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Cyclic behavior of DCFP isolators with elliptical surfaces and different frictions

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Abstract. Friction Pendulum isolators are tools developed in the past few decades. The simplest form of these isolators, are FPS whose main disadvantages are having a constant frequency independent of the frequency of the structure. For this reason, researchers have invented VFPI isolator whose frequency is variable and depends on displacement. Another friction pendulum isolator is DCFP isolator which is a combination of two FPS isolators. In this article, first by changing the geometry of DCFP isolator plates from spherical to elliptical, the motion and frequency equations of DVFPI isolators are defined, and then the seismic behavior of DVFPI isolators are analyzed in various geometric and plate friction settings using motion equations, and confirmed using ABAQUS software. The most important results of this study are that the hysteresis behavior of DVFPI isolators are severely nonlinear, its curve follows two distinct curvatures, and that the restoring force is faced with softening mechanism that limits the seismic force transmitted to the structure, whereas the restoring force in DCFP isolators increases linearly with increasing displacement.

Keywords: earthquake engineering; passive control; base isolation; DCFP; cyclic behaviour; VFPI

1. Introduction

Seismic isolation is defined as isolating the structure from the harmful stimulations of the earth by creating a flexible layer and absorbing energy between the structure and the foundation. The simplest form of isolation systems are Pure Frictional (PF) systems. This isolation system operates well in a wide range of input frequencies, and causes a reduction of the seismic force transmitted to the structure in the amount of its friction force (Mostaghel and Tanbakuchi 1983).

The primary weakness of PF isolators is supplying the restoring force. Therefore, during severe earthquakes, the isolated structure undergoes extensive and permanent displacements. For solving this problem, researchers developed the Friction-Pendulum Systems, whose simplest form is single FPS (Zayas *et al.* 1990). The important characteristic of this mechanism is its energy absorption, which is proportional to the friction and dependent on the slip speed and the material composition of the slipping surface (Trovato 2013). The behavior of FPS bearing was analyzed by Zayas *et al*. (1987), in the earthquake simulation experiment. Castaldo and Tubaldi (2015) examined the effect of FPS isolator characteristics on the seismic function of structures. The use of this system over the years indicates its functionality. Bearing supports with several spherical slip surfaces are derivatives of FPS systems that are invented for wider performance and optimal design. Among these are DCFP isolators that are more advanced than single FPS. DCFP uses two slip surfaces for enduring structure displacements during seismic activity. In fact, this isolator is a combination of two simple FPSs. Force and displacement equations for DCFP isolators, in various settings, were extracted by Fenz and Constantinou (2006). The double- and triple-linear behavior of DCFP isolators caused by the collision of two adjacent structures during a quake was examined by Khoshnoudian and Hemmati (2014), and the result was that with the collision of two adjacent structures, displacement is decreased and base shear was increased; of course, this conclusion depends on various parameters, including the distance between structures, severity of collision, interval of the periodic isolation, and the type of DCFP hysteric curve. In another study, Kim and Yun (2007), by analyzing the time history in a bridge isolated using DCFP, compared the advantages of using DCFP with triple-linear behavior relative to double-linear behavior. And, the effect of the perpendicular component of earthquake on the response of structures isolated using DCFP, was analyzed in the 1994 Northridge earthquake (Faramarz and Montazar 2010). The result was that the isolation period and the coefficient of friction affect the structure response, considering the perpendicular component. Furthermore, by comparing the performances of DCFP and FPS isolators in various risk levels, researchers reached the conclusion that DCFP isolators have better performance than FPS with regards to displacement Malekzadeh and Taghikhany (2010). Seismic responses of the three dimensional single-story building isolated by DCFP with different coefficient of friction and initial time period of top and bottom sliding surfaces are investigated under triaxial ground excitations (Shah and Soni 2017). The failure behavior of double friction pendulum bearings under pulse-type motions are investigated by Becker and Hamaguchi (2017) and the influences of DCFP design parameters are considered.

