Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Experimental Study on the Horizontal Vibration Isolation Performance of Foam Core Panels for Substation Foundations

Yongqiang Tian

182939516840163.com

State Grid Gansu Electric Power Company Longnan Power Supply Company

Xiaohu Chen

State Grid Gansu Electric Power Company Longnan Power Supply Company

Ziwang Cui

State Grid Gansu Electric Power Company Longnan Power Supply Company

Jiang Yan

State Grid Gansu Electric Power Company Longnan Power Supply Company

Yulong Qin

State Grid Gansu Electric Power Company Longnan Power Supply Company

Zhentao Li

State Grid Gansu Electric Power Company Longnan Power Supply Company

Yunjun Zhao

State Grid Gansu Electric Power Company Longnan Power Supply Company

Zihui Zhao

State Grid Gansu Electric Power Company Longnan Power Supply Company

Xiaohui Liu

State Grid Gansu Electric Power Company Longnan Power Supply Company

Jun Chen

State Grid Gansu Electric Power Company Longnan Power Supply Company

Article

Keywords: substation foundation, foam sandwich panel, horizontal isolation performance, experimental study

Posted Date: November 12th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11413052/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Experimental Study on the Horizontal Vibration Isolation Performance of Foam Core Panels for Substation Foundations

Yongqiang Tian[a,b], Xiaohu Chen[a], Ziwang Cui[a], Jiang Yan[a], Yulong Qin[a], Zhentao Li[a], Yunjun Zhao[a], Zihui Zhao[a], Xiaohui Liu[a], Jun Chen[a]

a) State Grid Gansu Electric Power Company Longnan Power Supply Company, Longnan, 730050 China

b) School of Civil Engineering, Lanzhou University of Technology, Lanzhou, Gansu 730050, China

Corresponding author: Yongqiang Tian, E-mail address: 18293951684@163.com

ABSTRACT

Seismic performance and structural safety of facilities shall be comprehensively considered in substation foundation design to maintain safe operation of substation facilities under seismic loading. A novel foam-sandwich-panel-based horizontal vibration isolation technology is proposed in this study to improve the horizontal seismic resistance of substation foundations. To investigate the vibration isolation response of substation foundations subjected to horizontal seismic excitation, a series of model tests were performed to assess the isolation performance of the vibration isolation system under different excitation frequencies. The influences of geometric design parameters of the foam sandwich-panel isolation structure on the vibration isolation effectiveness of the substation foundation were also examined. Test results reveal that the foam sandwich-panel isolation system achieves favorable horizontal vibration isolation performance over the entire excitation frequency range. Appropriate arrangement of foam

sandwich panels can substantially reduce the foundation's horizontal vibration response. The influence of panel thickness on isolation effectiveness varies with excitation frequency. Raising the elastic layer thickness of the sandwich panel, the width of the isolation surface, and the coverage range further improves the vibration isolation performance of the system.

KEYWORDS

substation foundation; foam sandwich panel; horizontal isolation performance; experimental study

1. Introduction

Seismic excitation poses a substantial threat to substation foundations and internal power facilities. Foundation slippage, subsidence or overturning may damage critical equipment such as transformers and high-voltage insulators, triggering large-scale power outages and endangering human life and property [1-2]. The 5.12 Wenchuan Earthquake damaged 171 substations of 35 kV and above, causing massive economic losses and hindering post-quake rescue. Conventional seismic designs strengthen structural stiffness yet cannot effectively block horizontal seismic transmission [3-5]. Accordingly, this work proposes a foam sandwich-panel vibration isolation scheme. Experimental investigations are performed to examine the isolation system's dynamic responses under varied excitation frequencies and quantify the effects of geometric parameters including core layer thickness, isolation surface width and laying range [6-7].

Domestic and international scholars have carried out extensive theoretical analyses, numerical simulations and model tests on building foundation vibration isolation [8-10]. Considerable achievements have been obtained regarding vibration isolation mechanisms, isolator material selection, air trench/wave barrier isolation systems, and foundation damping configurations [11]. Existing studies are mainly oriented toward civil buildings and transportation engineering [12-13]. Researchers have investigated key parameters including the modulus, thickness and laying range of isolation layers, revealed the dynamic response characteristics of foundations and superstructures under various excitation conditions, and established corresponding evaluation frameworks for vibration isolation performance, which lays a theoretical basis for the engineering implementation of foundation vibration isolation

technologies [14-15].

However, most existing studies concentrate on conventional buildings, while research concerning horizontal vibration isolation for foundations of special power infrastructures such as substations remains relatively limited. Substations house vibration-sensitive electrical equipment including transformers and high-voltage insulators, whose seismic isolation requirements differ markedly from those of conventional buildings [16-18]. Accordingly, this paper adopts foam sandwich panels as isolation components to experimentally investigate the horizontal vibration isolation performance of substation foundations [19-21]. The effects of varying excitation frequencies and geometric parameters on system isolation performance are explored. This work aims to supplement research on seismic isolation for power engineering foundations and offer technical references for seismic isolation design of substations in high-seismic-intensity regions [22-24].

