DAMPING EFFECT OF DOUBLE FRICTION PENDULUM BEARINGS FOR CIVIL BUILDINGS SUBJECTED TO EARTHQUAKES CONSIDERING VERTICAL EXCITATION FORCES

Hoang Phuong Hoa*

The University of Danang - University of Science and Technology, Vietnam

*Corresponding author: hphoa@dut.udn.vn

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Abstract - Earthquakes pose significant threats to humanity, with recent years witnessing an increase in both the intensity and frequency of seismic events worldwide. To mitigate the damage caused by earthquakes, various techniques have been developed. This article focuses on the application of Double Friction Pendulum (DFP) bearings for base isolation in three-story steel construction projects. The authors develop a system of differential equations describing the motion of the structural system equipped with DFP bearings. The Runge-Kutta numerical method, specifically the ode15s function in MATLAB, was used to solve these equations. The results of the calculations provide a comparison of the damping efficiency of the structural system with and without the use of DFP bearings, assessing the effectiveness of vibration isolation during an earthquake, with three components X, Y, and vertical considered.

Key words – Earthquake; structural control; base isolation; double friction pendulum bearings.

1. Introduction

The world has experienced many earthquake disasters. Some of the earthquakes that have occurred have caused great damage to people and property. The Tohoku earthquake of about 9 on the Richter scale caused a tsunami in Japan on March 11, 2011, causing estimated damage of about 360 billion USD. On June 2, 2023, a 7.8-magnitude earthquake in Turkey killed more than 55,700 people and collapsed many houses and bridges. Recently, at 11:35 on July 28, 2024, an earthquake with an epicenter in Kon Plong district, Kon Tum province, Vietnam with a magnitude of about 4.8 to 5 on the Richter scale made us feel it very clearly when we were several hundred kilometers away from the epicenter.

To minimize the damage caused by earthquakes to construction works such as bridges, roads, houses, dams, etc., the design of earthquake-resistant structures is an important task for design engineers. According to the modern design perspective, the concept of earthquake-resistant structural control has been proposed and divided into 3 main types: Active structural control; Passive, and Semi-Active. In this article, the author will introduce passive earthquake-resistant structural control techniques, using measures to isolate the structure's vibrations from the ground acceleration of earthquakes [1, 2].

For an earthquake to occur, the source of the vibrations is called the focus, while the point directly above it on the Earth's surface is known as the epicenter. The distance from the focus to the epicenter is referred to as the depth of the earthquake. An earthquake is classified as shallow when the focus is located at a depth of approximately 70 km or less. For example, the Gorkha earthquake that struck Nepal on April 25, 2015, measured 7.8 on the Richter scale and had a depth of 15 km, classifying it as a shallow earthquake.

In the past, due to various reasons such as limited calculation tools and the relatively minor impact of vertical shaking forces on structures, this influence was often overlooked. However, advances in technology and calculation equipment have changed this perspective. It is now understood that structures located near the epicenter are more significantly affected than those farther away. As a result, scientists believe that the influence of vertical shaking forces on structures near the epicenter is an important factor that must be considered.

This paper investigates the impact of vertical excitation forces on the motion and damping performance of structures mounted on Double Friction Pendulum Bearings (DFP), as illustrated in Figure 1.

The DFP bearing was calculated in detail for the bearing motion by D.M. Fenz in the research group of M.C Constantinou [3, 4] in 2006 and completed in 2008. The DFP bearing consists of two curved surfaces of radius R_1, and R_2 and a pendulum sliding on the two curved surfaces with friction coefficients $\mu_1 < \mu_2$. The horizontal displacement capacity of the bearing $d_{out} = d_1 + d_2$ (Figure 1).

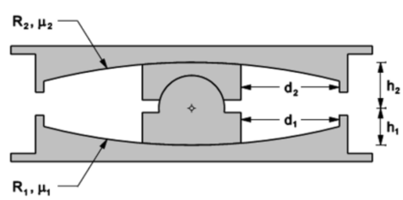

Figure 1. *Cross section of DFP pillow*

Studies on the influence of vertical earthquake excitation forces on construction are still quite limited. In Vietnam, a research group led by Hoa et al. conducted a study in 2021 [14] that examined the impact of vertical excitation forces in a general model applied to an 11-story steel frame. Additionally, Nam et al. investigated the influence of vertical excitation forces specifically for SFP friction sliding pendulum bearings [9].