All of the studies mentioned above, indicate the

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Table 1 Geometric characteristics of DCFP models

DCFPI Isolators				
Model	Case A		Case B	
Parameter	Surface 1	Surface 2	Surface 1	Surface 2
Radius (cm)	100	100	100	100
Coefficient of friction	0.02	0.02	0.04	0.04
T_o (s)	2	2	2	2
Displacement (cm)	20	20	20	20

Table 2 Geometric characteristics of DVFPI samples

DVFPI Isolators								
Model	Case A		Case B		Case C		Case D	
Parameter	Surface 1	Surface 2	Surface 1	Surface 2	Surface 1	Surface 2	Surface 1	Surface 2
d (cm)	20	20	20	20	20	20	20	20
B (cm)	4	4	4	4	4	9	4	9
T_o (s)	2	2	2	2	2	2	2	2
Coefficient of friction	0.02	0.02	0.02	0.04	0.02	0.02	0.02	0.04

importance of isolation frequency and the shape of hysteresis curve in clarifying the behavior of the isolator for use and analysis in other researches. In this study, the behavior of DCFP isolators with variable frequencies is analyzed, and the effect of geometric parameters of slip surfaces on hysteresis curvature in various geometric and frictional settings is examined.

2. Double variable frequency pendulum isolator (DVFPI)

This isolator is a combination of two single VFPI isolators (Pranesh and Sinha 2000). The plate of the VFPI isolator is elliptical; hence the vibration frequency decreases with an increase in displacement. Seismic response of the double variable frequency pendulum isolator under triaxial ground excitations are investigated by Panchal *et al.* (2010) and in another research The combined effect of change in the initial time period and the coefficient of friction on the seismic response of the DVFPI is also studied (Soni *et al*. 2011). The behaviour of liquid storage slender and broad tanks isolated by the double variable frequency pendulum isolator (DVFPI) is studies by Soni and Panchal (2011).

The force-displacement equation of DVFPI isolator is given by Equation (1) (Soni *et al.* 2010).

$$F_b = \left(\frac{k_{b1}(x_1)k_{b2}(x_2)}{k_{b1}(x_1)+k_{b2}(x_2)}\right)u_b + \frac{k_{b1}(x_1)F_{f2}Sgn(x_2)+k_{b2}(x_2)F_{f1}Sgn(x_1)}{k_{b1}(x_1)+k_{b2}(x_2)} \quad (1)$$

Where $K_{bi}(x)$, F_{f1}, F_{f2}, $Sgn(x)$ are the non-linear spring hardness coefficient for the restoring force, the isolation friction force in plate 1, the isolation friction force in plate 2 and the sign function for taking the direction of

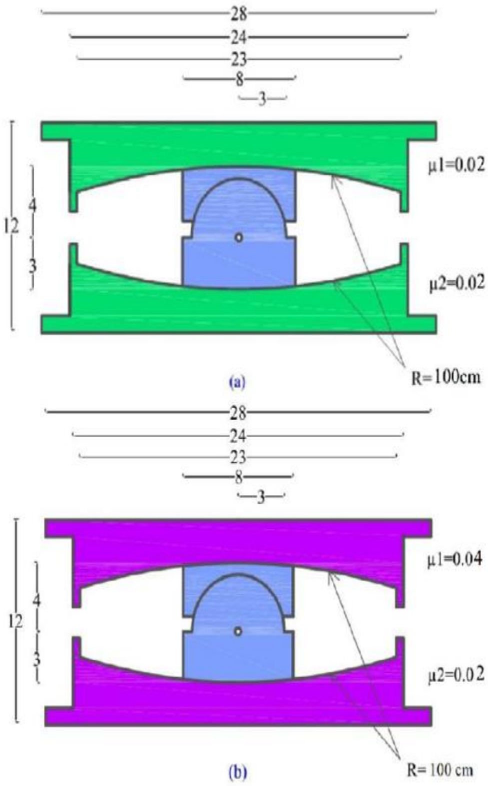

Fig. 1 Sample DCFP isolators modeled (a) with equal friction, and (b) with unequal friction

motion into account, respectively. Also, the frequency of each plate, based on displacement, is given by Eq. (2)

$$\omega^2{}_{b1}(x_1) = \frac{\omega^2{}_{I1}}{(1+r_1)^2\sqrt{1+2r_1}}, \omega^2{}_{i1} = \frac{gb_1}{{d_1}^2}$$

$$\omega^2{}_{b2}(x_2) = \frac{\omega^2{}_{I2}}{(1+r_2)^2\sqrt{1+2r_2}}, \omega^2{}_{i2} = \frac{gb_2}{{d_2}^2} \quad (2)$$

Where r_i is defined as follows

$$r_i = \frac{x_i sgn(x_i)}{d_i}, i = 1,2 \quad (3)$$

In Eqs. (2) and (3), a, b are the major and minor diameter of the ellipse, the center of the ellipse is the point C (0, b). The major diameter of the ellipse, a, is taken as a linear function of the sliding displacement, x (Eq. (4)).

$$a = x + d \quad (4)$$

Where d is a constant. This is geometrically equivalent to an infinite number of progressively larger ellipses transforming into one another with increase in sliding displacement.