Extensive research has been carried out on substation seismic isolation, predominantly focusing on isolation of electrical equipment supports and seismic mitigation of substation superstructures [25-26]. Numerical simulations and shaking table tests have been adopted to analyze the seismic protection performance of devices including rubber bearings and wire-rope dampers for vibration-sensitive electrical equipment such as transformers and instrument transformers, and to reveal the coupled dynamic response characteristics between equipment and foundations, providing theoretical support for the seismic design of power infrastructures [27-29]. Nevertheless, obvious limitations remain in existing studies. Most investigations concentrate on equipment-level isolation, whereas research on base horizontal seismic isolation of substation foundations is relatively scarce [30]. Conventional isolation bearings suffer from

high cost and complicated configuration [31-33]. Moreover, the parameter-dependent laws and isolation effectiveness of foam composite sandwich panels for horizontal base isolation of substation foundations have not been systematically verified experimentally [34-35].

To investigate the horizontal isolation performance of foam sandwich panels for substation foundations and reveal how different excitation frequencies and geometric parameters of sandwich panels affect the dynamic response of the isolation system, this paper designs and performs model tests to measure the dynamic characteristics of the isolation system under horizontal seismic excitation. The regulatory mechanism of each parameter on vibration isolation performance is analyzed, providing experimental evidence for the horizontal vibration isolation design of substation foundations in high-seismic-intensity regions.

2. Test Introduction

2.1 Test Overview

The model test was carried out in a steel model box with effective dimensions of 3.8 m (length) × 2 m (width) × 1.2 m (height). The box was filled with silty clay. Water was supplemented during filling, and the soil was compacted in layers, as illustrated in Figure 1. The physical and mechanical properties of the soil are listed in Table 1. To mitigate test errors induced by wave reflection at the bottom and peripheral boundaries of the model box, relatively soft materials were adopted for the boundary soil. The exciter, isolation barrier and vibration monitoring points were arranged sufficiently far from the box boundaries to minimize boundary effects.

Table 1 Physical and mechanical parameters of soil

ρ_s（kg/m^3）	E_s（MPa）	G_s（MPa）	ν_s

2000	60	23.08	0.3

Fig.1 shows the cross-sectional layout of the model test, including harmonic excitation Pe^{iwt}, foam sandwich-panel isolation barrier and acceleration sensors. Nine acceleration sensors A1–A9 are arranged on the ground surface with 400 mm spacing to capture vibration responses and evaluate horizontal isolation performance. The load application point is 400 mm away from the left boundary of the model box. The horizontal distance from the load center to sensor A1 is 100 mm, and the spacing between adjacent measuring points is 400 mm. The horizontal distances from sensors A1 to A9 to the left boundary of the model box are 500 mm, 900 mm, 1300 mm, 1700 mm, 2100 mm, 2500 mm, 2900 mm, 3300 mm and 3700 mm, respectively. To eliminate interference caused by reflected vibration waves at boundaries, the effective measuring points are arranged in the region far from the boundaries of the model box.

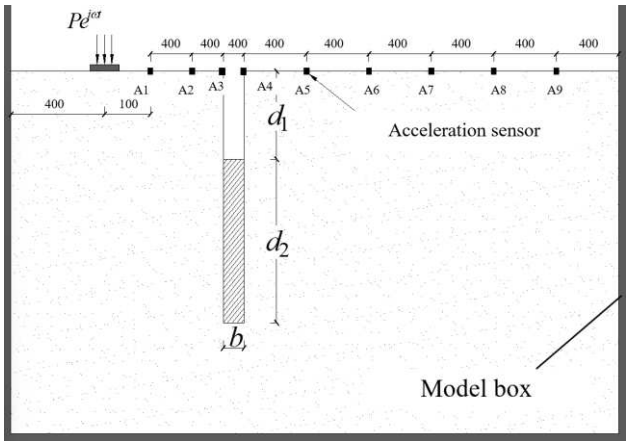


Fig.1 Model test schematic diagram

In this experiment, color steel EPS foam sandwich panels were used. The panels were composed of upper and lower color steel facing layers and polystyrene foam core material. The thickness of the core material used in the test was 50mm, and the facing layer was galvanized steel plate, as shown in Fig. 2. The physical and mechanical parameters of the corrugated plate are presented in Table 2.

