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Research Article

Seismic Behavior of Turbine-Generator Foundation under Strong Earthquake Action in Different Directions

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In order to study seismic behavior of half-speed turbine-generator foundation under horizontal earthquake loading in different directions, the 1/10 scaled model was designed and fabricated. The rigid foundation of half-speed turbine-generator sets can be seen as a complex space frame system. The tests were conducted under eight earthquake waves in two directions separately. The loading directions were along the axis of longitudinal and transverse. The seismic response of displacement and story drift was investigated by a pseudodynamic test. The hysteresis behavior and crack propagation were analyzed. From the research, it is shown that the maximum displacement of the foundation under the earthquake of intensity 7 is 15.20 mm (longitudinal), basically in the range of elastic deformation. The seismic response of earthquake input in different directions is obviously different. Under the same earthquake input, the seismic displacement along the axis of longitudinal is larger than that of transverse. Under the rarely earthquake of intensity 8, the foundation still keeps good working condition. The maximum elastic-plastic story drift is 1/191 under the limit value 1/50 provided in the Code for Seismic Design of Buildings. The deformation capacity of the structure meets the requirements of the current seismic design code of China.

1. Introduction

As a lifeline facility, once it is destroyed in earthquake, the turbine-generator foundation (hereinafter referred to as the “T-G foundation”) will cause serious disasters. The structure of the foundation is complex, the section size of the beam and column in frame foundation is large, and the operating platform is subjected to huge equipment weight. The T-G foundation can be approximately regarded as a single-layer reinforced concrete frame structure with a single span and a longitudinal span of 6 spans. The section size of the concrete component is between 2 and 4 meters, and the height is about 30 meters. The frame sets two intermediate platforms at different elevations of the lower end of the generator, and the plate thickness is about 0.5 meters. These intermediate platforms are arranged in the span of the two ends and are not connected with each other. As a special industrial structure, experimental research should be carried out in addition to theoretical methods for seismic response analysis. The experimental study on seismic performance of the foundation structure of half-speed turbine generator can be carried out, and the weak parts of the foundation under strong earthquake action can be further grasped for reference to the seismic safety design of the T-G foundation. The T-G foundation is actually a complex space system; the seismic performance, especially under strong earthquake, has not been adequately studied in China, or for this kind of structure system and the development of norms or standards, so we need to conduct experimental studies on this kind of structure system.

A comprehensive investigation on the dynamic characteristics of turbine-generator foundation systems is performed [1]. In this research, a 300 MW turbine-generator foundation system is analyzed under excitations from rotor unbalances and earthquakes. A pseudodynamic test of 1251 MW steam-turbine-generator foundation was carried out under intensity 7 frequently and rarely earthquake [2]. The model is 1/8 scaled. The results indicate that the

Table 1: Similarity relation of scale model.

Physical quantity	Coefficients
Geometry size	1 : 10
Stress/strain	1 : 1
Force (gravity, horizontal resistance, etc.)	1 : 100
Stiffness	1 : 10
Quality	1 : 1000
Time (period)	1 : 10
Acceleration	10 : 1

foundation has preferable seismic capability during the earthquake. Three examples of finite element analyses for seismic response of spring-supported T/G foundation were investigated [3]. Spring-supported T/G foundation could decrease velocity, acceleration, and inner force response of T/G deck and shaft. Literature [4] used a simulated earthquake shaking table test to input the El-Centro earthquake records and has measured the acceleration and the stress. A pseudostatic test was carried out at the same time. Literature [5] presents an alternative technique to the modal analysis of foundations. A large number of seismic tests have been carried out in China [6–9]. Literature [10] reviews and analyzes history and present situation of turbine-generator foundation in China for last ten years and then provides reference for designing of foundations of turbine generators.

In order to study the seismic behavior of T-G foundation, under strong earthquake action in different directions, the 1/10 scaled model was designed and fabricated according to similarity theory; pseudodynamic tests were carried out in two directions, respectively. The hysteretic curve of displacement and force, seismic response, including velocity, acceleration, and displacement, and crack propagation determine the seismic demand of T-G foundation and ultimately determine whether the T-G foundation meets the requirements of the Code for Seismic Design of Buildings (GB50011-2010) [11].

2. Test Situation

2.1. Scaled Model. The scale model of 1 : 10 is adopted, and the mass and gravity are separated due to the pseudodynamic test loading. The mass is simulated numerically in the computer, and the gravity is realized by the weight block. There are two separate quantities, $L = 1:10$ and $T = 1:10$, through calculating; the similarity coefficients used in the tests are shown in Table 1.

2.2. Model Design and Fabricate. The model of T-G rigid foundation is 7.38 meters long, 2.30 meters wide, and 2.53 meters high, as shown in Figure 1. The foundation can be regarded as a single-frame structure, with 14 columns, symmetrical in the direction of the long axis. The strength grade of concrete is C40, and the strength grade of steel bar is HRB400. The weight of generator concentrated on the foundation plate accounted for about forty percent of the total mass of the generator and the foundation. According to the similarity ratio of the weight, the weight of the generator is simulated by cast iron in accordance with the mass distribution of the equipment, as shown in Figure 2. The loading directions were along the axis of longitudinal and transverse of the foundation, which are shown in Figure 3. The horizontal load is applied by the hydraulic actuator. Reaction walls provide counterforce.

