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Seismic Isolation with Friction Pendulum System

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Summary

This work aims to develop a pre-design routine for seismic protection solutions for buildings based in friction pendulum systems. In this study is intended to perform a comparative analysis between the use of two base isolation systems, the High Damping Rubber Bearings (HDRB) and the Friction Pendulum System (FPS). The results and conclusions were obtained during the development of the work made for the Dissertation “Seismic Isolation with Friction Pendulum Systems” (Esteves, 2010)

I. Introduction

In the last decades, it has been seen a development in what is related to base isolation of buildings, to fulfill the need of design and construct buildings located in highly seismic areas that can face the destructive effects of seismic action. The seismic base isolation consists in the introduction of special devices, designated isolation devices, in the structure base, aiming to create a horizontal surface of discontinuity that allow to disconnect the structure from the horizontal movements generated by the seismic action. This technique allows to reduce the energy that the earthquake input in the structures, reducing the stresses in the structural elements and avoiding structural damages.

The Friction Pendulum System (FPS) is a base isolation system that has been won place in the market. Although it still hasn’t many uses as the rubber devices (elastomeric bearings), their popularity is increasing. In Portugal there aren’t examples of these kinds of devices’ applications in buildings.

This study focus on the comparison of results obtained from the use of the two different isolation bearings, the HBRB and the FPS bearings, in two structures, the Test structure and the Laboratory structure. With this comparison it is intended to get a pre-design model of the FPS bearings. The variables used to compare the results were the horizontal displacements in the base and the base reactions.

The evaluation of the seismic behavior of the isolated structures was made with the help of the program SAP2000 which performs computer analyses of tridimensional structural models.

Both for the isolated structures with HDRB and FPS bearings, the structural analysis method that was used was the non-linear time series analysis, with the use of seven artificial accelerograms. The time series analysis can be used either in the study of the isolation systems response with linear behavior (HDRB) or in the study of no linear behavior systems (FPS).

II. Friction Pendulum System – FPS

The FPS Bearings are constituted by two sliding parts. One of them contains a articulated chrome extremity, coated with Teflon or another composite material with a low and high capability of bearing which slides on the concave polished surface (spherical) that constitutes the second part.

The FPS devices have a working mechanism similar to a pendulum, after suffering a motion due to a seismic action, the structure goes back to its position because of its weight and the spherical form of the isolation devices sliding surface. Figure 1 shows the geometry of the FPS bearings, as it shown the connection between the motion of the pendulum and the motion of the FPS bearing.

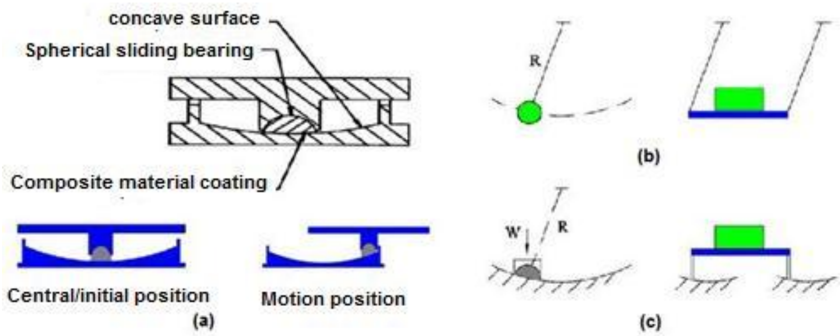

Figure 1- (a) Main components of the FPS bearing and FPS device movement; (b) and (c) motion of the pendulum and the FPS device, respectively

The FPS bearing behavior presents two stages: a static stage and a dynamic stage. The static stage happens when the force developed in the bearing due to the earthquake is lower than the static friction force. After the static friction force is prevailed, the bearing reaches the dynamic stage, where occurs an overlapping of the friction force creation effect and the development of a restitution force. Figure 2 shows the representation of the friction pendulum bearing behavior and the expression of the force developed in the bearing in both of the stages that were mentioned previously.

