Improvement of structures seismic response based on pendulum systems with double sliding surface

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Abstract: The seismic isolation of the construction structures is of particular importance because the optimum stability premises of the structures during the seismic events are ensured. There are different isolation methods but based on the structure base isolation principle, the friction pendulum bearing systems (FPBS) have been used with good results in equipping new structures and also in rehabilitating of the old buildings that had to be consolidated. The double surface friction Pendulum (DSFP) bearing is an improved version of the well-known single concave friction pendulum bearing (FPBS). The principal benefit of the DSFP bearing is represented by its capacity to accommodate substantially larger displacements compared to a traditional FPBS of identical plan dimensions. Moreover, there is the capability to use sliding surfaces with different radius of curvature and friction coefficients, offering the designer greater flexibility to optimize the protective system performance. Through these systems good seismic isolation results are achieved for the building structures where mounted interposed between the foundation and the superstructure realizing the disconnection between the two structural elements. The disconnection is important because the insulated structure vibration period is modified in the sense of its significant increase, also with the increase of structure lateral flexibility, ultimately reducing the ground acceleration and avoiding the efforts vertical transmission to the isolated structure upper levels. The double surface friction pendulum system ensures an important modification of the isolated structure behavior materialized through the seismic response mitigation. This paper describes the double surface friction bearing (DSFP) constructive details with operation principles and also presents some numerical analysis results related to force–displacement relation considering different values of curvature radius and friction coefficients of the two friction surfaces used.

1. Introduction

All protective systems used today at buildings were developed in time and gradually implemented into the structural assembly in order to ensure an enhanced behaviour for structural element where mounted against degradation or collapse due to earthquake actions.

Base isolation systems as the pendulum type based on the sliding friction force represent a good solution of anti-seismic insulation. They have been designed and introduced into the operation within buildings and bridges throughout the world, recording good results in terms of insulation.

Based on the initial model of friction pendulum system with sliding on concave surface, the double sliding surface systems type as well as three or more sliding surfaces have been developed that offer a higher relative displacement possibility of the structural elements where they are mounted.
The double concave friction pendulum bearing represents an enhanced solution according to the well-known single concave friction pendulum bearing. The advantages of the double sliding surface bearing are related to its capacity to accommodate substantially larger displacements compared to a traditional friction pendulum bearing of identical plan dimensions [1, 2].

Also, it is presented the capability to use sliding surfaces with varying curvature radii and friction coefficients, offering the designer greater flexibility in order to obtain better isolation performances.

This paper describes the principles of operation of the double pendulum bearing and presents the development of the force–displacement relationship.

The theoretical force–displacement relationship for double pendulum bearings with sliding surfaces having the same and then different radii of curvature and friction coefficients are numerically analysed [3].

2. Theoretical aspects of double pendulum seismic isolation systems

In addition to the friction pendulum bearings with sliding on a single spherical surface, double pendulum systems have been developed.

These systems operate on the same operating principle as simple systems, with the exception that they allow greater freedom of movement on the support, due to the relative displacement of the two sliding surfaces.

It can be said that these systems also achieve good seismic isolation results of the construction structures because they are interposed between the foundation and the superstructure, thus realizing the disconnection between the foundation and the superstructure.

![Figure 1. Schematically representation of double pendulum system.](image)

The construction of the double pendulum insulating system with friction, shown in figure 1, where the component parts are presented, represented by the two main sliding surfaces that can have the same radius of curvature but also different radii, as well as the central spherical support.

For the two main sliding surfaces with concave geometry two radii of curvature \( R_1 \) and \( R_2 \) are presented, two values of the vertical displacements described by \( h_1 \) and \( h_2 \), as well as different friction coefficients \( \mu_1 \) and \( \mu_2 \), depending on the nature of the materials used in the friction interfaces (figure 2) [4].
Figure 2. Geometrical limits involved in the operation of the double pendulum insulating system.

Under normal conditions there is no movement on the bearings, or very small displacements that result from road or rail traffic, which cannot be compared with the dynamic action of an earthquake.

At the moment of the occurrence of a seismic motion, the displacement begins with a slip on a single surface, until the first surface limit, then continues with the displacement allowed by the second surface, depending on the magnitude of the seismic event.

The double pendulum insulation system can thus provide an additional displacement reserve required when a single surface is exceeded by the seismic event motion. In case of displacement on both surfaces, the response of the insulation system can be described by the elastic force \( F_e \) (equation (1)) and the dry friction force \( F_f \) (equation (2)) whose relations are presented as follows [4, 5]:

\[
F_e = \frac{P}{R_1 - h_1 + R_2 - h_2} u
\]

where:

- \( P \) - static load;
- \( u \) - horizontal displacement.