2.3. Material Test Results. The model pouring is performed three times. Three concrete cubes of 150 mm × 150 mm × 150 mm were fabricated each time, and the compressive strength of the concrete cube specimen is obtained. Tensile tests were conducted of sampling of rebar in same batch. The test results are shown in Table 2. The properties of the material can meet the requirements of the experiment.

2.4. Test Scheme

2.4.1. Strong Earthquake Selection. Two sets of strong earthquake records and 1 set of artificial acceleration time-history curve shall be selected according to the Code for Seismic Design of Buildings. In this paper, two strong earthquake records: Imperial Valley (USA, 1979) and Alaska (USA, 2002), were selected from the Strong Ground Motion Database PEER for pseudodynamic tests. Not only strong motion records are used but also earthquake accelerations are synthesized. In longitudinal loading, an artificial wave is added according to the site of type I (site characteristic period is 0.3 s). Using seismic design response spectrum as the target response spectrum, an earthquake acceleration time-history curve was obtained. The peak value acceleration of an earthquake curve turned into the value corresponded to intensity. The maximum value for seismic acceleration of ground motion used in time-history analysis is 35 cm/s^2 when the seismic action is intensity 7 frequently, 100 cm/s^2 when intensity 7 fortification, and 400 cm/s^2 when intensity 8 rarely. These records were the input of earthquake acceleration for frequently, fortification, and rarely earthquake, as shown in Figures 4–11. The condition of seismic input is shown in Table 3.

2.4.2. Theoretical Formula. In the pseudodynamic test method, the central difference method is used to solve the discrete time dynamic equations [12], and the structural displacement d_{i+1} of time t_{i+1} is given by the following equation:

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

where d_{i+1}, d_i, and d_{i-1} represent the structural displacement of time t_{i+1}, t_i, and t_{i-1} separately, r_i represents restoring force at time t_i of the structure, and f_i represents seismic force at time t_i. M represents the mass of the model structure. The interval of time (Δt) in the calculation is 0.02 s. C is Rayleigh damping.