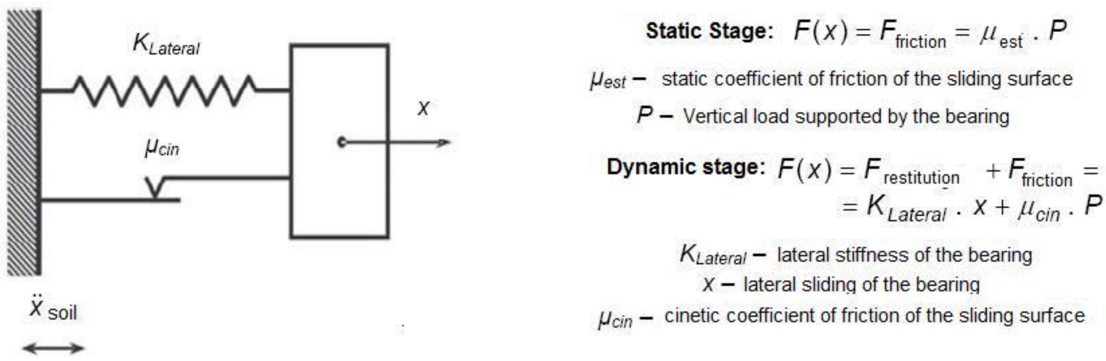

Figure 2- Sketch model of the FPS bearing operation and equations developed on bearing during static and dynamic stage.

The lateral stiffness of the FPS bearing which promotes the creation of the isolation system restitution force is represented by the equation 1:

$$K_{Lateral} = \frac{P}{R} \tag{1}$$

Where,

P - vertical load supported by the bearing,

R - Radius of curvature of the spherical surface;

The frequency of vibration from a FPS bearing is controlled by choosing the radius of curvature of the sliding surface, R, as it is observed by the deduction of the equation 2:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}} = \frac{1}{2\pi}\sqrt{\frac{P/_R}{P/_g}} \Leftrightarrow f = \frac{1}{2\pi}\sqrt{\frac{g}{R}} \tag{2}$$

Where

K - horizontal stiffness of the isolation system,

M - total mass of the superstructure,

P - total weight of the superstructure,

g - acceleration due to gravity,

R- Radius of curvature of the spherical;

The overlapping of the linear operation of a simple pendulum with the friction behavior of a block acted laterally over a planar surface can be understood through figure 3

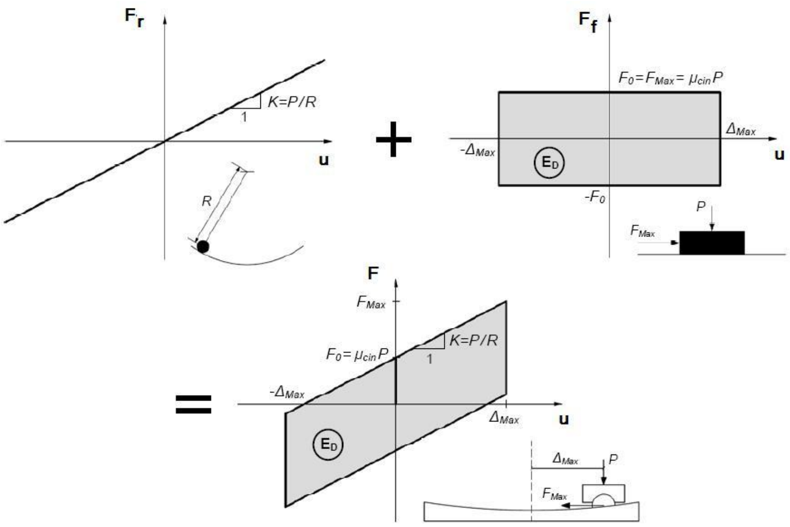

Figure 3- Definition of the FPS bearing normal behavior.

III. Cases Study

In the present work were analyzed 4 cases study. The cases study are based on the definition of two systems of seismic isolation composed exclusively of a type of isolation devices, being studied the implementation of high Damping rubber devices (HDRB) and the friction pendulum bearings (FPS). These two kinds of isolation devices are tested in two different structures. In a first stage, they will be analyzed in a Testing structure and in a further stage they will be analyzed in a Laboratory real structure.