Some foreign authors, such as Faramarz et al. [15], studied earthquake-resistant friction sliding double-surface bearings in 2010 for structures located near and far from the epicenter. Their research findings indicated that structures near the epicenter experience greater seismic forces than those located farther away. In 2019, Zhou et al. [16] examined the theoretical movement of DFP bearings while considering the vertical excitation force of earthquakes. Additionally, experimental research on a scaled 5-story steel structure model conducted by a research group led by Dao [17, 18] at the University of Nevada, USA, demonstrated that the influence of the vertical excitation force is significant and warrants attention.

It is evident that both domestic and foreign research primarily focuses on high-rise buildings or structures with large weights. However, many civil works, including the headquarters of small and medium-sized enterprises in Vietnam, are currently being built as 3 to 5-story buildings, and proper seismic design considerations for these smaller structures are lacking. This article will focus on studying the damping effect of friction-slip double-sided pendulum bearings, taking into account the vertical excitation force for low-rise buildings that are increasingly common in Vietnam, yet have not received adequate attention from designers and seismic design standards.

2. Structural calculation model with DFP bearings

2.1. Equation of motion [5, 6]

The DFP bearing has 2 friction elements. The first element is the sliding on surface 1 with the physical characteristics: mass m_{b1}, stiffness k_{b1}, friction coefficient μ_1, and sliding capacity d_1. The second element is the sliding on surface 2 with the physical characteristics: mass m_{b2}, stiffness k_{b2}, friction coefficient μ_2, and sliding capacity d_2.

Connecting the model of DFP bearing and the structure, we have the structural model with DFP bearing as shown in Figure 2. The system will have (*n+2)* degrees of freedom.

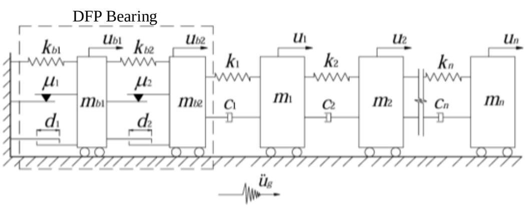

Figure 2. *Calculation model of seismic isolation structure using DFP bearings*

The stiffnesses k_{b1} and k_{b2} are determined from the restoring force component of the sliding equation, respectively on surfaces 1 and 2 as follows:

$$\begin{cases} k_{b1} = \dfrac{W}{R_{eff1}} \\ k_{b2} = \dfrac{W}{R_{eff2}} \end{cases} \quad (1)$$

where: W is the total weight above the bearing, R_{eff1} is the effective radius of curvature of sliding surface 1 and R_{eff2} is the effective radius of curvature of sliding surface 2.

Mass m_{b2} is the mass of the second sliding surface and m_{b1} is the mass of the pendulum (usually has a very small value). The mass is determined equivalent to the mass of a floor, denoted by m_i (*i* from 1 to *n* floors). The system of differential equations of motion of the seismic isolated DFP bearing structural system subjected to ground acceleration $\ddot{u}_g$ including *(n+2)* equations, is written as follows:

$$\begin{cases} m_{b1}(\ddot{u}_{b1}+\ddot{u}_g)+k_{b1}u_{b1}+F_{f1}+F_{r1}+k_{b2}(u_{b1}-u_{b2})-F_{f2}-F_{r2}=0 \\ m_{b2}(\ddot{u}_{b2}+\ddot{u}_g)+k_{b2}(u_{b2}-u_{b1})+F_{f2}+F_{r2}+k_1(u_{b2}-u_1)+c_1(\dot{u}_{b2}-\dot{u}_1)=0 \\ m_1(\ddot{u}_1+\ddot{u}_g)+k_1(u_1-u_{b2})+c_1(\dot{u}_1-\dot{u}_{b2})+k_2(u_1-u_2)+c_2(\dot{u}_1-\dot{u}_2)=0 \\ \ldots \\ m_n(\ddot{u}_n+\ddot{u}_g)+k_n(u_n-u_{n-1})+c_n(\dot{u}_n-\dot{u}_{n-1})=0 \end{cases} \quad (2)$$

The frictional force components on the curved surfaces in equation (2) are determined as follows:

$$\begin{cases} F_{f1} = \mu_1 W Z_1 \\ F_{f2} = \mu_2 W Z_2 \end{cases} \quad (3)$$

in there:

$$\mu = \mu_{\max} - (\mu_{\max} - \mu_{\min})e^{-\alpha|\dot{u}|} \quad (4)$$

with μ_{max} and μ_{min} being the coefficients of friction corresponding to the largest and smallest sliding velocities, α (s/m) being a constant depending on the surface pressure corresponding to each material, and $\dot{u}$ being the sliding velocity. The value of function Z is determined from the differential equation (5).

