STUDY ON SHAKING TABLE TEST OF THE ±800kV COMPOSITE POST INSULATOR WITH DAMPER DEVICE

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Abstract

As an important part of lifeline engineering, the electrical equipment in power system has high seismic vulnerability as a result of low strength materia and high-rise structure form. In order to improve the seismic performance of electrical equipment, a shaking table comparison test for seismic modeling with and without a damping device was carried out on an Ultra High Voltage composite post insulator to study the impact of the damping device on the dynamic characteristics and seismic response of electrical equipment. The white noise test results show that the first-order frequency of the post insulator is reduced from 0.56Hz to 0.53Hz with a damping device installed, 5.36% change range indicating that the damping device has less impact on the rigidity of the equipment structure, thereby having little effect on the normal operation of the equipment. In addition, the results of three types of seismic wave tests suggest that seismic response of the equipment and the ground motion peak acceleration have a linear change relationship in the test without a damping device, but have a nonlinear change relationship in the test with a damping device. After the composite post insulator with the damping device installed, the maximum stress damping rates and displacement damping rates reaching 69.55% and 55.15% respectively. The stress damping coefficient increases nonlinearly with the increase of ground action intensity. the greater the seismic actions, the better the damping effect of the damper. But the displacement damping coefficient of the test equipment with a damper installed varies insignificantly with ground action intensity in the effect of three types of seismic waves, that is greatly affected by the frequency characteristics of seismic waves based on the test results. Therefore, according to the test results, a damper installed in the pillar type electrical equipment functions as a connecting bolt and has no other impacts on the equipment in normal conditions, thereby ensuring the operation safety and stability of the equipment. and such a damper has the damping and energy dissipation effects, thereby reducing the seismic response and improving the seismic safety in seismic actions. The paper provides a reference basis for the study on the seismic performance of the electrical equipment with composite materials and application of damping technology.

Keywords: UHV composite post insulator, shaking table test, damper device, dynamic characteristics, seismic response

1. Introduction

As an important part of the lifeline project, the safe and stable operation of the power system has an extremely significant impact on the national economy, people's life and the function of other lifeline projects. Substations are important nodes along electric energy transmission lines. As porcelain insulation and support materials with low strength, high density and high fragility are adopted for lightning arresters, instrument transformers, post insulators and other pillar type electrical equipment at substations, these electrical equipment are of high earthquake vulnerability[1~6],suffering from serious damage in previous major earthquakes both at home and abroad. For this reason, scholars from different countries have conducted a number of studies on the seismic performance of such equipments. With the development of new material and insulation technology, composite electrical equipment that uses high-strength glass fibers as main mechanical and insulation materials and is externally covered with silicon rubber with resistance to fouling and creepage is applied to UHV and EHV substations and converter stations. Nevertheless, there have been few studies on the seismic performance and measures of such electrical equipment[7~9].

Despite the advantages of light weight and high strength in terms of mechanical properties, composite components have a smaller diameter and thickness (showing low flexural rigidity). Pillar type electrical equipment is structurally thin and high, requiring higher flexural strength of composite electrical components under seismic actions. Moreover, optimization methods, such as increasing the cross-sectional area of components, have limited improvement in seismic resistance, accompanied with higher costs in mold processing and electrical performance tests of corresponding equipment components. For these reasons, the shock absorption technology is applied, which can greatly improve the seismic resistance of electrical equipment without changing original equipment structure, thus having higher economical efficiency and applicability. The metal energy dissipator developed based on the structural and seismic response characteristics of pillar type electrical equipment has been verified by tests and applied to relatively rigid porcelain electrical equipment[10~12]. However, few studies have been conducted on the application of such equipment in relatively flexible composite electrical equipment.

Regarding the issues above, taking a UHV ±800kV composite post insulator of a particular type in a converter station as the study object, this paper aims to conduct a study on the seismic and shock absorption performance by using the seismic simulating shaking table method, which compares and analyzes the dynamic characteristics, stress and displacement response of the insulator, and discusses the seismic performance of composite post insulator and the impact of the damping device on the mechanical properties of the insulator, and provides technical support for the seismic design of composite electrical equipment and the application of corresponding shock absorption measures.

2. UHV Composite Post Insulator

With reference to the actual design and layout of electrical equipment in a converter station, the structure of UHV ±800kV composite support insulator in the test is shown in Fig. 1.