The Cases Study 1 and 2 (Testing structure with bearings HDRB and FPS, respectively) both aim the understanding of bearing device behavior. It is intended with these two cases study to estimate the characteristics that a FPS bearing should present to isolate a structure with the same horizontal displacements and forces that occurs in the same structure isolated with HDRB bearings. The result that is intended with the execution of these two study cases will be useful as a pre-design routine of the FPS bearings.

In the Study Cases 1 and 2, the Test structure were isolated with bearings dimensioned for five different frequencies, 0,5Hz, 0,65Hz, 0,75 Hz, 0,85 Hz, and 1,00Hz.

In a further stage, the obtained pre-design models were tested in a real structure, the Laboratory structure. It is intended to obtain the same values of horizontal displacements and base reactions that would be obtained using the HDRB or FPs bearings. The bearing devices used in the Laboratory structure were designed for the frequency of 0,5Hz.

III.1. Fixed base structure.

The preliminary process of the isolation base system design begins with the analysis of the fixed base structure to identify the fundamental modes of vibration of the structure.

The seismic isolation of the testing structure is granted by six bearing devices, while the seismic isolation in the Laboratory structure is obtained by using twenty eight bearing devices. In both structures the bearing devices were located immediately below of the columns and there are all at the same level.

From the Testing structure modal analysis, it was verified that the structure is characterized by a fundamental frequency of 4,56Hz. The two first modes of vibration match with deformation related to the translation according X and Y, respectively.

From the modal analysis, it was determined the natural frequency of the structure vibration which presents a value of 2,06Hz. The first and the third vibration mode match with deformations related to the translation according X and Y, respectively, while the second vibration mode matches with the global torsion of the structure according to Z.

The total mass of the superstructure of the testing structure is 50 tons, rather inferior to the Laboratory structure, which was calculated in 3819 tons.

III.2. Case Study 1 – High Damping Rubber bearing (HDRB)

The Case Study 1 aims the calculation of the reactions and displacements in the isolated structure Test with HDRB bearings.

Next, it will be presented the Base Reaction evolution and Base Displacements charts according the design frequency. The figure 4 and 5 show two lines that correspond to the design earthquake multiplied for a factor of 1,0 and 2,3 that amplifies the seismic action.

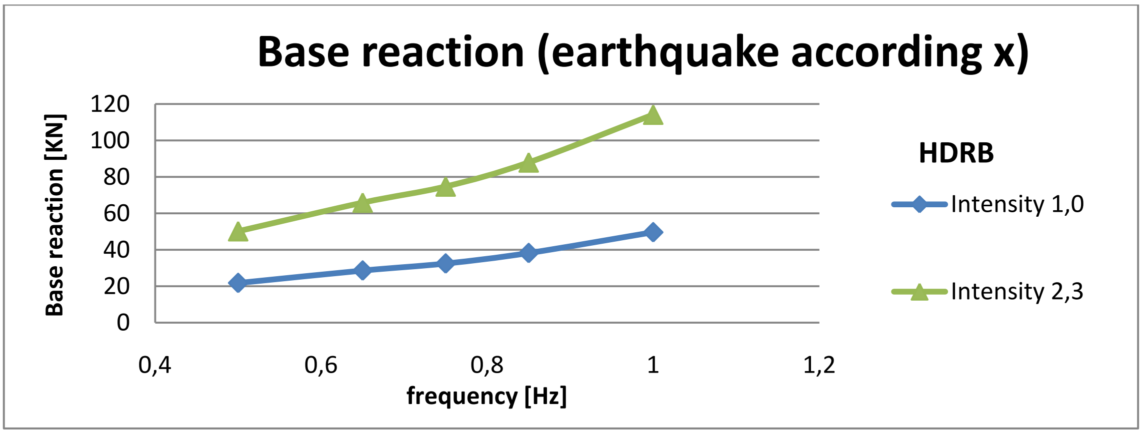

Figure 4- Relation frequency-reaction in the testing structure base.