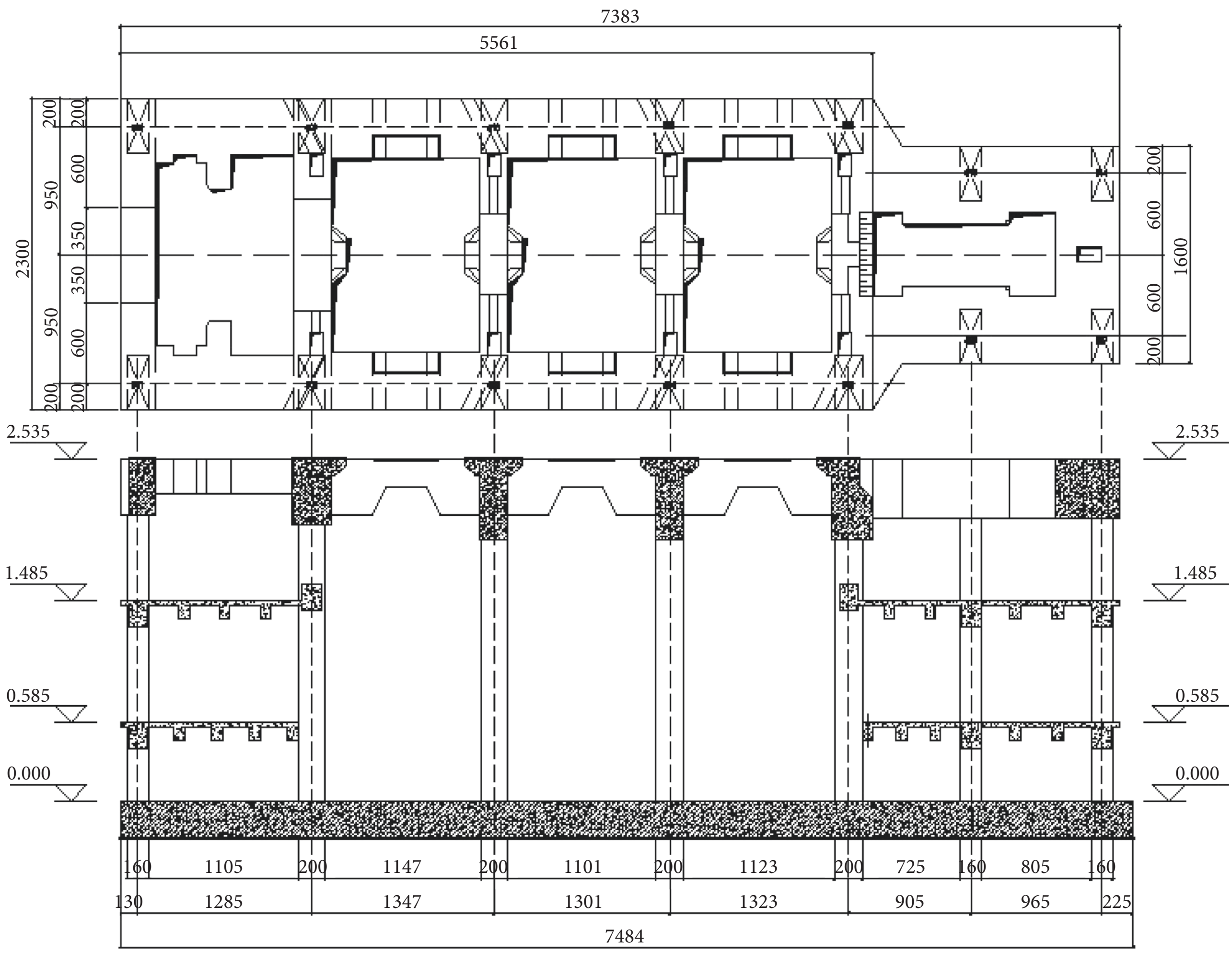

Figure 1: Layout drawing of test model (mm).

Figure 2: Test site and model.

Figure 3: Test setup (transverse load visual).

2.4.3. Experimental Parameters. The damping ratio was selected as 0.05 [13], according to the code [11]. The foundation was regarded as a single degree of freedom model with the equivalent mass method [14]. The model equivalent mass was 17,812 kg. The initial stiffness used in experimental input was 18.0×10^6 N/m. The earthquake accelerogram was adjusted according to the similarity theory before input to computer [15].

3. Test Results and Analysis

3.1. Seismic Response

3.1.1. Displacement Response. The high-precision displacement sensors (LVDT) were laid out on the structure model to control the displacement of the pseudodynamic test and measurement plate. All columns and joints

Table 2: Material test results (MPa).

Material	Location		Specimen 1	Specimen 2	Specimen 3
Concrete	Base plate		44.2	45.7	40.0
	Column		43.2	47.7	44.9
	Platform		44.1	42.9	44.5
Reinforced bar	ɸ10	f_y	395	394	382
		f_u	555	515	540
	ɸ16	f_y	450	455	460
		f_u	655	655	685
	ɸ20	f_y	430	445	445
		f_u	555	550	555

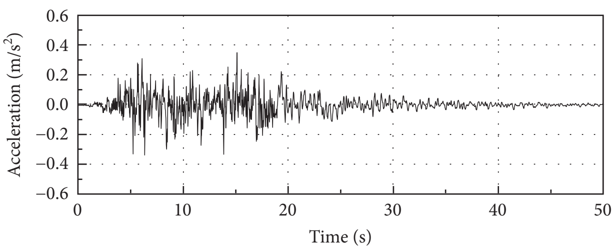

Figure 4: Earthquake acceleration time-history curve of intensity 7 frequently of synthesized (transverse input).

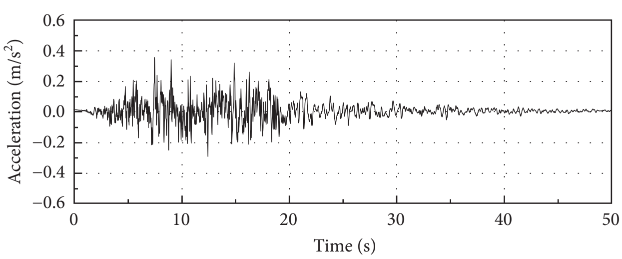

Figure 5: Earthquake acceleration time-history curve of intensity 7 frequently of synthesized (longitudinal input).

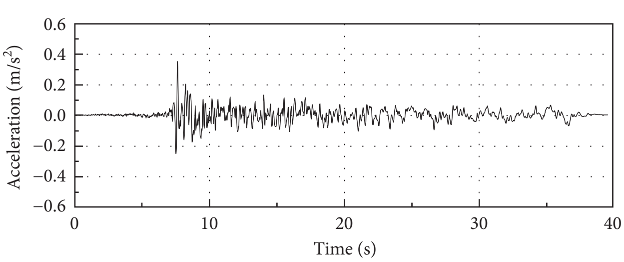

Figure 6: Earthquake acceleration time-history curve of intensity 7 frequently of Imperial Valley (transverse input).

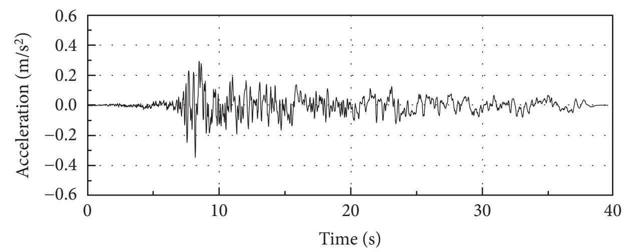

Figure 7: Earthquake acceleration time-history curve of intensity 7 frequently of Imperial Valley (longitudinal input).

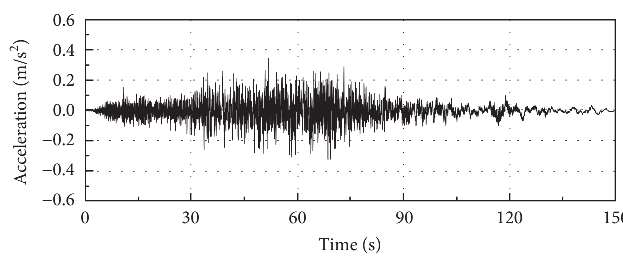

Figure 8: Earthquake acceleration time-history curve of intensity 7 frequently of Alaska (transverse input).