As shown in the figure, the equipment is 16.1 m high as a whole and its upper part consists of 5 identical insulators with the basic structural parameters shown in Table 1, the total height of 12.27 m and the total weight of 2,300 kg. Each insulator is a solid rod structure with the outer diameter of 280 mm. To meet the requirements of electrical functions and safe ground clearance, most equipments in a substation or converter station shall be connected by supports. A lattice support is generally used in engineering applications and tests, with the height of 3.83 m, the upper heel span of 800 mm×800 mm and the lower heel span of 1,200 mm×1,200 mm, and the specification of φ192×12 for main steel pipes and φ83×8 for auxiliary ones. In the test, the steel plate at the bottom of the support is fixedly bolted to the seismic simulating shaking table.

Table 1 Parameters of the Equipment

Model	Mass(kg)	Height(m)	Outer Diameter(mm)	Modulus of Elasticity(GPa)	Breakdown Stress(MPa)	Breakdown Strength (MPa)
FZMW1-800	2300	12.27	280	25	80	128

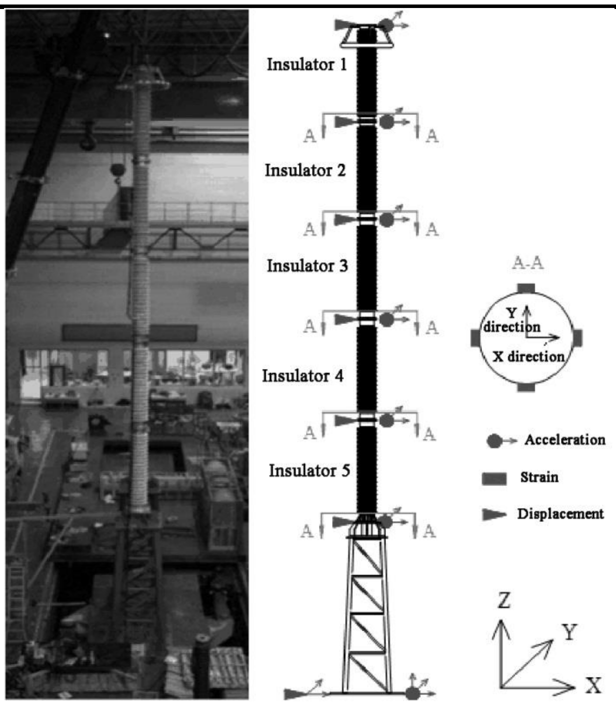
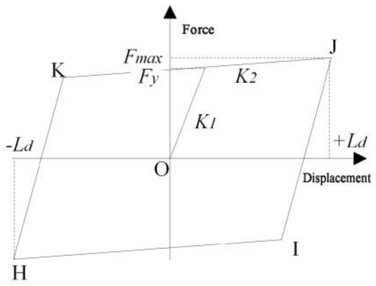
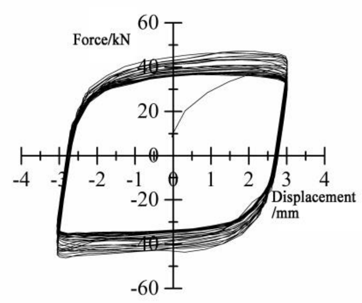


Fig. 1 Arrangement of UHV PI and Sensors in the Test

3. Damper for Electrical Equipment

Featuring dynamic recrystallization at low temperature, lead can absorb the energy dissipated during stress deformation. Therefore, the lead damper which developed based on a shear stress mode has been applied to porcelain electrical equipment, and its metal material characteristics show that the mechanical model is a bilinear restoring force model curve (as shown in Fig. 2-(a)), where: L_d is the loading displacement, F_y is the yield force, F_{max} is the maximum loading force, K_1 is the pre-yield rigidity and K_2 is the post-yield rigidity. According to the structural parameters of the test equipment and the parameters of the damper model, a numerical simulation calculation model is established for the calculation of seismic actions. Through calculation, optimal damper performance parameters (yield force 42 kN, maximum displacement 5 mm, pre-yield stiffness 118 kN/mm and post-yield stiffness 1.22 kN/mm) which is suitable for the equipment are selected from multiple groups of analysis results. The damper manufactured on this basis is subject to the low-cycle reversed mechanical property test (as shown in Fig. 2-(b)) and the hysteresis test with the hysteresis curve shown in Fig. 2-(c). The test results show that the performance parameters are basically in line with the simulation results. It can be seen from the trend of the hysteresis curve that the damper has a smaller post-yield stiffness and a relatively full hysteresis loop, indicating that the damper has a better energy dissipation performance. The damper is installed at the connection between the equipment and the support, replacing original connecting bolts.