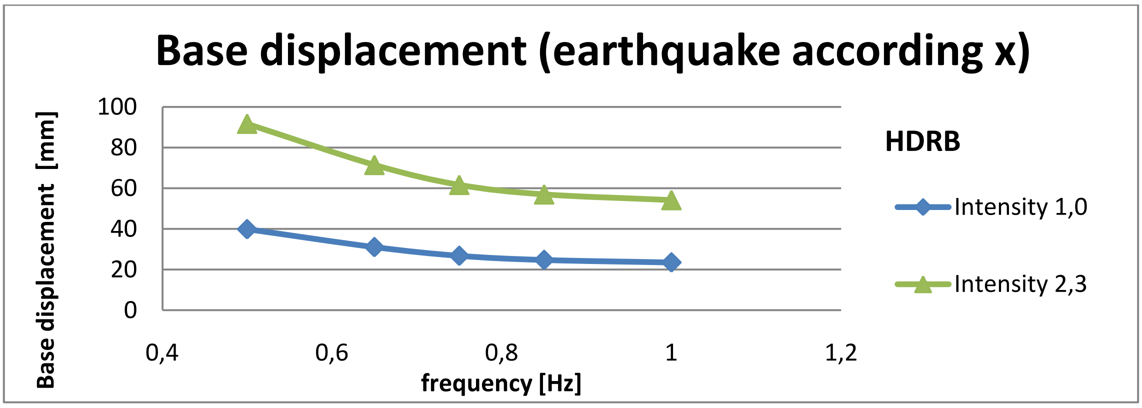

Figure 5- Relation Frequency – Displacement in the testing structure base.

It is verified that the reduction of the force increases as much higher is the difference between the frequencies of the fixed or isolation base. On the one hand it was concluded the response of a isolated structure with HDRB is linear, that is, when the seismic action is intensified to 2,3, it is also verified a increase of 2,3 times the value of the Base Reactions.

On the other hand, it is observed that the displacements increase with the increase in the difference between the fixed and isolated Base. As it was concluded for the seismic action intensification effect in the value of the Base Reactions, in relation to the base displacements it happens the same; t hey increase linearly with the increase of the seismic action.

III.3. Case Study 2 – Friction Pendulum System (FPS)

In the Case Study 2 it is intended to analyze the isolated testing structure behavior with FPS devices. It will be analyzed the forces evolution in the base and horizontal displacements base according the different friction coefficients.

Here are presented the charts concerned to the Base Reactions and Base Displacements evolution as function of the different adopted friction coefficients for the FPS bearings. The two following figures (figures 6 and 7) present the results for the earthquake design multiplied by a factor of 1, 0 and 2, 3 that amplifies the seismic action.