3. Modeling of the isolators

In this article, the cyclic behavior of DVFPI in various geometric and frictional settings are extracted, and compared with the results of Fenz and Constantinou (2006). Two samples of DCFP isolators and four samples of DVFPI isolators are modeled. Considering that only the analysis of

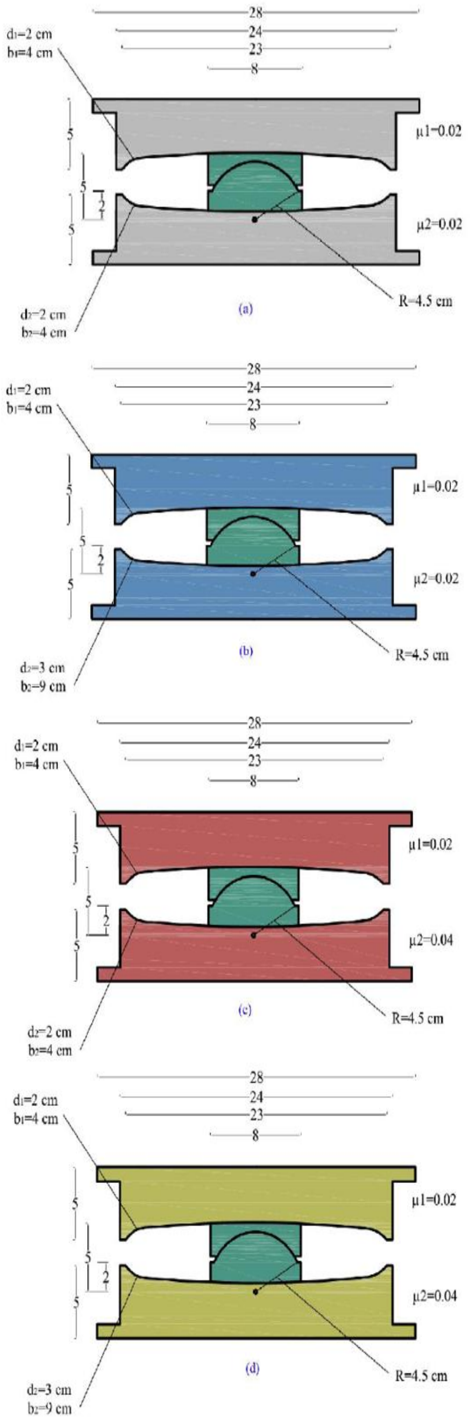

Fig. 2 Sample DVFPI isolators modeled, (a) with equal friction and geometry, (b) with equal friction and unequal geometry, (c) with unequal friction and equal geometry and (d) with unequal friction and geometry

isolators is of concern, the ABAQUS software is used for analysis and modeling. Geometric and frictional characteristics of these models are given in Tables 1 and 2, and Figs. 1 and 2.

In this study, ABAQUS 6.14 Software (2014) is used for analyzing the seismic behavior of DVFPI insulators. ABAQUS software is finite element analysis software that has extensive function in engineering fields. The following assumptions are considered in modeling (Fig. 3):

1. No twisting or bending occurs in the upper plate during the slip.

2. Isolators are only subjected to three-cycle, harmonic lateral movement with constant frequency of 0.1 Hz and a range of 10 cm.

The displacement capacity is large enough so that the slider does not collide with the sides of the isolator.

