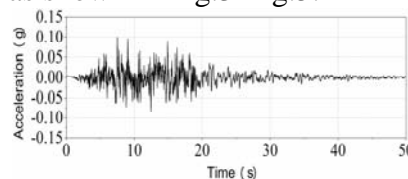


Fig.4 Acceleration time history
artificial synthesis

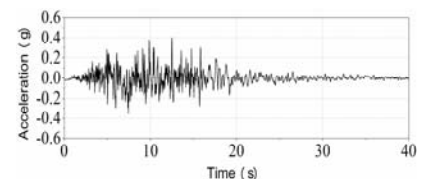


Fig.5 Acceleration time history
artificial synthesis

7th intensity medium earthquake

7th intensity medium earthquake

8th intensity rare earthquake

Loading and testing device. The test used the vertical loading method, connected the back strength wall and the foundation roof with the actuator. A total of 70 pieces of strain gauges were pasted on the surface of the steel bars in foundation members to study the stress of each member. Sixteen displacement sensors were arranged at top of columns, foundation roof, intermediate platform plates and baseplate respectively.

Main experimental parameters. The damping ratio of 0.05 was selected, according to the specification[9]. The foundation was regarded as a single particle model with the equivalent mass method; model equivalent mass was 26728Kg; initial stiffness was $48.4 \times 10^6 \text{N/m}$. The pre tightening force of 170.4t was applied to simulate gravity. The earthquake accelerogram was adjusted according to the similarity theory before inputting computer. Other parameters as shown in table 1.

Table 1 Testing parameter

experimental condition		Peak acceleration	duration (s)	time step (s)
7th intensity medium earthquake	Imperial Valley	0.1g	40	0.02
8th intensity rare earthquake	Synthesis	0.1g	50	0.02
	Synthesis	0.408g	40	0.02

Revision of theoretical formula. In the pseudo dynamic testing method, the central difference method is used to solve the discrete time dynamic equations[10], and the structural displacement d_{i+1} of time t_{i+1} is given by Eq.(1).

$$d_{i+1} = (M + \frac{\Delta t}{2} C)^{-1} [2Md_i + (\frac{\Delta t}{2} C - M)d_{i-1} - \Delta t^2 (r_i - f_i)] \quad (1) \quad \Delta r = \frac{d_i}{H} \cdot F \quad (2)$$

Where d_{i+1}, d_i, d_{i-1} = the structural displacement of time t_{i+1}, t_i, t_{i-1} ; r_i = restoring force at time t_i of the model; f_i = seismic force at time t_i . As shown in Fig 6, assuming that the total vertical force of the hydraulic loading system is concentrated on the single loading device. During the test, horizontal earthquake will make the foundation roof for horizontal displacement of d_i , and there will be a certain degree of tilt of the vertical hydraulic loading device, the vertical pretightening force will produce horizontal component, which will make the measured value of the force sensor larger than the actual recovery force of the structure. So considering to modify the Eq.(1). Δr is computed by Eq.(2).

where F = total vertical pre tightening force; H = the height difference between the model and the top of the bottom. The modified displacement formula is calculated by Eq.(3).

$$d_{i+1} = (M + \frac{\Delta t}{2} C)^{-1} [2Md_i + (\frac{\Delta t}{2} C - M)d_{i-1} - \Delta t^2 (r_i - \Delta r - f_i)] \quad (3)$$

Analysis of test results

Acceleration responses of the foundation roof. According to the similarity theory, model data was got from the prototype data. Acceleration time history of the foundation roof in three conditions are shown from Fig. 6 to Fig.8.

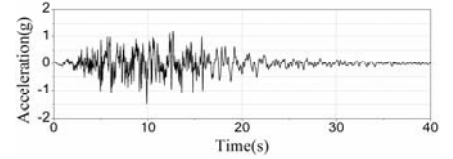
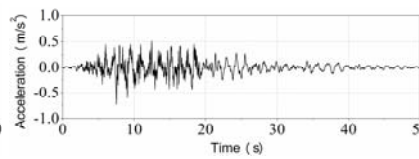
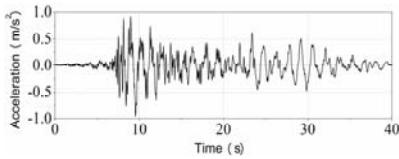


Fig.6 Acceleration time history of the foundation roof Imperial Valley
Fig.7 Acceleration time history of the foundation roof artificial synthesis
Fig.8 Acceleration time history of the foundation roof artificial synthesis
 7th intensity medium earthquake 7th intensity medium earthquake 8th intensity medium earthquake

Table 2 lists the maximums of the acceleration response of the foundation roof in three conditions and their corresponding acceleration amplification factors.