(a) Bilinear Model (b) Hysteresis Test of Damper (c) Hysteresis Curve

Fig. 2 Theoretical Model and Mechanical Testing of the Damper

4. Shaking Table Test

4.1 Parameters of Shaking Table

The test is conducted on the seismic simulating shaking table in the State Key Laboratory of Chongqing Communications Technology Research & Design Institute Co., Ltd. The shaking table has a size of 3m×6m, a maximum load of 35t, a maximum acceleration of 1.0g (g is the acceleration of gravity, taken as 9.81 m/s2), an operating frequency of 0.1 Hz~50 Hz and a maximum overturning moment of 70 t·m. All indicators of the shaking table meet the test requirements.

4.2 Seismic Wave

Ground motions propagate in rock and soil in the form of wave. Due to the uncertainties factors such as fault mechanism, the char acteristics of hypocenter and propagation path, seismic waves are highly uncertain. To meet the requirements of envelopment and applicability for the test results, the test is conducted with 2 seismic waves (i.e. El_Centro and Taft) and 1 artificial wave converted from a response spectrum with a long predominant period (0.1s ~ 0.9s). The contrast test on seismic waves is conducted by scaling the seismic waves using the peak acceleration as an indicator. Fig. 3 shows the frequency spectrum curves and seismic waveform at the peak acceleration of 0.1 g (i.e. PGA=0.1g).

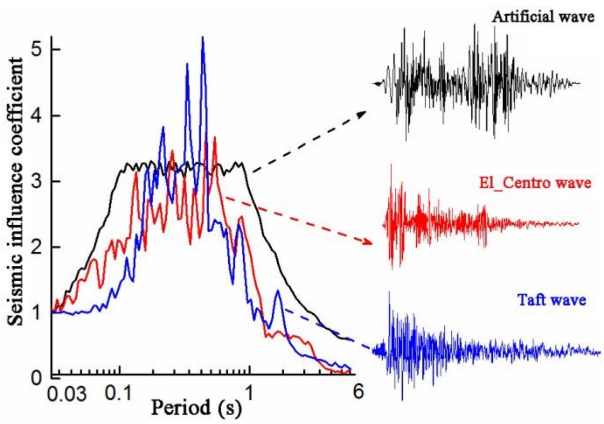


Fig. 3 Frequency Spectrum Curves and Earthquake Waves

4.3 Layout of Measuring Points

Fig. 1 shows the layout of measuring points in the test. The support insulator mainly suffers from flexural deformation under seismic actions, with the maximum flexural strain response occurring at the bottom of the insulator and the maximum displacement response at the top. And for this reason, 4 strain gauges are uniformly arranged along the cross sections at the roots of composite bushings of two insulators respectively, totaling 20 strain gauges. In the test, the strain gauges are subject to stability compensation and are reset before each test. Meanwhile, a total of 14 accelerator meters and 14 displacement meters are also arranged for the test, i.e. 2 accelerator meters and 2 displacement meters at the top flange of each of the five insulators, and the rest in the X and Y directions on the surface of the shaking table and on the top of the support.

4.4 Test Condition

To compare the application effects of damper, we need to make sure that the conditions of seismic test are the same as those of damping test, as shown in Table 2 in detail. The equipment is first subject to the seismic test and then to the damping test by removing the bolts connecting the equipment and the support and then installing a damper. Since the white noise test is intended to test the dynamic characteristics of equipment structure and check the equipment for any structural damage in the test, it shall be conducted during PGA tests of all grades. Tests with 3 seismic waves are conducted at each grade of PGA during increment of PGA from 0.1 g to 0.4 g step by step.