Stainless steel is the material forming the parts of the seismic isolator, which is used in different types of isolators, depending on the mechanism of motion and energy absorption, in combination with other materials. The mechanical characteristics of the steel used, according to ASTM standards, are given in the Table 3:

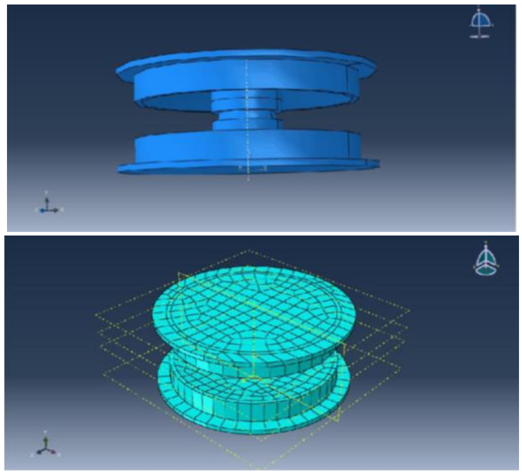

Fig. 3 The modeled isolator in ABAQUS software

Table 3 Characteristics of materials in modeled samples

Type of steel	Density (gr/cm^3)	Coefficient of friction	Surface hardness (μm)	Pressure capacity (Mpa)	Elasticity module (Mpa)	Poisson's ratio	Yield stress (Mpa)	Final resistance (Mpa)
ASTM A240 type 304	8.03	0.04-0.12	0.5	13.8-24	193×10^3	0.305	290	655
ASTM A167 type 304	8.03	0.03-0.06	0.25	30-45	193×10^3	0.29	215	505

Since we are concerned with the behavior of the isolator subjected to lateral movement, the loading conditions for all the samples modeled are the same, and given as follows:

1. Concentrated vertical load of 6000 N.

2. Subjected to comprehensive pressure of 1 Mpa.

3. Lateral movement as three complete sinusoidal cycles with a range of 10 cm and constant frequency of 0. 1Hz.

Considering the loading system mentioned, in the first stage, the vertical load of 6000 N is applied to the upper plate. Then a pressure of 1 Mpa is applied to the outer surface of the upper plate, and finally lateral harmonic movement, with the mentioned range and frequency is applied to the lower plate in the horizontal direction. Due to the importance of displacement in structure response and non-linear geometric effects, non-linear analysis is performed in order to obtain a more accurate examination of the behavior of isolators.