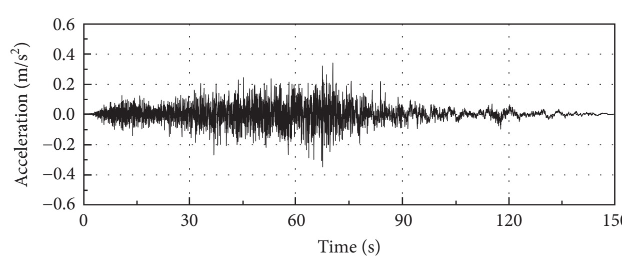

Figure 9: Earthquake acceleration time-history curve of intensity 7 frequently of Alaska (longitudinal input).

between column and platform were laid out on the displacement measuring points. The base plate is also arranged to measure the displacement in order to monitor it. The displacement responses of the foundation plate are shown in Figures 12–19. The maximum displacement of different locations in foundation is shown in Table 4.

In the stage of intensity 7 frequently earthquake, at the transverse input, the maximum displacement occurs at about 17.0 s, 8.5 s, and 35.0 s when synthesized, Imperial Valley, and Alaska earthquake input separately. The displacement response of the synthesized wave is the largest. At the longitudinal input, the maximum displacement occurs at about 9.0 s, 8.5 s, and 46.0 s when synthesized, Imperial

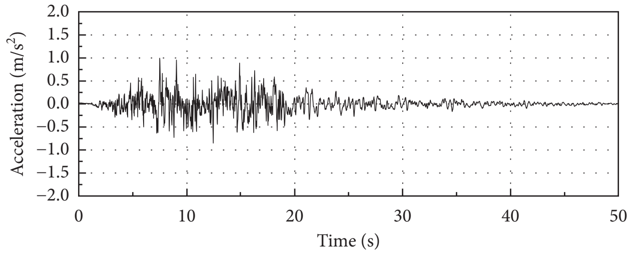

Figure 10: Earthquake acceleration time-history curve of intensity 7 fortification of synthesized (longitudinal input).

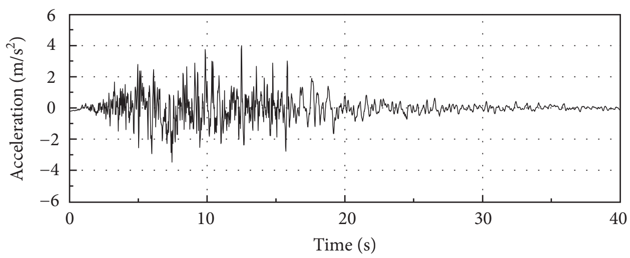

Figure 11: Earthquake acceleration time-history curve of intensity 8 rarely of synthesized (longitudinal input).

Table 3: Seismic input.

Direction	Intensity	Type
Transverse (X)	7 frequently	Synthesized Imperial Valley Alaska
Longitudinal (Y)	7 frequently	Synthesized Imperial Valley Alaska
	7 fortification	Synthesized
	8 rarely	Synthesized

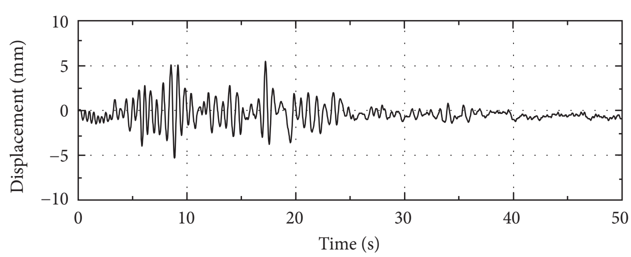

Figure 12: Displacement response curve of intensity 7 frequently of synthesized (transverse input).

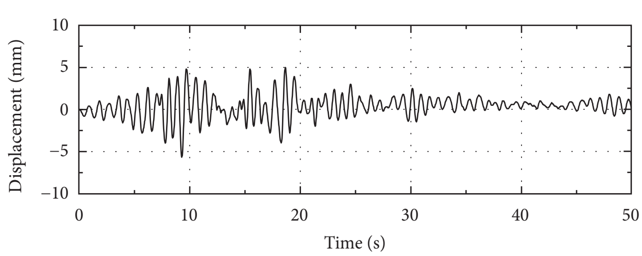

Figure 13: Displacement response curve of intensity 7 frequently of synthesized (longitudinal input).

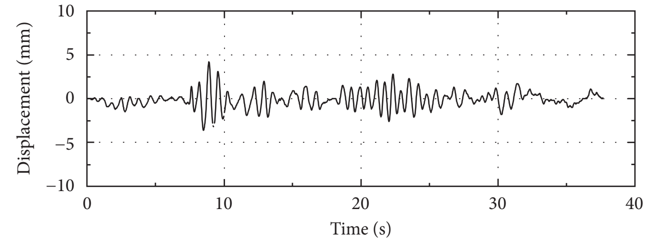

Figure 14: Displacement response curve of intensity 7 frequently of Imperial Valley (transverse input).