Table 2 Test Condition of Seismic and Damping Tests

Condition	Seismic Exciting Wave	Target PGA	Test Content
1	White noise	0.07g	Dynamic characteristics of test equipment
2	Artificial wave	0.10g	Dynamic response test of equipment
3	El_Centro wave	0.10g	Dynamic response test of equipment
4	Taft wave	0.10g	Dynamic response test of equipment
5	White noise	0.07g	Dynamic characteristics of test equipment
6	Artificial wave	0.20g	Dynamic response test of equipment
7	El_Centro wave	0.20g	Dynamic response test of equipment
8	Taft wave	0.20g	Dynamic response test of equipment
9	White noise	0.07g	Dynamic characteristics of test equipment
10	Artificial wave	0.30g	Dynamic response test of equipment
11	El_Centro wave	0.30g	Dynamic response test of equipment
12	Taft wave	0.30g	Dynamic response test of equipment
13	White noise	0.07g	Dynamic characteristics of test equipment
14	Artificial wave	0.40g	Dynamic response test of equipment
15	El_Centro wave	0.40g	Dynamic response test of equipment
16	Taft wave	0.40g	Dynamic response test of equipment
17	White noise	0.07g	Dynamic characteristics of test equipment

5. Analysis of Test Results

5.1 Analysis of Dynamic Characteristics

Spectral analysis using FFT is conducted based on the time-history data of acceleration at the top of the equipment in the white noise test. Table 3 shows the first-order frequency results obtained by seismic test and damping test. It can be seen from the frequency analysis results that in the aseismic structure, the equipment frequency basically remains stable at 0.56 Hz before the test and after the acceleration tests, without any changes in the equipment structure. Whereas in the damping test, the structure frequency is 0.53

Hz in the first white noise test and slightly lower in the subsequent ones. By evaluating the impact of the damper on the rigidity of the equipment based on the initial white noise frequency results of the two tests, we can know that the frequency of the equipment with a damper reduces by 5.36%, meeting the requirement set forth in the specification[12] that the first-order inherent frequency of the damping structure of the electrical equipment shall not reduce by more than 10% compared to the electrical equipment without a damper, so that the damper can meet the requirements of normal use function and thus serve the function of a bolt under normal conditions, without any other adverse impact on the equipment.

Table 3 Frequency of Seismic and Damping Tests

Condition	Aseismic Structure Frequency/Hz	Damping Structure Frequency/Hz
1	0.56	0.53
5	0.56	0.52
9	0.56	0.52
13	0.57	0.51
17	0.56	0.51

In the test on the damping structure by increasing PGA from 0.1 g to 0.4 g, the equipment frequency reduces by 3.77% from 0.53 Hz to 0.51 Hz, indicating that the damper changes slightly with the increase of seismic actions, which has an impact on the equipment structure frequency. After the test, the damper is subject to inspection, and is found visually intact without any abnormalities but has a slight decrease in the fastening force of its connecting bolts, and this is why the equipment structure frequency reduces in case of a ground motion of a higher grade. In actual engineering applications, dampers shall be subject to visual and fastening force inspections in case of moderate and high-magnitude earthquakes, and abnormalities (if any) shall be handled in time.

5.2 Stress Response Analysis

In the tests under various conditions, the maximum strain occurs in the direction of exciting force at the root of bottom insulator, and the stress results are obtained by multiplying the strain obtained by the modulus of elasticity of material. The stress results of the seismic and damping tests and the corresponding damping coefficient are shown in Table 4. As specified in the specification[13], the damping coefficient is calculated as per the formula below:

$$\mu = \frac{\sigma_f - \sigma_b}{\sigma_f} \tag{1}$$

Where: μ — damping coefficient; σ_f — stress under the condition of no damper for electrical equipment; σ_b — stress of the damping structure of the electrical equipment.

Fig. 4 shows the trend curves of stress and PGA in the seismic and damping tests. The seismic test with 3 seismic waves shows that the stress basically increases linearly with the increase of PGA, the stress response of the equipment reaches the maximum under the effect of the artificial wave and there is an insignificant difference under the effect of the El_Centro and Taft waves. The frequency spectrum curves show that the spectral value of the artificial wave reaches the maximum within 0.53 Hz ~ 0.56 Hz, so does the stress response as a result of frequency spectrum characteristics. The stress response of the equipment with a damper installed reduces significantly. With the greater seismic actions, greater maximum displacement response of the damper and greater post-yield energy dissipation (area of hysteresis loop), the equivalent damping ratio of the damper to the equipment increases, resulting in a non-linear increase trend of the damping coefficient with the increase of PGA.