$$Y\dot{Z} + \gamma|\dot{u}|Z|Z|^{\eta-1} + \beta\dot{u}Z^{\eta} - A\dot{u} = 0 \quad (5)$$

Combining the Bouc-Wen model and experiments, Constantinou et al. proposed a model to determine the friction force in sliding bearing devices with high precision, specifically the friction coefficient is determined in equation (4), and the friction force is determined in equation (6). The constants in equation (5) including *A, Y,* β, γ and η are also determined by the author from experiments [10, 11].

$$F_f = \mu W Z \quad (6)$$

The impact force components are determined by equation (7).

$$\begin{cases} F_{r1} = k_{r1}(|u_{b1}| - d_1)sign(u_{b1})H(|u_{b1}| - d_1) \\ F_{r2} = k_{r2}(|u_{b2} - u_{b1}| - d_2)sign(u_{b2} - u_{b1})H(|u_{b2} - u_{b1}| - d_2) \end{cases} \quad (7)$$

The system of differential equations of motion (2) will be solved by the fourth-order Runge-Kutta numerical method (using the ode15s function in Matlab) to determine the response of the structure and DFP.

2.2. Effect on vertical ground acceleration

For structures located near the epicenter, the reality shows that the influence of the vertical excitation force (perpendicular to the plane created by X and Y) is often much greater than that of structures located far from the epicenter. Therefore, when considering the vertical excitation component, the total weight above the bearing W will change (plus the inertial force component caused by the vertical ground acceleration A_z [7, 8, 9]. When considering the vertical excitation force, we consider the entire structure above as a rigid block with a variable weight $V_{(t)}$ and determined as follows:

$$V_{(t)} = W\left(1 + \frac{\ddot{a}_{gz}}{g}\right) \quad (8)$$

in which: $\ddot{a}_{gz}$ is the vertical acceleration component of the ground (creating the vertical excitation force), and g is the acceleration of gravity. We see that in equation (8) if we do not consider the vertical acceleration of the ground ($\ddot{a}_{gz}$ = 0), $V_{(t)}$ is equal to W of the structural system again as calculated in the plane created by the X and Y axes.

3. Numerical example analysis

To illustrate the structural behavior through the above mathematical model and evaluate the damping efficiency of the seismic isolation device, a numerical example is analyzed as follows.

The assumed analysis structure is a three-story steel building. The technical parameters are presented in Table 1.

Table 1. *Structure parameters*

Parameter	Symbol	Unit	Value
Damping ratio	ξ	%	5
Stiffness of each floor	k_i	kN/mm	60
Mass of each floor	m_i	kNs^2/mm	0.513
Time period	T_1	S	0.713

The specifications of the DFP bearings selected in this analysis are shown in Table 2.

Table 2. *DFP parameters*

Parameter	Symbol	Unit	Value
Slide radius 1	R_1	mm	3000
Slide radius 2	R_2	mm	3000
Height from the radius of curvature of the sliding surface 1 to the center of the spindle (Figure 1)	h_1	mm	40
Height from the radius of curvature of the sliding surface 2 to the center of the spindle (Figure 1)	h_2	mm	60
Horizontal travel of bearing for sliding surface 1	d_1	mm	500
Horizontal travel of bearing for sliding surface 2	d_2	mm	500
Coefficient friction of sliding surface 1	μ_1	-	0.04-0.06
Coefficient friction of sliding surface 2	μ_2	-	0.06-0.08
Correction factors	A	-	1
	Y	mm	0.25
	Γ	-	0.9
	B	-	0.1
	H	-	2
Friction coefficient correction parameter	α	s/mm	0.02

The ground acceleration data is the actual acceleration tape of the Northridge earthquake taken from [12]. The horizontal acceleration profile is shown in Figure 3. The peak acceleration of this acceleration tape is 0.874g.

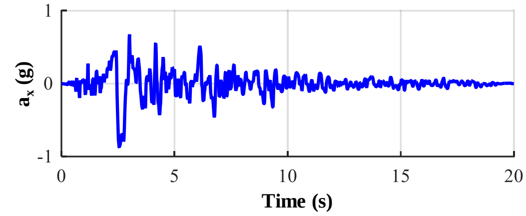

Figure 3. *Horizontal ground acceleration*

This earthquake had a very large vertical component, the vertical PGA value was 0.958g. The vertical acceleration profile is presented in Figure 4.