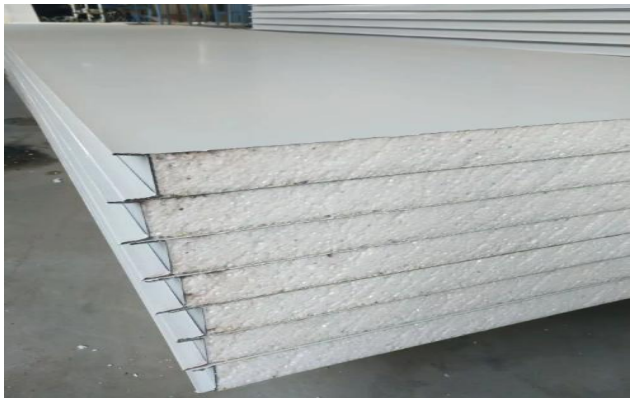


Fig. 2 Foam core board used in the test

Table 2 Physical and mechanical parameters of WIB

ρ_w （kg/m^3）	E_w （GPa）	G_w （GPa）	ν_w
2400	30	11.54	0.3

After the filling of the model box is completed, the surface of the foundation is leveled to install the exciter and vibration sensor. The trenches are excavated using a Luoyang shovel, as shown in Fig. 3.



Fig. 3 Installation Diagram of Exciter and Vibration Sensor

2.2 Test plan

A total of 15 different operating conditions were designed for the tests, taking into account the effects of the depth of the foam core panel, the depth of the wave-blocking plate, the

thickness of the barrier, and the length of the barrier. The excitation frequencies used in the tests were 6Hz and 20Hz. Table 3 presents the model test plan.

Table 3 Model test plan (cm)

	Number	Depth	Thickness	Length
No vibration isolation	1	0	0	0
Depth of foam core board	2	20	10	80
	3	30	10	80
	4	40	10	80
	5	20	10	80
Thickness of foam core board	6	20	5	80
	7	20	10	80
	8	20	20	80
Length of foam core board	9	20	10	40
	10	20	10	60
	11	20	10	80

2.3 Testing equipment

The excitation system consists of the German APS400 type exciter and the corresponding signal generator; among them, the maximum excitation force of the APS400 type exciter is 445N, and the frequency range is from DC to 200Hz. The measurement system is composed of sensors and data acquisition instruments; among them, the sensor is the 941B type vibration sensor; the data acquisition instrument is the INV3018CT type 24-bit high-precision data acquisition instrument, and it is equipped with the DASP V11 data acquisition and analysis

104 software.

105 **2.4 Data analysis plan**

106 As shown in Equation (1), the vibration isolation effect of the combined barrier is
107 represented by the amplitude attenuation coefficient A_r. Clearly, the smaller the value of A_r, the
108 better the vibration isolation effect.

$$A_r = \frac{a_1}{a_0} \quad (1)$$

109 where a_1 represents the amplitude of acceleration at the monitoring point when there is an
110 isolation barrier. a_0 represents the amplitude of acceleration at the monitoring point when there
111 is no vibration isolation barrier.

112 **3. Analysis of test results**

113 **3.1 Comparison of experiments with numerical results**

114 Numerical simulations were conducted using finite element software and compared with the
115 results of model tests. The comparison results are shown in Fig.4. The model size is 3.8 m × 2
116 m × 1.2 m. A free tetrahedral mesh was used for grid division, and the element size was set as
117 $1/8L_R$. The absorbing boundary adopted a perfect matching layer. Based on the soil parameters,
118 the Rayleigh wave velocity in the foundation soil was obtained as V_R = 100 m/s. The frequency
119 similarity coefficient derived from the elastic similarity law was used in the finite element
120 model, and the excitation frequency was set at 5 Hz. To provide a more intuitive observation,
121 the Rayleigh wave wavelength LR was used to perform dimensionless processing of each
122 geometric parameter in the numerical simulation results.

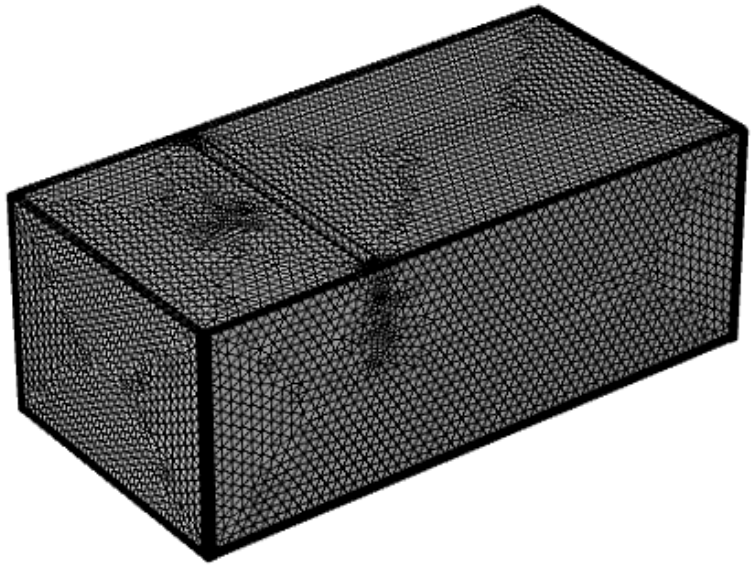


Fig. 4 Finite Element Model Grid

The test results were verified and compared using the finite element numerical simulation method. As shown in Fig.5, the overall trend of the measured curve from the test and the calculated curve by the finite element method is highly consistent, and the numerical deviation is small.