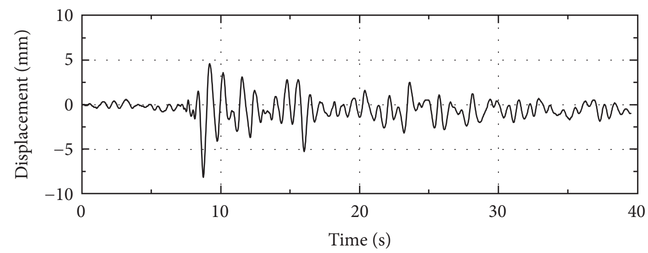

Figure 15: Displacement response curve of intensity 7 frequently of Imperial Valley (longitudinal input).

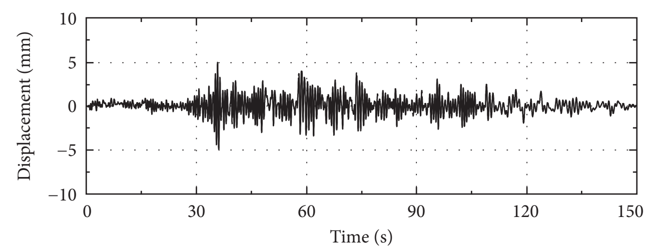

Figure 16: Displacement response curve of intensity 7 frequently of Alaska (transverse input).

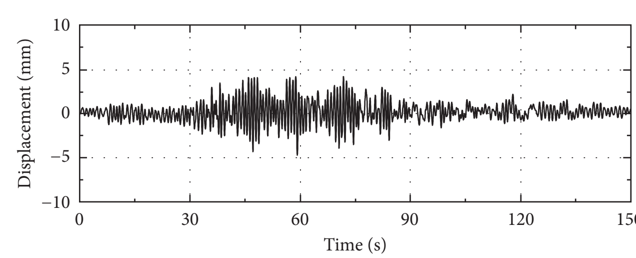

Figure 17: Displacement response curve of intensity 7 frequently of Alaska (longitudinal input).

Valley, and Alaska earthquake. The maximum displacement response occurs in Imperial Valley wave.

The longitudinal input is larger than the transverse input. So, the longitudinal input is applied in the intensity 7 fortification earthquake. The maximum displacement of plate is 15.20 mm and occurs at about 17.5 s, which is far from the ultimate state of the structure. The displacement response of fortification earthquake is 2-3 times larger than that of the frequently earthquake level, basically consistent

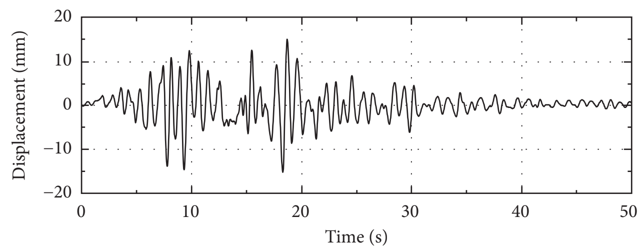

Figure 18: Displacement response curve of intensity 7 fortification of synthesized (longitudinal input).

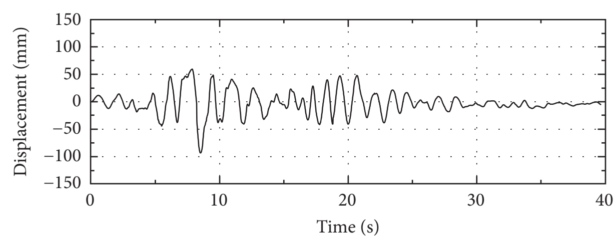

Figure 19: Displacement response curve of intensity 7 rarely of synthesized (longitudinal input).

Table 4: The maximum displacement of different locations in foundation (mm).

Direction	Transverse (X)			Longitudinal (Y)				
Intensity	7 frequently			7 frequently			7 fortification	8 rarely
Type	Synthesized	Imperial Valley	Alaska	Synthesized	Imperial Valley	Alaska	Synthesized	Synthesized
Plate	**5.50**	4.20	5.00	5.70	**8.20**	4.70	**15.20**	93.20
Column top	4.58	3.73	4.14	5.49	7.67	4.40	13.18	88.60
Second platform	4.13	3.55	3.67	4.31	4.80	3.85	11.49	77.67
First platform	0.95	0.77	0.85	1.36	1.60	1.29	3.62	25.03

with the input proportion relationship. Transverse loading will affect the longitudinal mechanical properties; however, this project is more concerned about the longitudinal seismic behavior, so the transverse input is no longer conducted.

From the early elastic-plastic numerical simulation and the frequently earthquake test, it is found that the longitudinal seismic capacity is weak. The intensity 8 rarely earthquake of artificial synthesized is conducted in the pseudodynamic test at longitudinal direction. Synthetic seismic waves can better reflect the seismic response of the structure, which are applied in intensity 7 fortification and intensity 8 rarely earthquake. The maximum displacement of the plate is similar at transverse input, which means three earthquake waves' characteristics are close to structural characteristics. In this time, both artificial and strong earthquake records can be used for seismic inputs. What is different is that, the maximum of displacement occurs when the strong earthquake records of Imperial Valley are used as the longitudinal input. It can be seen from Table 4 that the displacement of the plate, column, and beam column joints decreases successively from big to small. Under the same working condition, the tendency of displacement of each part is the same. The maximum displacement of plate is 93.20 mm and occurs at about 8.5 s.