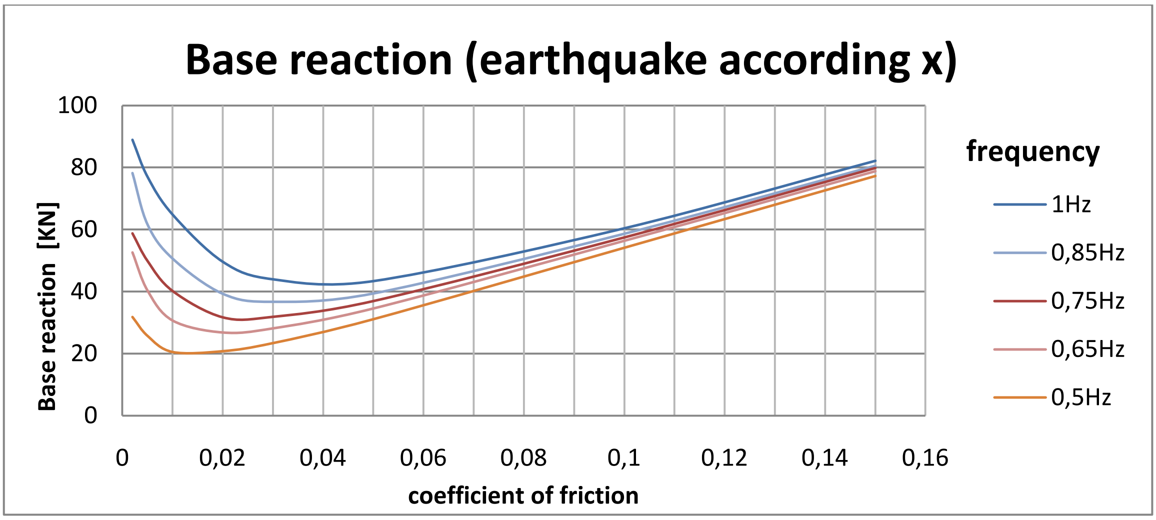

Figure 6 – Relation of the base – Coefficient of friction for the testing structure with an 1,0 intensity earthquake acting according x.

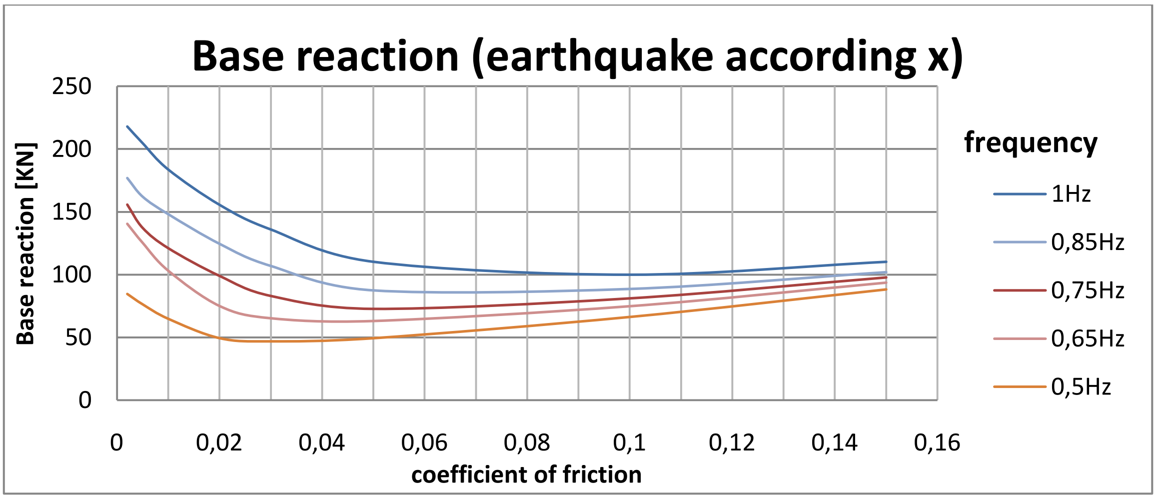

Figure 7 – Relation of the base – Coefficient of friction for the testing structure with an 2.3 intensity earthquake acting according x.

It is verified that the values of the Base reactions always have higher values for higher frequencies, as it was also concluded with the HDRB bearings.

It is observed there is a range of friction coefficients values in which were obtained minimal values for the Base Reactions. It can be assured that using FPS devices can be reached a set of friction coefficients that lead to a convenient solution, in this case between 0,01 and 0,05.

With regard with seismic intensity increasing, it is concluded that as the intensity increases, the charts lines tend to stabilize with the friction coefficients increases.

The two charts that relate the FPS bearings coefficient of friction and the Base displacements (figure 8 and 9) are presented then.