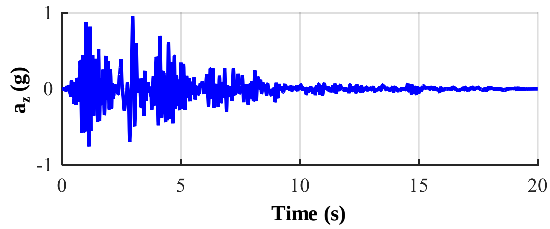

Figure 4. *Vertical ground acceleration*

To see the dominant period of the accelerating band, the response spectrum is analyzed as illustrated in Figure 5. The dominant period of this accelerating band is near the region 0.7 s.

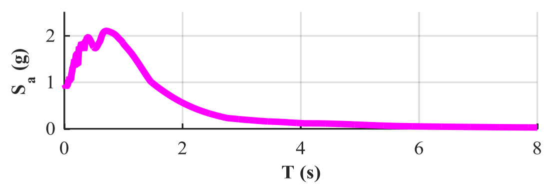

Figure 5. *Response spectrum of horizontal acceleration*

3.1. Evaluation of seismic insulation performance of DFP bearings

Time history analysis of the model for the case of ignoring vertical ground acceleration was performed using a numerical solution. The response of absolute deceleration efficiency for the first and third floors is plotted in Figures 6 and 7, respectively. The deceleration efficiency on the third floor is particularly impressive, at approximately 93%.

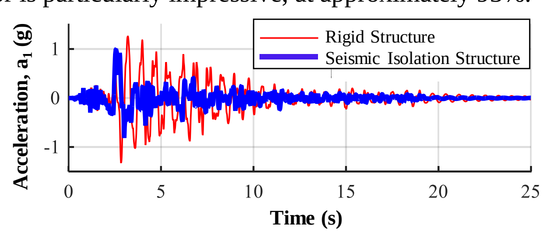

Figure 6. *Acceleration reduction efficiency of the first floor*

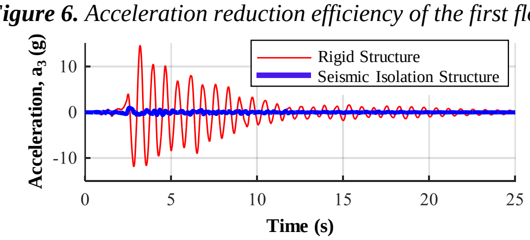

Figure 7. *Acceleration reduction efficiency of 3rd floor*

The shear force reduction efficiency in the first and third floors is shown in Figures 8 and 9, respectively. In which, the shear force reduction efficiency in these two floors is 92% and 88%, respectively.

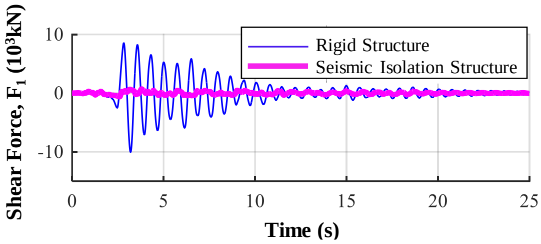

Figure 8. *Shear force reduction efficiency of 1st floor*

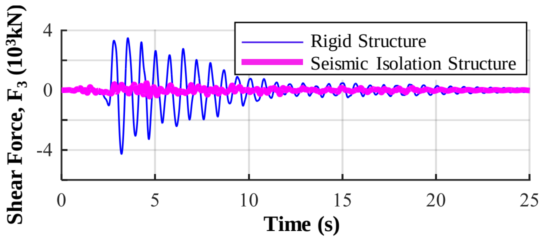

Figure 9. *Shear force reduction efficiency of 3rd floor*

3.2. Evaluation of the influence of vertical ground acceleration

Conduct model analysis while considering the vertical ground acceleration component. The results show that absolute acceleration in the floors tends to increase, with the first floor increasing by 9.29% and the third floor increasing by 4.57%. These results are illustrated in Figures 10 and 11.