3.1.2. Story Drift. Table 5 lists the maximum story drifts at each position of foundation. In the transverse horizontal direction and frequently earthquake input, the maximum value of story drift is 1/3594; at the longitudinal direction, the value is 1/2750. In the longitudinal horizontal direction and fortification earthquake input, the maximum value of story drift is 1/1292. Under the rarely earthquake, the value is 1/191. "Code for Seismic Design of Buildings" (GB50011-2010) provides that the elastic limit value of story drifts of reinforced concrete frame is 1/550 when frequently earthquake, and the value is 1/50 when rarely earthquake. So, the deformation capacity of spring vibration isolation foundation is in line with China's current seismic design code requirements in the case of frequently and rarely earthquake. The ductility of the foundation is proved to be perfect. The maximum value of story drift occurs at bottom and second platform in generator side when transverse input and at bottom and second platform in high-pressure cylinder side when longitudinal input. This indicates

Table 5: The story drift of different locations in foundation.

Direction		Transverse (*X*)			Longitudinal (*Y*)				
Intensity		7 frequently			7 frequently			7 fortification	8 rarely
Type		Synthesized	Imperial Valley	Alaska	Synthesized	Imperial Valley	Alaska	Synthesized	Synthesized
Table and plate		1/4609	1/6035	1/5070	1/4447	1/3091	1/5394	1/1668	1/272
High-pressure cylinder side	Bottom and second platform	1/4659	1/5914	1/5528	**1/3446**	1/3094	**1/3857**	**1/1292**	**1/191**
	Bottom and first platform	1/8046	1/11319	1/6848	1/4312	1/3656	1/5519	1/1617	1/233
Generator side	Bottom and second platform	**1/3594**	**1/4236**	**1/4045**	1/3855	**1/2750**	1/4535	1/1709	1/274
	Bottom and first platform	1/6177	1/7608	1/7011	1/5080	1/4875	1/4046	1/1446	1/200

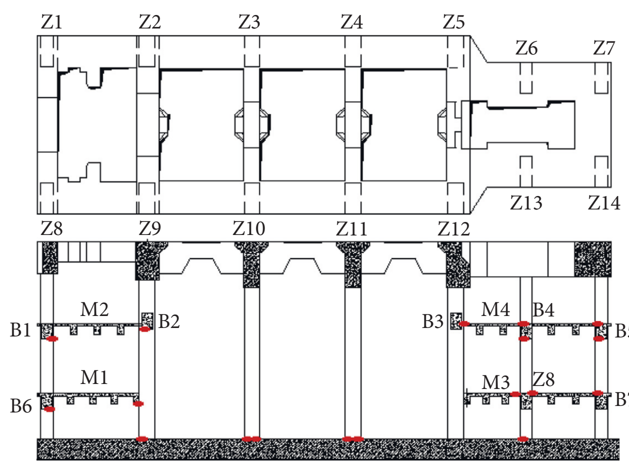

Figure 20: Distribution of main cracks of foundation model.

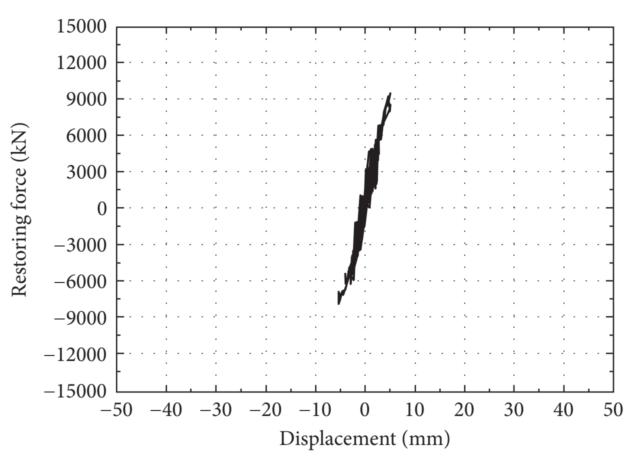

Figure 21: Hysteresis curve of intensity 7 frequently of synthesized (transverse input).

the structural layer displacement concentrates in the middle platform, which the designer should be paid the attention to. The displacement response can be effectively controlled within the allowable range of the specification [16].

3.2. Crack Propagation. Under the frequently earthquake input, the foundation frame has no cracks. In the fortification earthquake input, at the longitudinal direction, the horizontal crack first occurs at B3 beam. Then, it occurs at

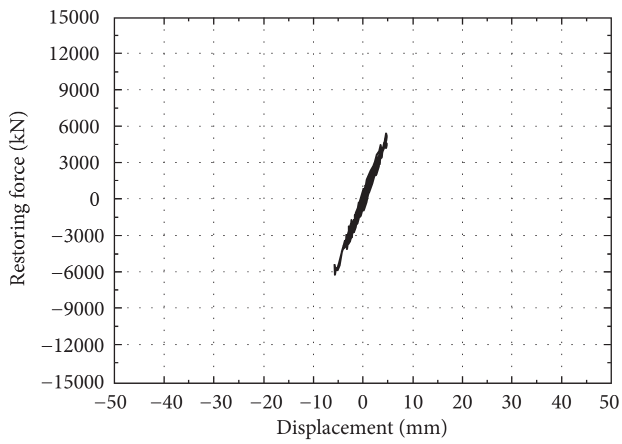

Figure 22: Hysteresis curve of intensity 7 frequently of synthesized (longitudinal input).