Table 2 Maximum acceleration of the roof and the amplification factor

experimental condition	7th intensity medium earthquake		8th intensity rare earthquake
	Imperial Valley	Artificial Synthesis	Artificial Synthesis
Maximum acceleration of the roof (m/s^2)	0.91	0.69	1.52
Acceleration amplification factor	0.93	0.7	0.38

Inter-story drift angle. The maximum inter-story drift angle of 7th intensity medium earthquake is 1/514 at the baseplate and the roof, while it is 1/154 at the 2nd story of generator side and the baseplate during 8th intensity rare earthquake. According to the specification[9], For reinforced concrete frame structure, the limit value of elastic story drift is 1/550 under the action of frequently earthquake; the limit value of elasto-plastic story drift is 1/50 under the action of rare earthquake. The test results show that the deformation capacity of the prototype meets the requirements of current seismic codes in different conditions.

The strain of the bars. As shown in table 3, under different operation conditions, in the beam column joints of 1st and 2st story, the steel bar strain of upper part of the joint is larger than that of bottom of the joint. The maximum value of the steel bar strain is located in the upper part of the beam column joints at 1st story during 7th intensity medium earthquake, while the maximum is located at the column root during 8th intensity rare earthquake. The strain of all steel bars are less than the yield strain of HRB400.

Table 3 Maximum value of the steel bar strain in different position

Experimental condition	7th intensity medium earthquake		8th intensity rare earthquake
	Synthesis	Imperial Valley	Synthesis
Column root	306	537	1415
1st story joint(below joint)	65	85	257
1st story joint(upon joint)	390	650	1102
2ed story joint(below joint)	186	224	370
2ed story joint(upon joint)	192	251	547
Column capital	25	15	30
Roof beam	17	16	35

Hysteresis loops and energy dissipation. Fig.9-Fig.11 are the hysteresis loops of the foundation in different conditions. Under the action of the medium earthquake, the hysteretic loops is basically linear, and low energy dissipation capacity to foundation, no stiffness degradation. Under the action of the rare earthquake, energy dissipation capacity has increased, the slope of the curve is slightly lower under the action of multiple loads, no obvious plastic deformation, and no obvious residual deformation.

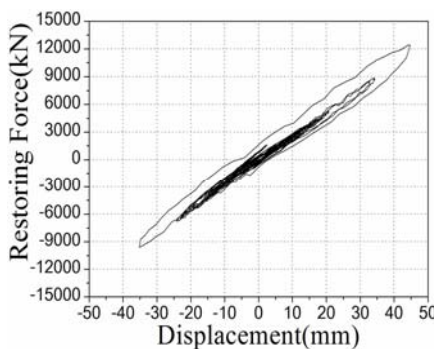


Fig 9 Hysteresis loop
Imperial Valley

7th intensity medium earthquake

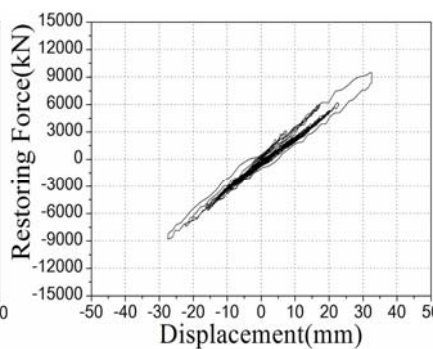


Fig 10 Hysteresis loop
artificial synthesis

7th intensity medium earthquake

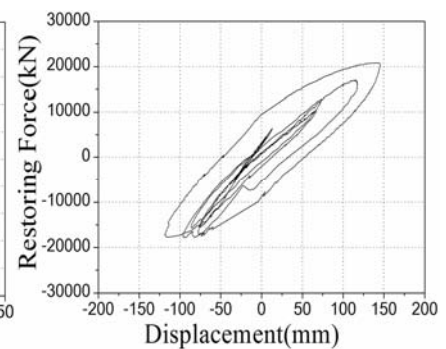


Fig 11 Hysteresis loop
artificial synthesis

8th intensity rare

Cracks of the structure. Under the action of the medium earthquake, there are almost no cracks in the structure. Under the action of rare earthquake, a diagonal crack is first observed in the upper part of the beam column joint of the 2en story. With the enhancement of seismic load, there are a few horizontal cracks appeared in the root of some columns, some of local cracks appeared in the beam column joint of the 1st story. Peak displacement of the structure appears at the 7.88s moment, at the

same time, maximum crack width of the structure located at the beam column joints is only 0.05mm measured by Crack observation instrument. After the test, no obvious crack was found.

Slippage of the spring vibration isolation system. There were not any relative slippages between the spring vibration isolator and the capital of columns during the tests.

Conclusions

The gravity was simulated by applying the pretightening force with hydraulic servo loading system. This system could not only load to the desired value multi-point synchronously, uniformly and accurately, but also could load to hundreds of tons or even more. Loading process is safe and reliable, also easy to operate.

The results show that, under the action of 7th intensity medium earthquake and 8th intensity rare earthquake, the acceleration amplification factors are all smaller; inter-story drift angles of each story are in accordance with the specification requirements; the strain of the bars are less than the yield strain. The structure is in the elastic stage under the action of medium earthquake; some of characteristics of elastic plastic deformation shown under the action of rare earthquake, the structure could play a good capacity of energy dissipation; no relative slipping between the spring vibration isolator and the capital of columns.

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