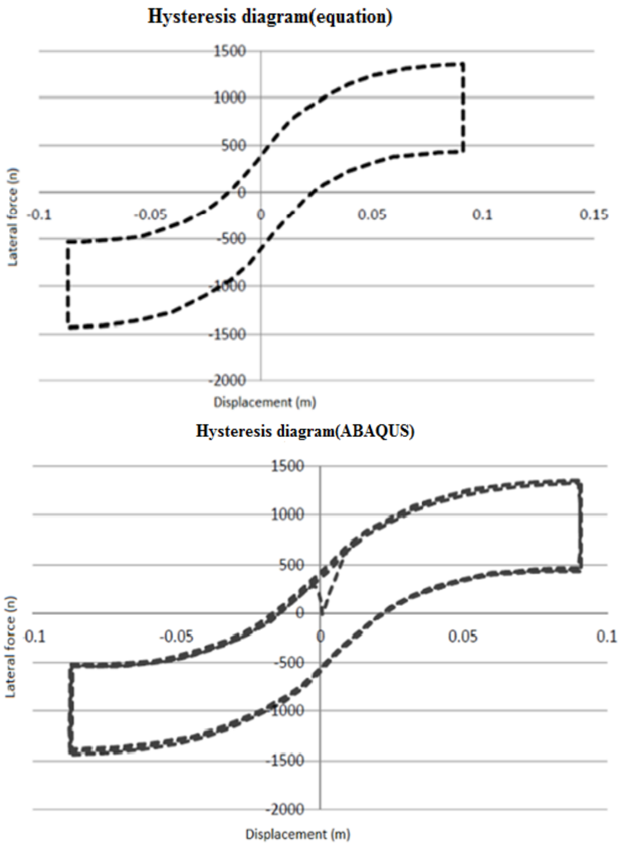

Fig. 4 Hysteresis diagram of DVFPI isolator with equal geometry and friction

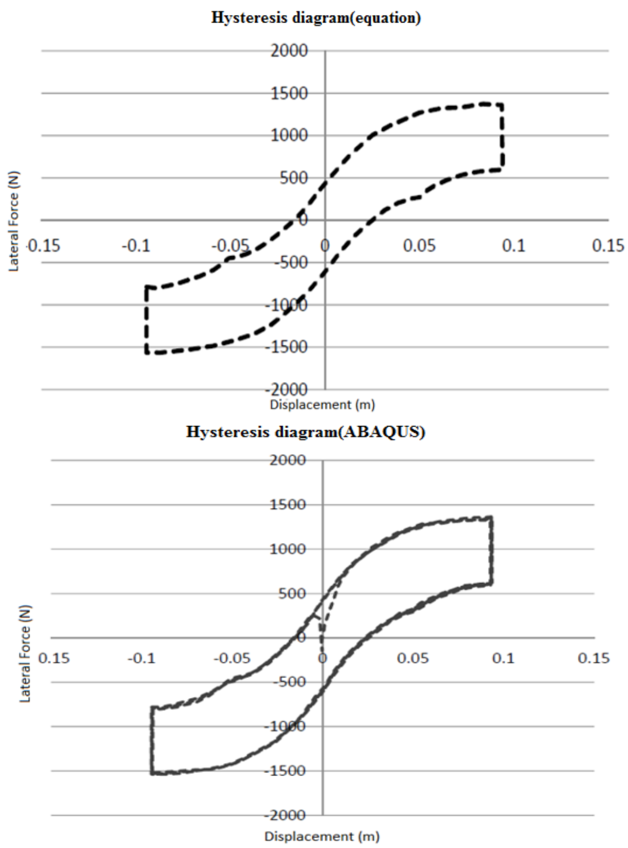

Fig. 5 Hysteresis diagram of DVFPI isolator, unequal geometry and friction

4. Analysis of the results from the software and solving equations

4.1 Equal geometry and friction

According to Fig. 4, the hysteresis behavior of DVFPI isolator is not as simple as the behavior of DCFP isolator. The reason is that when an object revolves around a specific center, due to the distance of the object to the center of revolution being constant, the coordinates of the object, at any moment, are simply obtained using a linear equation. However, when that same object is moving on an elliptical surface, in addition to the coordinates of the object, its distance to the center of the ellipse also changes at every moment. The hysteresis diagram obtained from numerical analysis conforms to the diagram from force and displacement equations.

4.2 Equal geometry and unequal friction

In the diagram of Fig. 4, similar to the other conditions, the behavior is non-linear, however due to the unequal coefficients of friction; we notice more complex non-linear behavior, such that during the unloading process, after the domination of the lateral force on the force of friction, two different curve paths are taken to complete the cycle. By analysis of the DCFP isolator, when the coefficients of friction are not equal, the behavior of the isolator changes from single-linear to double-linear Fig. 5.