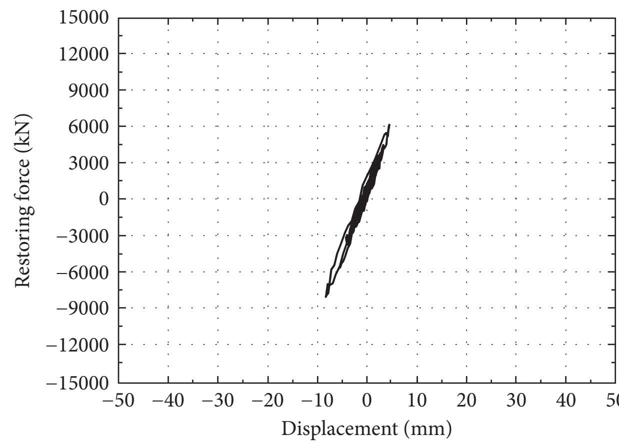

Figure 24: Hysteresis curve of intensity 7 frequently of Imperial Valley (longitudinal input).

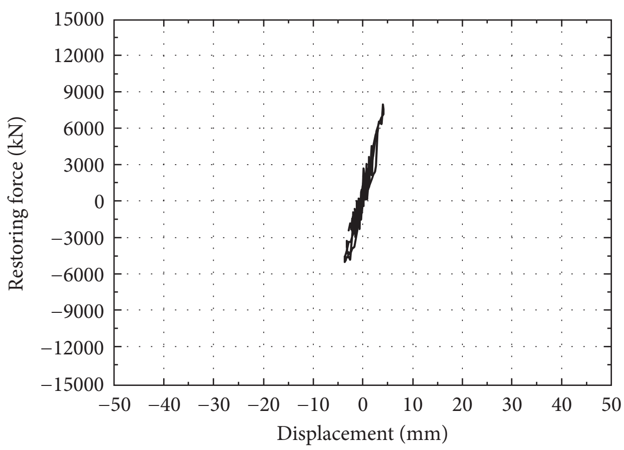

Figure 23: Hysteresis curve of intensity 7 frequently of Imperial Valley (transverse input).

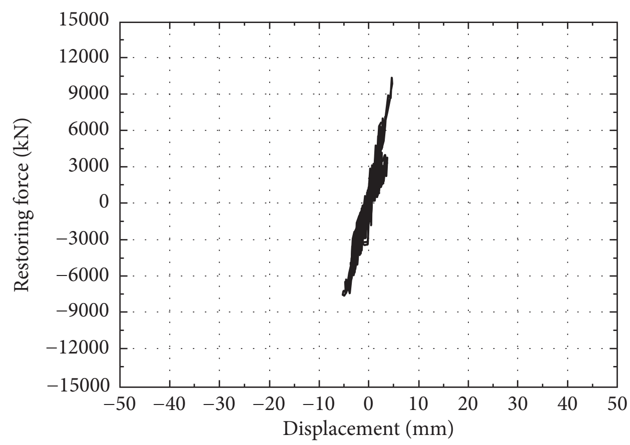

Figure 25: Hysteresis curve of intensity 7 frequently of Alaska (transverse input).

columns Z3 and Z10. In the longitudinal direction, horizontal crack occurs at the joint between the beam B4 and the platform M4. During the test of the rarely earthquake of intensity 8, the propagation of the crack is observed. The cracks first appeared in the connection of beam column joints, beam B2, and platform M2, with load increasing; the maximum crack width is 0.05 mm. Cracks appear at the important position of the structure, such as joint between the beam B6 and M1, joint between column C9 and M1. Horizontal cracks appear in columns such as Z2, Z4, Z6, Z9, Z10, and Z14. After the test, the cracks are not obvious. Figure 20 shows the main crack distribution. In the case of rarely earthquake, cracks have appeared; they are mainly concentrated at the beam-column joints, and some of the column roots also have a small amount of cracks. The cracks are mainly distributed locally, extending within a certain range without forming through cracks. Therefore, it can be inferred that the structures are basically intact under the action of rare earthquakes. The test shows that the foundation of the turbo generator is slightly damaged under the action of rare earthquake, and it can be used without repair [17].

3.3. Hysteresis Behavior. As shown in Figures 21–28, in frequently earthquake of intensity 7, the restoring force and displacement curves of the structure are basically linear and are surrounded by the hysteresis loop area, which is very small; in the loading process, the stiffness degradation is not obvious, and the structure is in the elastic state [18]. Along with the experiments, the hysteresis curves appear as a slightly nonlinear structure, which is due to the earthquake loading; concrete columns and beams in the individual parts have a little injury, and these microcracks are caused by opening and closing of the whole structure with a nonlinear. In fortification earthquake of intensity 7, from the hysteretic curve, the structure has a strong nonlinear appearance.