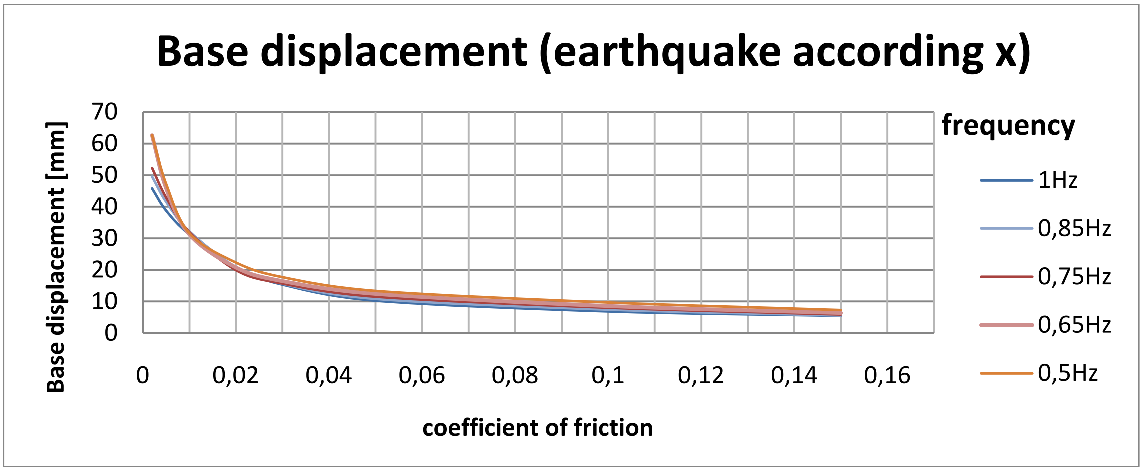

Figure 8 – Base Displacement – coefficient of friction for the testing structure with a 1,0 intensity earthquake acting according x

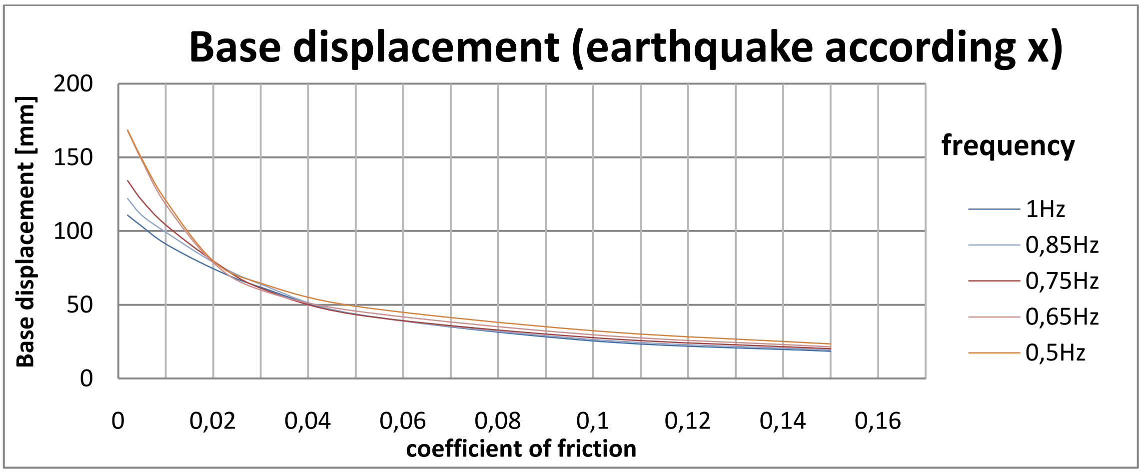

Figure 9 – Base Displacement – coefficient of friction for the testing structure with a 2, 3 intensity earthquake acting according x

As it was expected, the friction coefficients increasing conducted to a decrease in the displacement in the base.

It is observed that there isn't a great difference of displacement values in the base for different frequencies. It is verified that with friction coefficients values lower than 0,02, the displacements increase in excess.

So it is concluded that for this structure the range of friction coefficients values that optimize the forces and displacements in the base is between 0,02 and 0,05.

III.4. Comparison of the results

In this section, the Case Study 1 and the Case Study 2 will be compared. With this comparison is intended to estimate what are the required characteristics in a FPS device, that allows an isolated structure with HDRB and FPS bearings to present similar horizontal displacement and forces in the base.

The figures 10 and 11 show the charts that relate the forces in the base and the displacements in the base for the testing structure isolated with both bearings, HDRB and FPS, for the design seismic action, affected by different intensities.