Due to the disconnection made by the double pendulum isolation system between the foundation and superstructure, the relative movement is ensured with different vibration period that protects it from the ground acceleration amplitudes.

\[
F_f = \frac{\mu_1 (R_1 - h_1) \cdot P + \mu_2 (R_2 - h_2)}{R_1 - h_1 + R_2 - h_2}
\]

If the curvature radius of the two sliding surfaces is equal \( (R_1 = R_2) \) and the vertical displacement identical \( (h_1 = h_2) \) then the system behaves as a simple friction pendulum bearing isolation system.

For the equilibrium position on the supports, the relations (equation (3) and (4)) can be written as follows [3, 6]:

\[
N \sin \varphi + F_f \cos \varphi = P
\]

\[
N \sin \varphi + F_f \cos \varphi = F
\]
Due to the fact that the movement initially appears only on one of the sliding surfaces, it turns out that there will be different displacements on the supports \( u_1 \) and \( u_2 \) (equations (5) and (6)) as well as different angles \( \phi_1 \) and \( \phi_2 \) which will be described in the following relations:

\[
\begin{align*}
\quad u_1 &= (R_1 - h_1) \sin \phi_1 \quad (5) \\
\quad u_2 &= (R_2 - h_2) \sin \phi_2 \quad (6)
\end{align*}
\]

Thus, can be written the relations for the lateral forces developed on the main sliding surfaces of the double insulating system based on the dry friction force, function of vertically formed angles (equations (7) and (8)) during the system operation [3, 6]:

\[
\begin{align*}
F_{s1} &= \frac{P}{(R_1 - h_1) \cos \phi_1} \cdot u_1 + \frac{F_{\mu1}}{\cos \phi_1} \quad (7) \\
F_{s2} &= \frac{P}{(R_2 - h_2) \cos \phi_2} \cdot u_2 + \frac{F_{\mu2}}{\cos \phi_2} \quad (8)
\end{align*}
\]

where:
- \( F_{s1}, F_{s2} \) represents the lateral force exerted on a single sliding surface;
- \( F_{\mu1}, F_{\mu2} \) friction force.

For reduced displacements the angles are small and the relations can be written as follows (equations (9) and (10)) [4, 5]:

\[
\begin{align*}
F_{s1} &= \frac{P}{(R_1 - h_1)} \cdot u_1 + F_{\mu1} \quad (9) \\
F_{s2} &= \frac{P}{(R_2 - h_2)} \cdot u_2 + F_{\mu2} \quad (10)
\end{align*}
\]

There are presented some intermediate positions permitted by the double pendulum system type being highlighted the allowed specific displacements by means of the insulating system.

![Figure 3](image-url)

**Figure 3.** The movement stages allowed by the double pendulum isolation system: (a) Sliding motion on the lower sliding surface (case 1); (b) Movement on both main sliding surfaces (case 2); (c) The support stabilization tendency (case 3) [4, 5].

If the main sliding surfaces have a different friction coefficient \( \mu_1 \neq \mu_2 \), friction forces are different \( F_{s1} \neq F_{s2} \) and the movement will appear on the surface where the friction force is smaller.
The movement on the first surface with a lower friction coefficient continues until the limit of the frictional force corresponding to the second surface is reached, when movement on the second main surface is allowed.

Figure 3 shows schematically the movement possibilities allowed by the double pendulum insulation supports with dry friction, through three different cases for which the corresponding force-displacement relations can be written as follows: [6]

- Case 1 - The frictional force on the lower surface is exceeded as a value by the lateral force, at which point the sliding motion appears on this surface (figure 3(a)). The corresponding force-displacement relation (equation (11)) can be written as follows:

\[ F = \frac{P}{R_s} u_2 + F_{\mu_2} \]  

(11)

- Case 2 - The movement on the lower surface encounters an increasing resistance to displacement on the concave surface, which leads to reaching the limit of the frictional force on the upper sliding surface (figure 3(b)). Once this limit is exceeded, there is a sliding motion and on the second surface. For this case the relation of the force (equation (12)) can be expressed as follows:

\[ F = \frac{P}{R_1 + R_2} (u_1 + u_2) + \frac{F_{\mu_1} (R_1) + F_{\mu_2} (R_2)}{R_1 + R_2} \]  

(12)

- Case 3 - Corresponds to the tendency to place the superstructure at the initial position due to the action of its own weight, the movement on the upper surface stops due to the frictional force which has thus exceeded the lateral forces and the movement on the lower surface continues until the equilibrium position (figure 3(c)). The force relation (equation (13)) is written for the movement on the lower sliding surface:

\[ F = \frac{P}{R_s} u_2 + F_{\mu_2} \]  

(13)

3. Numerical analysis on double pendulum isolation system operation

A numerical analysis is performed for the double pendulum isolation system type in order to highlight the influence of the characteristic parameters in the operation of this type of protective system.

The behavior of the double pendulum isolation system is described by the hysteresis curve described by the lateral force depending on the relative displacement on the supports.

Distinct cases are analyzed in which the values for the ratio between the lateral force \(F\) and the static load on the supports \(P\) are calculated.