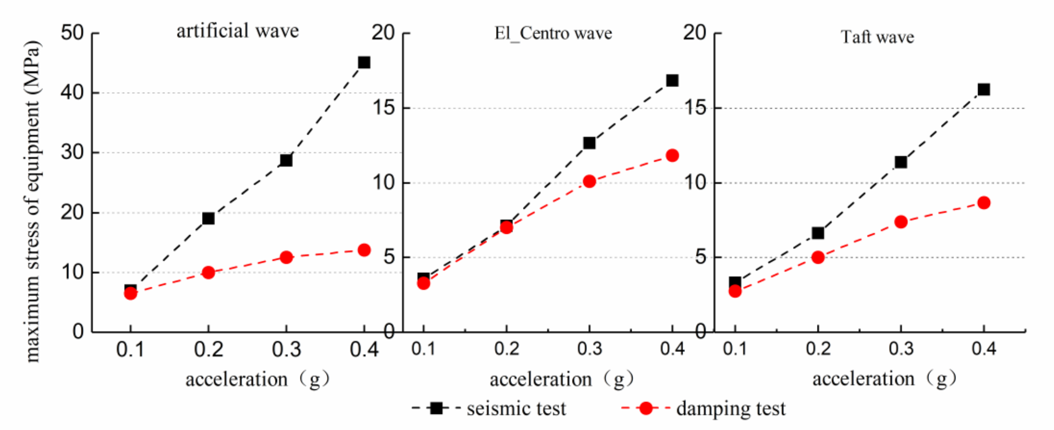


Fig. 4 Stress Trend Curves of Seismic and Damping Tests

Fig. 5 shows the trend curves of the damping coefficient. Under the effect of 3 seismic waves, the damping coefficient increases nonlinearly with the increase of PGA, indicating that the greater the seismic response of the equipment, the higher the damping coefficient of the damper. In the test under PGA = 0.4 g, the damping coefficient is up to 69.55%, 29.61% and 46.64%, respectively, showing a significant damping effect. The damping coefficient reaches its maximum under the effect of the artificial wave and the minimum under the effect of the El_Centro wave, which is related to the frequency spectrum characteristics of seismic waves. In the white noise test, the damper is in the pre-yield stiffness and functions as a connecting bolt, and is in the post-yield stiffness under the effect of seismic waves of strong ground motion. In the latter case, the equipment frequency reduces significantly. The frequency spectrum curve of seismic waves shows lower energy of the El_Centro wave and higher energy of the artificial wave at low frequency. With further consideration of the energy absorption and dissipation effect of the damper, the damping structure of the equipment shows a significant difference in the damping coefficient under the effect of 3 seismic waves.

Table 4 Stress Result of Seismic and Damping Tests

Test Condition	Seismic Test Stress/MPa	Damping Test Stress/MPa	Damping Coefficient
2	6.95	6.48	6.76%
3	19.01	10.01	47.34%
4	28.71	12.5	56.46%
6	45.09	13.73	69.55%
7	3.58	3.27	3.07%
8	7.12	7.01	3.33%
10	12.64	10.1	20.09%
11	16.82	11.84	29.61%
12	3.33	2.76	17.12%
14	6.63	5.02	24.28%
15	11.36	7.37	35.12%
16	16.23	8.66	46.64%

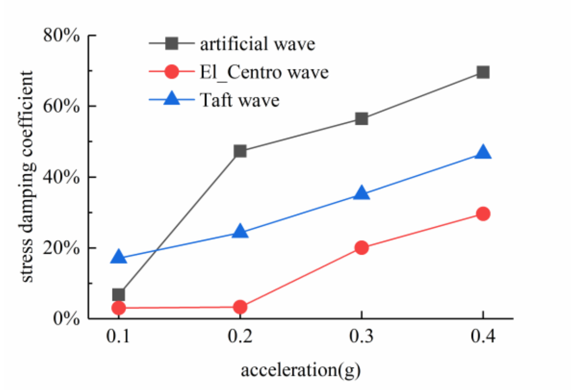


Fig. 5 Trend Curves of Damping Coefficient

5.3 Displacement Response Analysis

As composite electrical equipment is relatively flexible, attention shall also be paid to the displacement response under seismic actions. Since the displacement result obtained through the tests is an absolute value and the relative displacement of the structure under seismic actions is considered as a seismic performance indicator of the structure, the relative displacement result can be obtained by calculating the difference according to the time-history data of displacement of the shaking table and the top of the equipment. Table 5 shows the maximum relative displacement of the equipment under various operating conditions. For the equipment with a damper installed, the displacement damping coefficient at the top of the equipment is obtained with reference to the calculation formula of the damping coefficient and based on the displacement response in the seismic test.