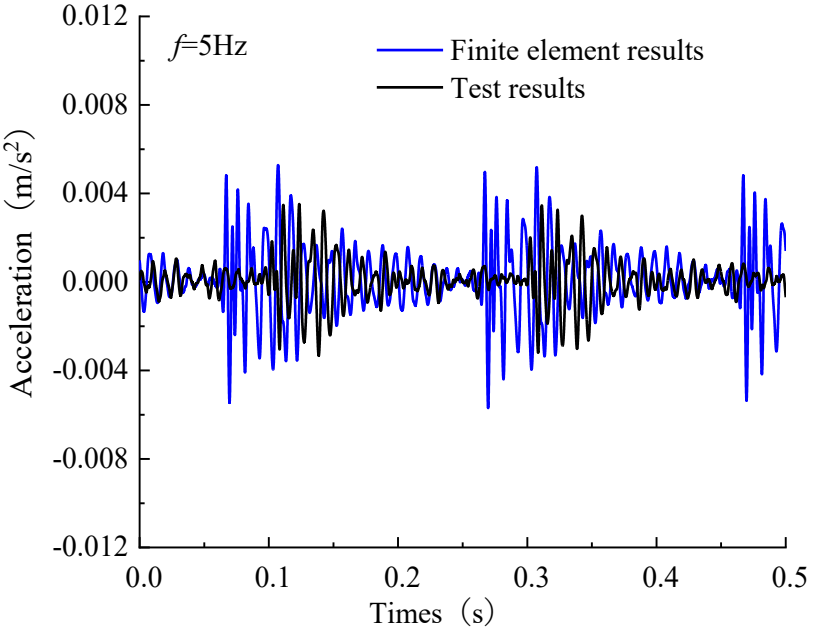
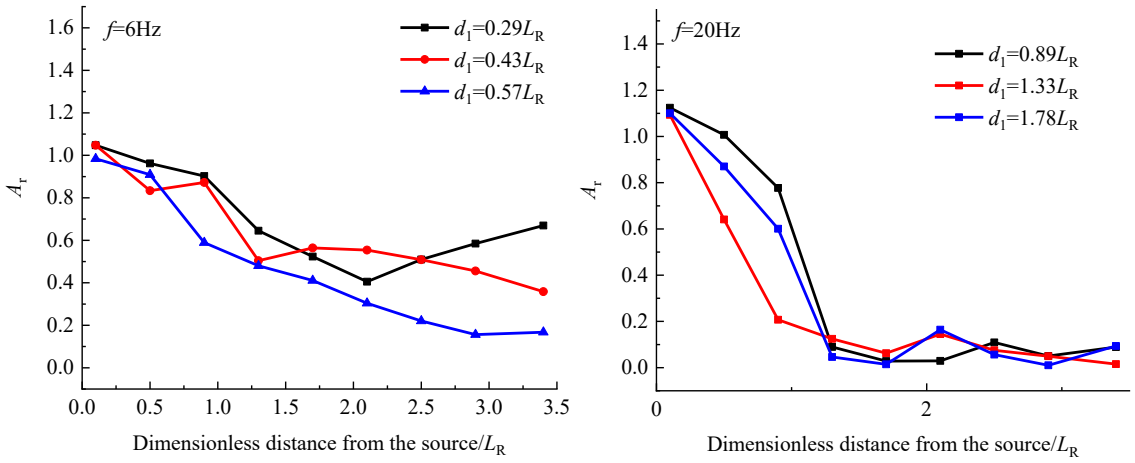


Fig. 5 Comparison between experiments and numerical simulations

3.2 Parameter Analysis

In the model test, the designed thicknesses of the foam sandwich panels were 0.29 L_R, 0.43L_R, and 0.57 L_R respectively. The influence of the analysis depth on the vibration isolation effect of the foam sandwich panels was analyzed. In the finite element model, the corresponding similar models were established. Fig.6 shows the curves of the attenuation coefficient of the ground acceleration amplitude obtained from the model test and the numerical model respectively. In the figure, A1 to A9 are all the vibration monitoring point positions set in the model test.