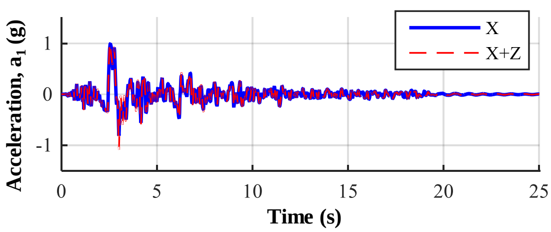

Figure 10. *Effect of vertical ground acceleration on absolute acceleration of 1st floor*

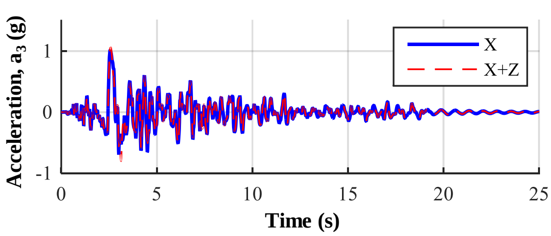

Figure 11. *Effect of vertical ground acceleration on absolute acceleration of 3rd floor*

The influence of the vertical acceleration component on the floor shear force is very clear, as shown in Figures 12 and 13. The first floor increased by 41.85%, while the third floor increased by 24.81%. The calculation results indicate that the shear force, when considering the vertical excitation force, acts along the column body of the structure. When designing the column system of a building, engineers typically design it to withstand compression and moment; thus, the vertical excitation force does not significantly affect the potential for structural failure. However, it is important to note that the base shear force of the structure increases by more than 40%, providing a valuable reference for designers.

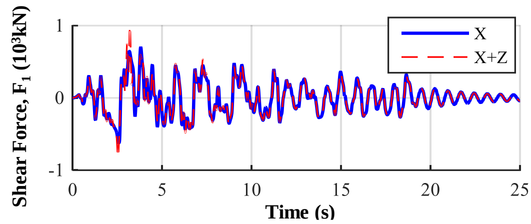

Figure 12. *Effect of vertical ground acceleration on first floor shear force*

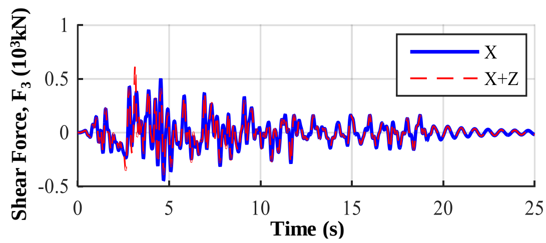

Figure 13. *Effect of vertical ground acceleration on 3rd floor shear force*

The effect of vertical acceleration on the bearing displacement also showed an increase but not significant, approximately 6.77 %, shown in Figure 14.

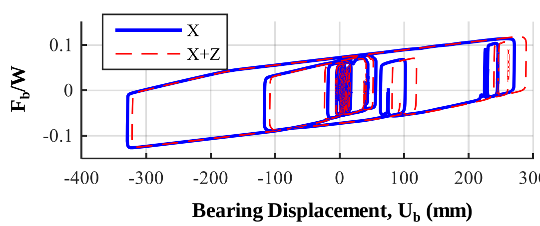

Figure 14. *Effect of vertical ground acceleration on bearing displacement force*

DFP bearings are designed primarily to isolate ground vibrations in the horizontal direction. According to the calculation results shown in Figure 14, although the influence of vertical excitation force is minimal, it is important to note that if vertical excitation is considered, the acceleration value of the structure increases. This is crucial, as designers or seismic design standards that ignore this value may overlook factors that affect the safety of the structure.

4. Conclusion

Isolating earthquake vibrations for construction works is a popular technique nowadays. The technique of using DFP friction sliding double-sided bearings to isolate vibrations caused by ground acceleration when an earthquake occurs has brought high efficiency when considering the earthquake-resistant 3-story building structure and the vertical excitation force as an example. Through the results of numerical analysis, we see that:

For horizontal damping efficiency, the acceleration reduction efficiency of the 3rd floor of the building is up to about 93%, and the shear reduction efficiency of the 1st floor is about 92%, while the 3rd floor is about 88%.

For vertical efficiency, there is a tendency to increase, in which the first-floor increases by 41.85% and the third floor increases by 24.81%, a significant increase that we cannot ignore. However, when considering the vertical excitation force, the displacement of the bearing does not increase much; according to the calculation, it is only about 6.77%, which is consistent with reality because the structure of the seismic isolation bearing mainly allows (controls) the structure to have horizontal displacement without collapsing when a strong earthquake occurs.

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