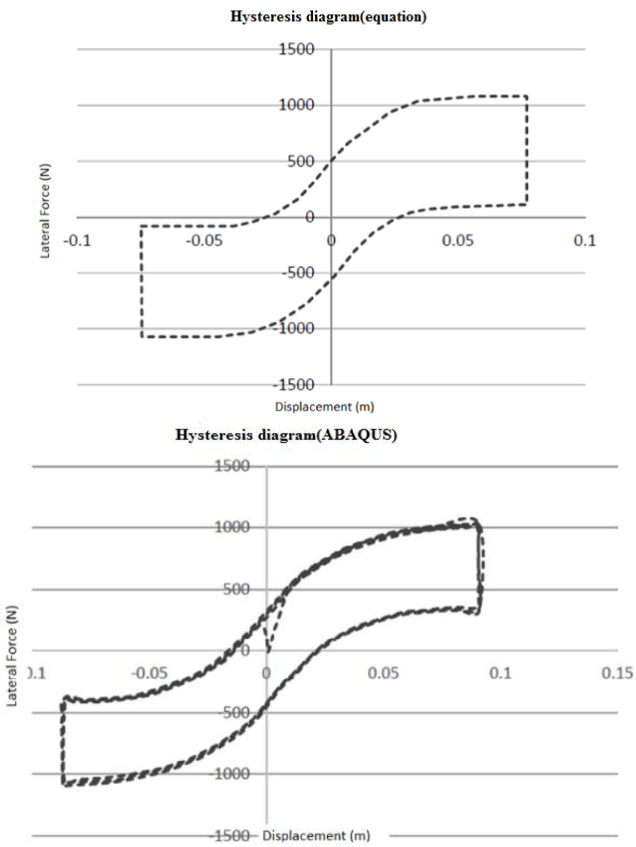

Fig. 6 Hysteresis diagram of DVFPI isolator, unequal geometry and equal friction

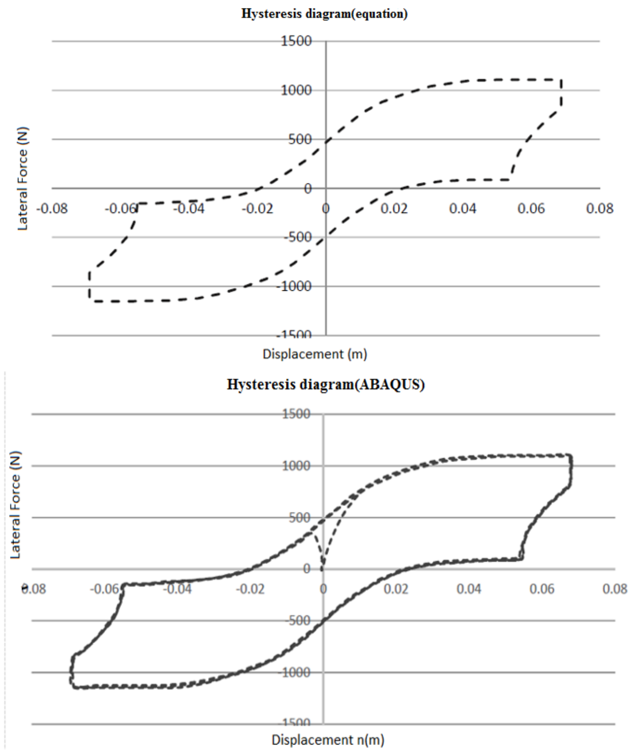

Fig. 7 Hysteresis diagram of DVFPI isolator, in the 4th case (unequal geometry equal friction)

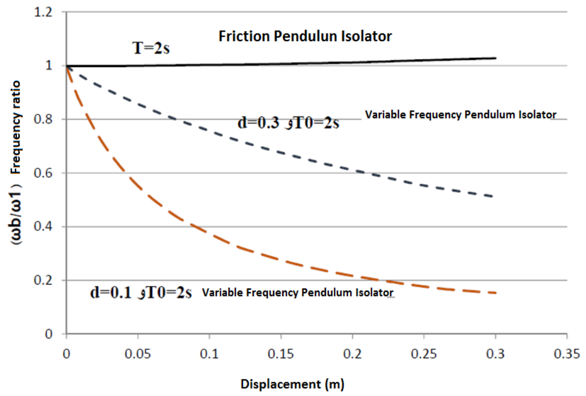

Fig. 8 Effect of parameter d on the decrease of frequency with respect to displacement compared to DCFP isolator (Mashaiekhi 2015)

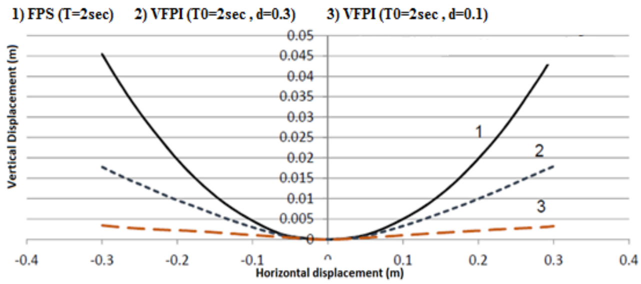

Fig. 9 Effect of parameter d on vertical displacement, compared to DCFP isolator

4.3 Unequal geometry and equal friction

In this case, similar to the first case, the behavior is non-linear. But with the difference that the range of isolator force changes is less. The curve becomes more linear toward the end of the path. Here, similar to the first case, since the distance to the center of movement changes at every moment, the behavior of the isolator is non-linear, and the same behavior is predicted for the other cases. The hysteresis diagram of Fig. 6 shows that after the start of the movement until the change in loading direction, a curved path is followed and a force two times the force of friction should be applied to start movement in the opposite direction.