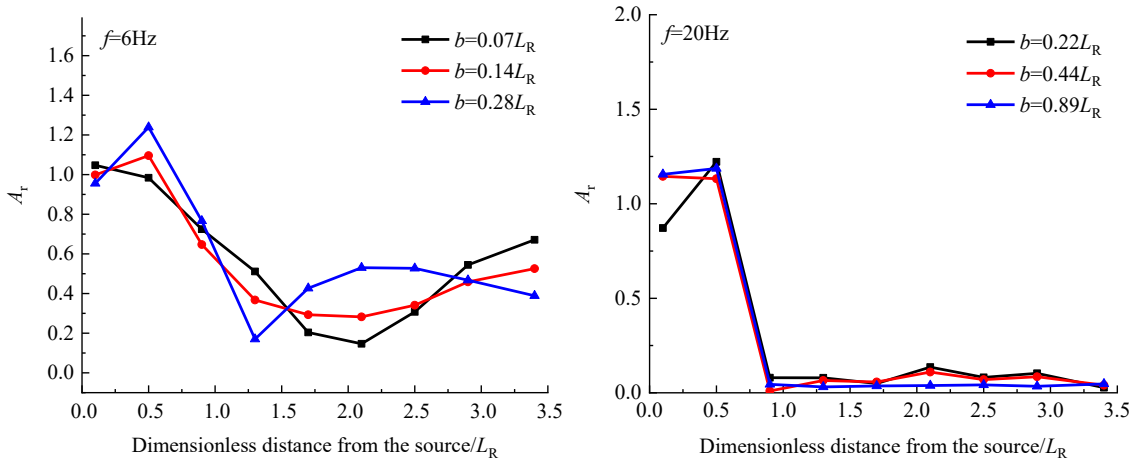
(a) f = 6Hz (b) f = 20Hz

Fig.6 Effect of depth of foam sandwich plate on vibration isolation performance

By comparing the amplitude attenuation coefficient curves at different depths in Figure 7, it can be seen that the depth has a significant impact on the vibration isolation effect of the foam sandwich panel. Here, when the frequency is relatively high (f = 6Hz), increasing the depth is beneficial for vibration isolation, and it will reach a relatively ideal vibration isolation effect until then. Through the above analysis, it can be known that generally speaking, when the conditions permit, appropriately increasing the depth is beneficial for the vibration isolation of

the combined barrier; when f = 20Hz, the change in the depth of the foam sandwich panel has little effect on the vibration isolation effect, because at this time, the depth is relatively large compared to the wavelength of this frequency, and it has achieved a very ideal vibration isolation effect. Through the above analysis, it can be known that generally speaking, when the conditions permit, appropriately increasing the depth is beneficial for the vibration isolation of the combined barrier; however, due to the change in depth causing a corresponding change in the burial depth of the foam sandwich panel, when the frequency is very low, the change pattern is difficult to predict, and the design should be carried out according to the actual situation.

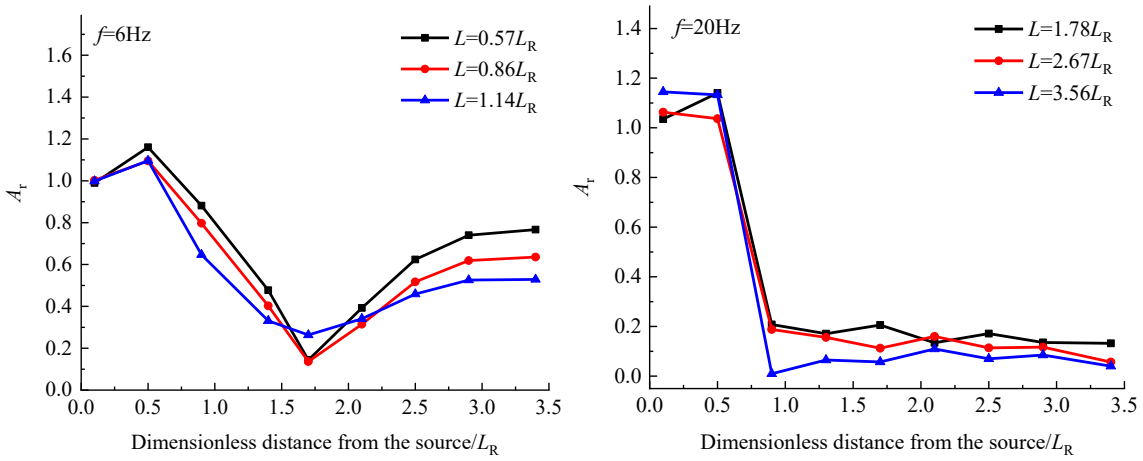
The thicknesses of the designed barriers were 0.07 L_R, 0.14 L_R and 0.28 L_R respectively. Fig. 7 shows the curves of the attenuation coefficients of the ground acceleration amplitudes when the excitation frequencies were 6 and 20 Hz. From Fig. 7, it can be observed that the vibration isolation effect of the foam sandwich panel gradually improves as the thickness of the barrier increases. At f = 20 Hz, since the wavelength of the vibration wave is relatively short at this time, the combined barrier can already achieve a very ideal vibration isolation effect, so further increasing the thickness of the barrier has no effect.