Table 1 presents the numerical values based on which the hysteretic curves corresponding to the analyzed cases were obtained.

| Case no. | Radius of curvature of surfaces [m] | Height of pivot pieces [m] | Coefficients / frictional forces [kN] | Static load [kN] |
|----------|-----------------------------------|-----------------------------|--------------------------------------|-----------------|
| 1        | \(R_1=6; R_2=5;\) \(h_1=0.15; h_2=0.2\) | \(\mu_1 = 0.04; \mu_2 = 0.055\) | 180                                  |
| 2        | \(R_1=6; R_2=5;\) \(h_1=0.15; h_2=0.2\) | \(F_{\mu_1} = 7.2; F_{\mu_2} = 9.9\) | 180                                  |
| 3        | \(R_1=5\) \(R_2=5\) \(h_1=0.15; h_2=0.2\) | \(\mu_1 = 0.04; \mu_2 = 0.055\) | 180                                  |
| 4        | \(R_1=6; R_2=5\) \(h_1=0.15; h_2=0.2\) | \(\mu_1 = 0.02; \mu_2 = 0.04\) | 180                                  |
The movement is limited to a value of 0.4 m as the maximum value while different values are chosen for the two main sliding surfaces radius of curvature \((R_1)\) and \((R_2)\) different values for the height of the two pivot components \((h_1)\) and \((h_2)\) as well as different values for the friction coefficients \((\mu_1)\) and \((\mu_2)\) while the static load \((P)\) is maintained at a constant value.

The diagram of the relationship between the lateral force and the static load on the supports as a function of the imposed displacement, shown in the figure 4, is highlighting the absolute values for the friction coefficients of the two surfaces at which there is a sliding displacement with the involvement of the dry friction forces.

![Figure 4. Hysteresis curve for case 1.](image)

The movement on the support encounters a proportional resistance to the displacement due to the geometry of the sliding surfaces until a point where the maximum value of the lateral force is recorded, when the dynamic action is reversed and the force decrease is inevitable (figure 5).

The displacement on the support occurs when the value of the friction coefficient corresponding to the upper sliding surface \((\mu_1)\) is exceeded and continues on the first surface until the value of the friction coefficient \((\mu_2)\), which corresponds to the second main sliding surface, is exceeded.

![Figure 5. Hysteresis curve for double insulation system corresponding to case 2.](image)

The lateral force corresponding to the moment at which the sliding motion appears on the second sliding surface is greater than the effective friction force acting at the level of both sliding surfaces, a force that is calculated on the basis of an effective friction coefficient greater than the friction value of the upper surface \((\mu_1)\) and less than the coefficient corresponding to the second surface \((\mu_2)\).
The force-displacement relation obtained for the double pendulum insulating system with sliding on the concave surface forms a hysteresis loop that provides information regarding the amount of energy dissipated using the insulating system. The total dissipated energy is shown by the area contained within the hysteresis loop described by the isolating device based on the input data initially declared.

Following is analyzed the double pendulum insulating system with sliding on a concave surface, with the change in the value for the radius of curvature of one of the sliding surfaces. It is presented the hysteresis loop described by the double pendulum sliding insulating system for three different values adopted for the radius of curvature of the upper sliding surface (figure 6).

The radius of curvature decreases for one of the sliding surfaces is obtained an increase in energy dissipation amount explainable by increasing the displacement resistance on the support and the need for greater energy consumption.

![Figure 6. Hysteresis curve of the double pendulum sliding insulation system obtained for different upper sliding surface radius of curvature - case 3.](image)

The amount of dissipated energy by means of dry friction forces provided by the contact surfaces depends directly on the friction coefficients that act at the level of the two main sliding surfaces. A change in the values of these coefficients directly leads to a change in the characteristics of the double pendulum sliding friction isolator system which leads to a change in the amount of dissipated seismic energy as shown by the hysteretic curve presented in figure 7.

The case of the coefficients change is analyzed while and the results show that using higher friction coefficients a larger hysteresis curve area described by the lateral force is obtained when moving on the supports, which means a greater amount of dissipated energy through the isolation system.

![Figure 7. Hysteresis curve of the double pendulum insulating system obtained for changing the friction coefficients - case 4.](image)
On the other hand, higher friction coefficients mean greater rigidity for the insulation system, which is not desirable because loads resulting from seismic actions can be transmitted vertically through the insulation system, from the foundation to the superstructure.

4. Conclusions
The friction pendulum isolation system represents an optimum solution frequently used in base isolation of structures around the world.

The double sliding pendulum offer an improved freedom of movement for structural elements where mounted.

In this paper where analyzed the parametric conditions of operation for the double pendulum bearing showing the amount of dissipated energy according with main geometric and functional parameter values.

Four different cases were considered for numerical analysis and the results show special values on which the hysteresis diagrams are presented.

The hysteresis loop area represents the amount of energy dissipated by the isolation system.

Double pendulum bearing represents an improved pattern of seismic isolation system based on friction pendulum bearing due to the advantages related to higher displacements allowed for the structural elements where it is interposed.

5. References
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