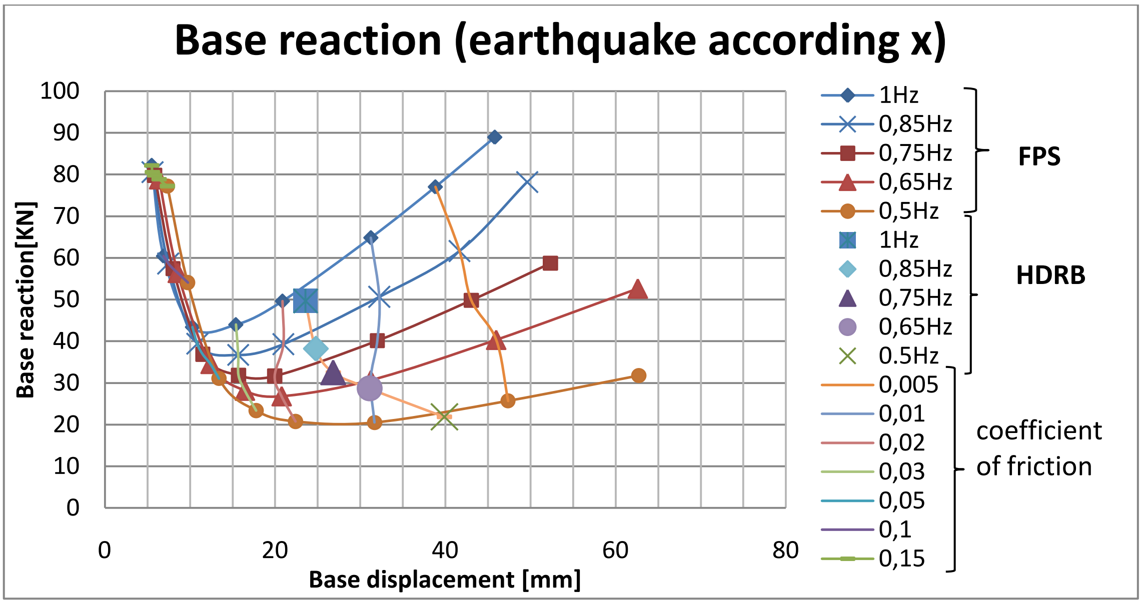

Figure 10 – comparative analysis of the forces and displacements in the base of the isolated testing structure with the HDRB and FPS bearings when subjected to 1,0 intensity seismic action.