(a) f = 6Hz (b) f = 20Hz

Fig.7 The influence of foam sandwich plate thickness

The lengths of the designed barriers are 0.57L_R, 0.86 L_R and 1.14 L_R respectively. Fig. 8 shows the curve of the attenuation coefficient of ground acceleration amplitude obtained from the model test. From Fig. 8, it can be observed that the improvement effect is more obvious in the areas closer to the vibration source, while it gradually weakens as the distance increases. At higher frequencies, the improvement effect is very significant.



(a) f = 6Hz (b) f = 20Hz

Fig. 8 The influence of the length of foam sandwich panels

To study the influence of the change in the elastic modulus of the wave-damping plate on the vibration isolation effect of the foam sandwich panel, the depth of the foam sandwich panel was set as $d_1 = 0.2L_R$ and $d_2 = 0.4L_R$. Considering the elastic modulus ratios between the foam sandwich panel and the elastic foundation as E_w/E_s = 0.001, 0.01, 1, 100, 1000, the vibration isolation effect of the combined isolation barrier was observed and the calculation results are shown in Fig.9.

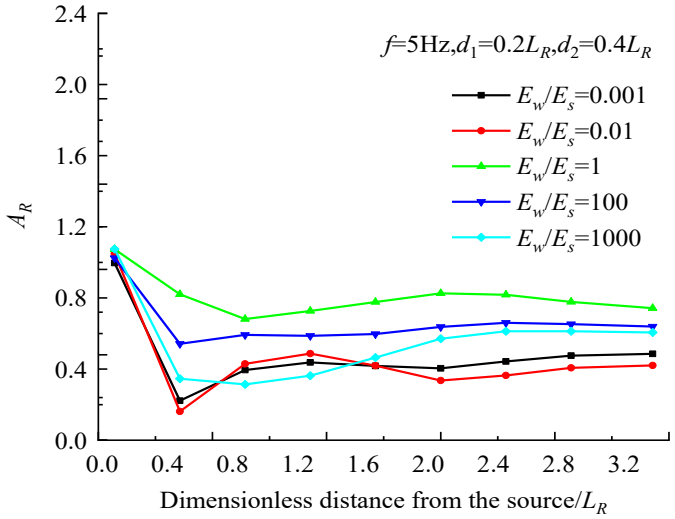


Fig. 10 Effect of elastic modulus of foam sandwich panel on vibration isolation

From Fig.9, it can be seen that the closer the elastic modulus of the foam sandwich panel and the elastic foundation are, the worse the vibration isolation effect is. The vibration isolation effect is the worst when $E_w/E_s = 1$; moreover, by comparing the vibration isolation effects of $E_w/E_s > 1$ and $E_w/E_s < 1$, it is found that the vibration isolation effect of $E_w/E_s > 1$ is better than that of $E_w/E_s < 1$. This indicates that the elastic modulus of the foam sandwich panel is greater than that of the elastic foundation, and the combined vibration isolation barrier has a better vibration isolation performance. In the design of the vibration isolation barrier, the elastic modulus of the wave resistance plate can be adjusted to obtain a better vibration isolation effect.

3.3 Vibration Isolation Effect Analysis

To evaluate the horizontal vibration isolation performance of foam core boards, harmonic excitation with a frequency of f=100Hz was adopted in the test. Fig. 10 presents the horizontal vibration responses of the test model under two working conditions, i.e., with and without the foam core board. It can be observed from Figure 10 that the installation of foam core boards significantly suppresses the acceleration amplitude, demonstrating an obvious vibration attenuation effect. Accordingly, applying foam core boards to the horizontal vibration isolation

of substation foundations can effectively mitigate the vibration impact induced by earthquakes and other external vibration sources on substation structures.