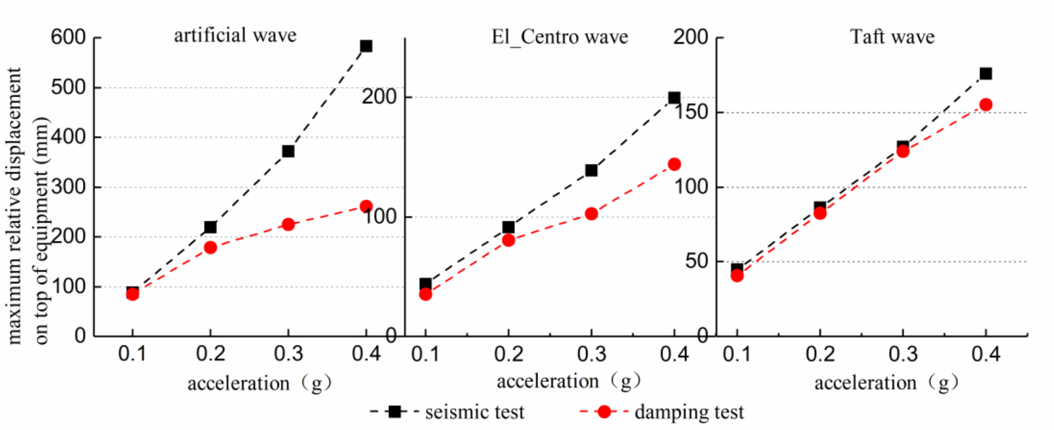


Fig. 6 Displacement Trend Curves of Seismic and Damping Tests

It can be seen from the displacement results in Table 5 that in the seismic test, the displacement response of the equipment reaches the maximum under the effect of the artificial wave and the minimum under the effect of the Taft wave; in the damping test, the displacement response reduces significantly under the effect of the artificial wave and slightly under the effect of the Taft wave, showing a significant difference under the effect of different seismic waves. In the test under PGA=0.4 g, the displacement damping coefficient is up to 55.15%, 27.89% and 11.82% respectively, showing a significant difference.

As shown in Fig. 6, the trend curves of displacement and PGA in the seismic and damping tests indicate a linear increase trend of the displacement response with the increase of PGA. As the damper is connected between the equipment and the support in series, the displacement deformation is inevitable during energy dissipation. As a result of the deformation at the bottom of the equipment, the displacement response at the top of the equipment increases accordingly, leading to inconsistency between the law of displacement change and the law of stress change in the damping test. As shown in Fig. 7, it can be seen from the trend curves of relative displacement damping coefficient of the equipment that under the same PGA of three seismic waves, the displacement damping coefficient is the most significant and has the trend to increase gradually with the increase of PGA under the effect of the artificial wave, which reaches the minimum under the effect of the Taft wave, and shows no significant changes of displacement under the effect of the Taft wave and the El_Centro wave.

Table 5 Displacement Result of Seismic and Damping Tests

Test Condition	Displacement in Seismic Test/mm	Displacement in Damping Test/mm	Damping Coefficient
2	87.87	84.98	3.29%
3	218.98	178.8	18.35%
4	372.13	224.42	39.69%
6	582.58	261.28	55.15%
7	43.57	35.5	18.52%
8	91.28	80.64	11.66%
10	139.09	102.7	26.16%
11	199.48	143.84	27.89%
12	44.7	40.72	8.90%
14	86.21	82.46	4.35%
15	126.94	123.97	2.34%
16	175.77	155	11.82%

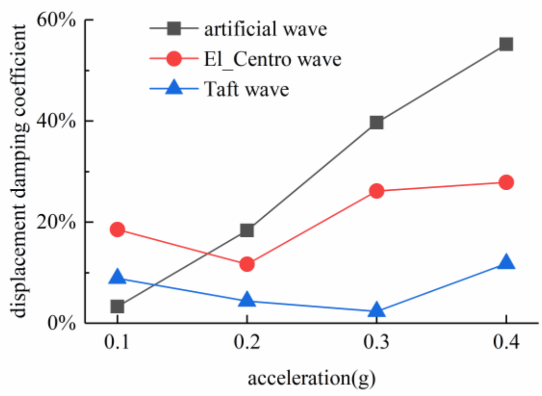


Fig. 7 Trend Curves of Displacement Damping Coefficient

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