4.4 Unequal geometry and friction

In the hysteresis diagram of Fig. 7, similar to the previous case, two curves are seen in the diagram; the differences in the concavity and range of these curves are more noticeable in the case of unequal geometry and friction than the case with equal geometry and unequal friction. In this case, when returning, after the lateral force reaches the friction force (with a smaller coefficient of friction) the slider begins to move on a curved path until the lateral force dominates the force of friction, and continues on a new curved path. In this regard, it is necessary to mention that the most complex and the most optimal behavior of a DVFPI is obtained in this mode. The reason for the complex behavior is the inequality of the isolator parameters that influence one another and form the general behavior of the isolator. Regarding optimal design, it can be said that since it is possible to assign different characteristics for each of the sliding plates, taking the type of structure, the input load, and the desired performance level into account, the designer is free to design the isolator with optimal behavior.

5. The effect of changing the geometric parameters of DVFPI (b, d) isolator and comparing it to DCFI isolator

As shown in Fig. 8, one of the advantages of DVFPI isolators compared to DCFP is that by increasing the displacement, the frequency decreases. Also, by changing the parameter *d* from 0.1 to 0.3, the less the value of this parameter, the isolator frequency with increasing displacement decreases.

Considering the equation of the geometry of slide plates, by drawing the geometry of a plate of these two types of isolators with the same initial frequency, we notice that the amount of vertical displacement in variable frequency pendulum isolator is much less than the vertical displacement DCFP isolator, and by increasing the value of *d* from 0.1 to 0.3, end vertical displacement increases (Fig. 9). This point is more important in strong vibrations.

The graph of the restoring force normalized to weight versus vertical displacement is shown in Fig. 10. According to this figure, the restoring force in big displacements remains almost constant. This behavior is introduced as a softening mechanism for a single-plate isolator with

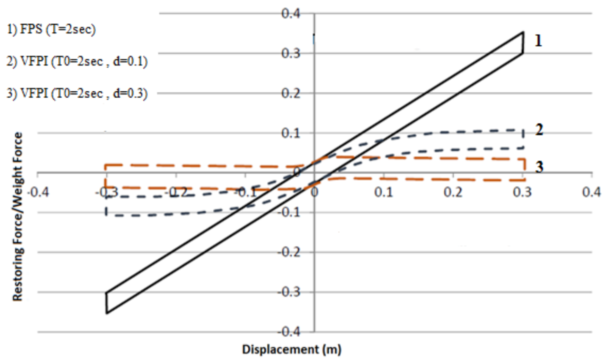

Fig. 10 The effect of parameter *d* on the restoring force relative to displacement, compared with DCFP isolator

variable frequency, so that the maximum force transmitted to the structure, in strong earthquakes is limited and the least damage is done to the isolator structural systems. Furthermore, by increasing the value of *d* from 0.1 to 0.3 the softening mechanism is decreased. This is true while the restoring force in a spherical plate increases linearly with displacements.

6. Conclusions

In this research, first by changing the geometry of DCFP isolator plates from spherical to elliptical , the motion and frequency equations of DVFPI isolators are defined, and then the seismic behavior of DVFPI isolators are analyzed in various geometric and plate friction settings using motion equations and the following results are obtained:

- The behavior of DVFPI is severely non-linear. When the geometric and frictional characteristics of slide planes are equal, hysteresis diagram follows one curve, but when the frictional coefficients are different, the behavior is more complex and the hysteresis diagram follows a path with two different curvatures.
- Vertical displacement in DVFPI isolator is much less than the vertical displacement of DCFP. In DVFPI isolator, the more value of the major diameter of the ellipse (*d*), the more vertical displacement.
- In DVFPI, as the displacement increases, the frequency of the isolator decreases. Whereas in DCFP isolator, this value is constant. In DVFPI insulators, as the value of the major diameter of the ellipse increases, the ratio of frequency decrease to displacement decreases.
- The restoring force in DCFP isolators increase linearly with increasing displacement. Whereas in a DVFPI isolator, the restoring force is faced with softening mechanism which limits the force transmitted from the earthquake to the structure, and this mechanism decreases with increasing major diameter of the ellipse (*d*).
- Among the different modes of isolators, the mode with unequal geometry and friction, because of variations in characteristics, help the designer to achieve an optimal design of the structure, considering the structure, the input load, and its behavioral characteristics.

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