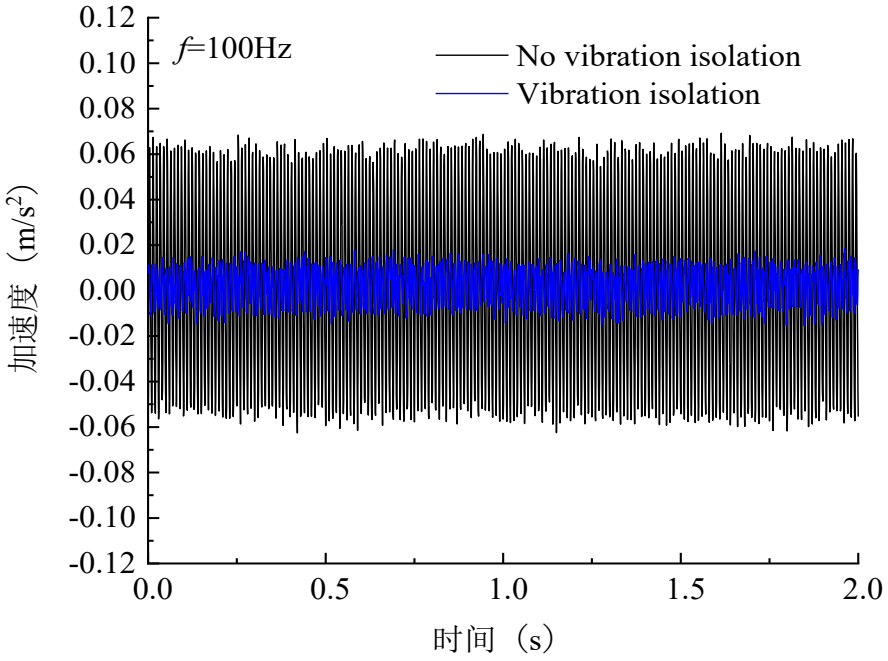


Fig.10 Comparison of with and without vibration isolation

4.Conclusions

In this paper, to improve the horizontal seismic performance of substation foundations, this paper presents a novel horizontal vibration isolation technique employing foam core panels. Model tests were carried out to explore the vibration response characteristics of the isolation system under excitation with different frequencies, and to analyze the effects of geometric parameters on the vibration isolation performance. The main conclusions are drawn as follows:

(1) Increasing the depth of foam core panels contributes to the vibration isolation performance of the isolation barrier, while such improvement becomes insignificant under low-frequency excitations.

(2) The vibration isolation performance of the barrier improves with the increase in the depth,

thickness and length of the foam core panel.

(3) Compared with the barrier without vibration isolation measures, the foam core panel barrier exhibits favourable vibration isolation performance across various excitation frequencies.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (52408368), Lanzhou University of Technology Hongliu outstanding young talent support program.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

REFERENCES

[1] Liang H, Blagojevic N, Xie Q, et al. Seismic risk analysis of electrical substations based on the network analysis method[J]. Earthquake Engineering & Structural Dynamics, 2022, 51(11): 2690-2707.

[2] Liang H, Xie Q. System vulnerability analysis simulation model for substation subjected to earthquakes[J]. IEEE Transactions on Power Delivery, 2021, 37(4): 2684-2692.

[3] Wang Y. Lessons learned from the “5.12” Wenchuan Earthquake: evaluation of earthquake performance objectives and the importance of seismic conceptual design principles[J]. Earthquake engineering and engineering vibration, 2008, 7(3): 255-262.

[4] Wang Y, Zhong X, Wang Q, et al. Mechanism and Characteristics of Jishixiongguan

Failure Induced by Jishishan MS6. 2 Earthquake, China[J]. Shock and Vibration, 2025, 2025(1): 5424830.

[5] Wang X, Wang Y, Li Y, et al. Correlation between the excess cavity gas pressure and the dynamic response of a slope cavity under strong earthquake conditions[J]. Soil Dynamics and Earthquake Engineering, 2025, 191: 109222.

[6] Gao G, Li N, Gu X. Field experiment and numerical study on active vibration isolation by horizontal blocks in layered ground under vertical loading[J]. Soil Dynamics and Earthquake Engineering, 2015, 69: 251-261.

[7] Liu J, Li X, Cao J, et al. Geometric parameter effects on bandgap characteristics of periodic pile barriers in passive vibration isolation[J]. Symmetry, 2024, 16(9): 1130.

[8] Yao X, Wu B. Progress in seismic isolation technology research in soft soil sites: A review[J]. Buildings, 2024, 14(10): 3198.

[9] Domadzra Y, Bhandari M, Hasan M. Seismic response of base-isolated buildings: exploring isolator properties[J]. Asian Journal of Civil Engineering, 2024, 25(5): 4197-4209.

[10] Cheng X, Li Q, Hai R, et al. Research progress and prospects of seismic performance on underground structure embedded in soft soil foundation[J]. Scientific Reports, 2024, 14(1): 21883.

[11] Mazumdar A, Sarkar A, Barman R, et al. Barrier-based ground vibration mitigation: a state-of-the-art review[J]. Innovative Infrastructure Solutions, 2026, 11(7): 405.

[12] Liu Y, Deng Y, Liu Z, et al. Integration of building information modeling (BIM) with transportation and facilities: Recent applications and future perspectives[J]. Buildings,

2024, 14(2): 541.

[13] Taheri A, Sobanjo J. Civil integrated management (CIM) for advanced level applications to transportation infrastructure: A state-of-the-art review[J]. Infrastructures, 2024, 9(6): 90.