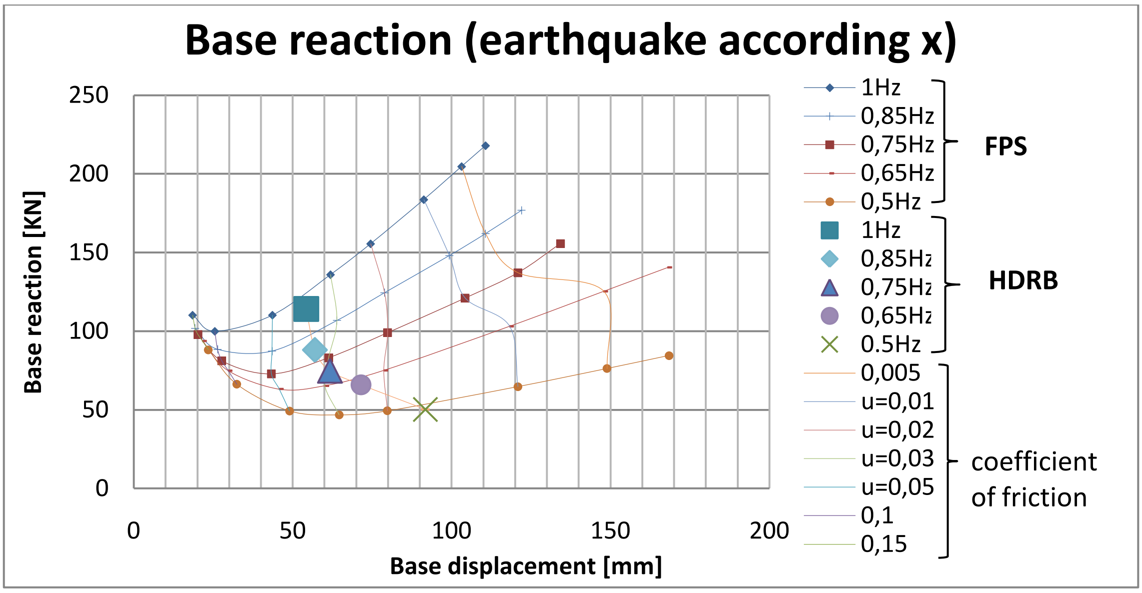

Figure 11 – comparative analysis of the forces and displacements in the base of the isolated testing structure with the HDRB and FPS bearings when subjected to 2,3 intensity seismic action

Through these charts it is possible to select the FPS bearing characteristics so that the structure when subjected to the same seismic action has the same behavior that would have if it was isolated with HDRB bearings.

By the analysis of the two charts previously shown it is verified that the set of values of the friction coefficient from the FPS devices, that guaranty that the forces in the base and the horizontal displacements are similar to those obtained using HDRB devices according the seismic intensity.

For a 1.0 intensity earthquake, it is observed that the set of values of the friction coefficient that restrain the line that represents the using of the HDRB devices is between 0,0005 and 0,02. When the seismic action is affected by a 2,3 factor that intensifies it, it is observed that the coefficient set of values varies between 0,01 and 0,05.

III.5. Laboratory structure

The Case Study with the Laboratory structure aims estimate the FPS bearing characteristics, based in the pre-dimensioning models obtained in the analysis of the Case Study 1 and 2. It is intended, in this case, design to obtain the same values of horizontal displacements and forces in the base, that were obtained in the Case Study 3, using the HDRB bearings.

The FPS bearings used to isolate the laboratory structure were designed with a 0,99 radius of curvature (frequency of 0,5Hz) and a friction coefficient of 0,007 or 0,015, respectively, when the seismic action is affected by a 1,0 or 2,3 intensity factor.

It was verified that the selected characteristics for the FPS bearings met the target since it is possible to obtain base reaction values very close to those obtained with HDRB bearings. In relation to the horizontal displacements in the base, it was observed that when the earthquake act just in one direction it is possible to obtain displacements in the base nearly equal, either using HDRB or FPS bearings. On the other side, when the earthquake acts in two directions simultaneously the displacements values quite diverge.

IV. Conclusions

The FPS devices present a unique characteristic in relation to other types of bearings. Their horizontal stiffness is directly proportional to the superstructure weight and it is independent from the natural vibration frequency value of the isolated structure.

A seismically isolated structure with FPS bearings, present the same displacements and forces base that it would present if it was isolated with HDRB bearings, if it were designed to a friction coefficient between 0,005 and 0,02, for a 1,0 and 1,5 intensity earthquake and between 0,01 and 0.05, when the seismic action is multiplied by a 2,3 factor.

According with the obtained results in the Cases Study 1 and 2, can be concluded that there is a set of coefficient of friction values between 2% and 5% that optimize the displacement values and base forces. Friction coefficient values higher than 5% result in lower displacement values in the base, but higher forces, while friction coefficient lower than 2% is verified lower base forces values, but higher horizontal displacements. It was seen that is possible, by modifying the parameters, from which the FPS bearings design depends, the curvature radius and the friction coefficient, to obtain similar displacements and forces values in the base of the testing structure that would be obtained using the HDRB bearings.

When the pre-designg charts obtained from the comparative analysis of the Cases Study 1 and 2 in the base structure were tested, it was concluded that these had a rather reasonable estimate for the needed characteristics of the FPS bearings. When the seismic action acts in two directions simultaneously, the horizontal displacements values in the base of the Laboratory structure using FPS bearings quite vary when compared with the obtained values when using HDRB bearings.

Therefore it is concluded that the FPS devices allow a greater versatility, in what concerns the determination of the isolation solution, considering that the definition of its behavior is dependent of a higher number of parameters.

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