As can be seen from Figure 28, the slope of the loading curve decreases slightly with the increase of load when the rarely earthquake occurs, and the area of the circle is larger than that of the earthquake. The slope of the restoring force displacement curve decreases gradually, and the structural stiffness shows certain degradation. The structure has strong nonlinearity.

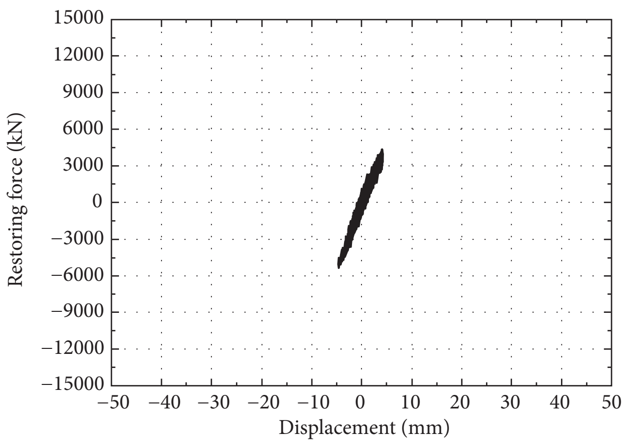

Figure 26: Hysteresis curve of intensity 7 frequently of Alaska (longitudinal input).

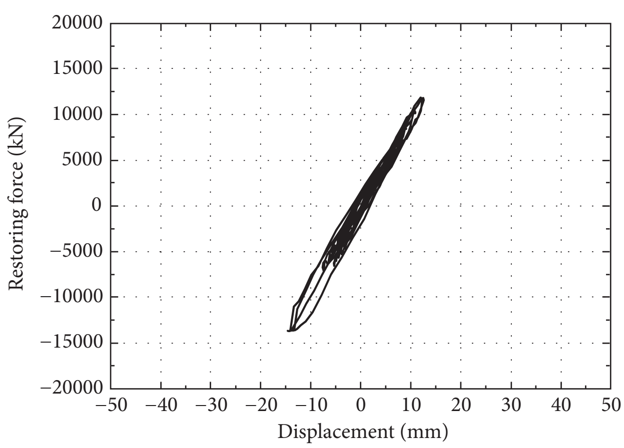

Figure 27: Hysteresis curve of intensity 7 fortification of synthesized (longitudinal input).

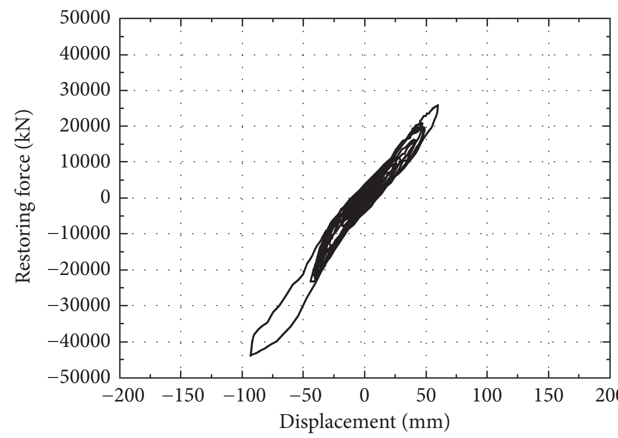

Figure 28: Hysteresis curve of intensity 7 rarely of synthesized (longitudinal input).

4. Conclusions

In this paper, the pseudodynamic experimental study in different directions on the seismic performance of the 1 : 10 model of T-G foundation is carried out. After the analysis of the test results, the following conclusions can be drawn:

(1) The data of pseudodynamic tests in each group have good coincidence characteristics. In the frequently and fortification earthquake of intensity 7, the foundation has good working performance; the maximum displacement of the plate is 15.20 mm (longitudinal), in the range of elastic deformation. The story drift meets the elastic displacement limit 1/550, which is specified in the code GB50011-2010 for seismic design of buildings.

(2) Under the action of intensity 8 rarely earthquake, the foundation still keeps good working condition. According to the test result, the restoring force and displacement curve were analyzed. The structure cracks mainly occurred in the position of beam-column joints; joint force is more complex. Propagation and extension of cracks are in a certain range. In addition, cracks appear in the column root, and the structure shows a certain elasticity and plasticity. The story drift meets the elastic-plastic displacement limit which is 1/50 specified in the code GB50011-2010 for seismic design of buildings.

(3) Under action of earthquake in different directions, it is shown that the maximum displacement occurs in synthetic seismic waves in the stage of intensity 7 frequently earthquake at the transverse input, whereas it occurs in Imperial Valley waves at the longitudinal input. The longitudinal input is applied in the intensity 7 fortification and intensity 8 rarely earthquake. The influence of earthquake input in different directions on the structure is different.

(4) Through the tests, under longitudinal loading, columns between beams and platforms were easily destroyed. Due to the presence of multiple platforms, the height of columns was reduced, thus triggering failure happened.

To sum up, the stiffness and strength of the structure met the design requirements and can maintain the elasticity under large earthquakes. The structure has typical characteristics of a concrete frame structure.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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