[14] Yang Z, Sun J, Zhang Y, et al. A systematic evaluation of the empirical relationships between the resilient modulus and permanent deformation of pavement materials[J]. Buildings, 2025, 15(5): 663.

[15] De Carolis S, Putignano C, Soria L, et al. Effect of porosity and pore size distribution on elastic modulus of foams[J]. International Journal of Mechanical Sciences, 2024, 261: 108661.

[16] Swain A, Abdellatif E, Mousa A, et al. Sensor technologies for transmission and distribution systems: A review of the latest developments[J]. Energies, 2022, 15(19): 7339.

[17] Secic A, Krpan M, Kuzle I. Vibro-acoustic methods in the condition assessment of power transformers: A survey[J]. IEEE access, 2019, 7: 83915-83931.

[18] Lin Y S, Chan R W K, Tagawa H. Earthquake early warning-enabled smart base isolation system[J]. Automation in Construction, 2020, 115: 103203.

[19] Hu Z W, Xu Z D, Zhang L Y, et al. Full-scale shaking table test on a precast sandwich wall panel structure with a high-damping viscoelastic isolation and mitigation device[J]. Engineering Structures, 2025, 329: 119797.

[20] Zhu H, Guo T, Zhi G, et al. Effects and Control Mechanisms of Isolation Barriers on Metro Train-Induced Building Vibrations[J]. Applied Sciences, 2026, 16(16): 8125.

[21] Lu Z, Brennan M J, Yang T, et al. An investigation of a two-stage nonlinear vibration isolation system[J]. Journal of Sound and Vibration, 2013, 332(6): 1456-1464.

[22] Cao X, Zhou F, Liu J, et al. Experimental study and numerical analysis for vibration isolation performance on open trench and wave impeding block combined vibration isolation barrier[J]. Soil Dynamics and Earthquake Engineering, 2024, 177: 108418.

[23] Le T D, Ahn K K. A vibration isolation system in low frequency excitation region using negative stiffness structure for vehicle seat[J]. Journal of Sound and Vibration, 2011, 330(26): 6311-6335.

[24] Cao X, Yang Z, Zhou F, et al. Horizontal vibration characteristics of end bearing pile under SH wave in saturated frozen soil considering the influence of superstructure[J]. Soil Dynamics and Earthquake Engineering, 2026, 202: 110046.

[25] Saadeghvaziri M A, Feizi B, Kempner Jr L, et al. On seismic response of substation equipment and application of base isolation to transformers[J]. IEEE Transactions on power delivery, 2009, 25(1): 177-186.

[26] Li Y, Jiang H, Ning Z, et al. Influence of Equipment–Structure Interaction on Seismic Response of Seismically Isolated Substation Building[J]. Journal of Earthquake and Tsunami, 2026: 2650008.

[27] Li Y, He Y, Liu Y, et al. Effect of site soil and bus bars on the seismic performance of an isolated power transformer[J]. Journal of Earthquake and Tsunami, 2024, 18(02): 2350039.

[28] Cao X, Yang Z, Zhou F, et al. Analysis of horizontal dynamic response of end-bearing piles in saturated frozen soil under hydro-thermo-mechanical-seismic coupling effects[J]. Cold Regions Science and Technology, 2026: 104880.

[29] Chen S, Guo X, Luo J, et al. Seismic response mitigation of indoor substation prefabricated steel frames using a dual-layer hybrid isolation system: An experimental and numerical

study[J]. Journal of Building Engineering, 2025: 114521.

[30] Li S, Tsang H H, Cheng Y. Shaking table tests on geotechnical seismic isolation of electrical transformers using recycled tire rubber-soil mixtures[J]. Construction and Building Materials, 2025, 497: 143886.

[31] Nie G, Wang Z, Shi Y, et al. Shaking table test of three-dimensional base-isolated liquid storage tanks in power plants[J]. Soil Dynamics and Earthquake Engineering, 2026, 200: 109793.

[32] Rajabnejad H, Hamidi H, VaseghiAmiri J. Experimental investigation of a novel suspended column pendulum isolation system[J]. Soil Dynamics and Earthquake Engineering, 2026, 209: 110461.

[33] Morales C A. A new approach to inertial damper design to control base displacement in isolated buildings[J]. Journal of Vibration and Control, 2022, 28(23-24): 3539-3549.

[34] Xue H, Zhang J, Xu J, et al. Seismic response of disconnected piled raft foundations: effects of cushion layer types based on shaking table tests[J]. Soil Dynamics and Earthquake Engineering, 2026, 200: 109863.

[35] Zhang C, Zhang N, Wang J, et al. Vibration reduction and isolation performance of a platform foundation and column base of an ancient wooden structure based on the energy transfer analysis[J]. Journal of Low Frequency Noise, Vibration and Active Control, 2022, 41(3): 1178-1191.