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Vibration Control of the Structure using Friction Pendulum System

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Abstract
Base isolation system is one of the device used to reduce the damage caused to structure due to vibrations. It is placed beneath every supporting point , located between foundation and the main structure .One type of Base Isolation is Friction Pendulum System, which basically uses principle of pendulum which increases the natural period so as to reduce to the strongest forces during seismic event.FPS uses geometry and gravity to achieve the desired isolation results. This study physically demonstrates the concept of FPS using shaking table, specially designed concave surface, and bearings. The responses of a multi degree of freedom system with and without base isolation are measured simultaneously and compared for forced vibrations using the accelerometers attached at each floor of the model . The Newmark's Beta Method was applied to find the storey displacements of fixed and isolated structures subjected to harmonic motion using Mat Lab tool. Comparing and contrasting performance of FPS with fixed structure was carried out. Maximum storey displacement, frequencies, acceleration and storey drift were also determined for both fixed and base isolated structures. Overall , the FPS showed significant improvement in the dynamic response of the structure by reducing the acceleration sufficiently.

Keywords: *Base Isolation: Friction Pendulum System (FPS): Harmonic motion: Natural period: Storey drift:*

Introduction

Earthquake is one of the natural calamity which has taken many millions of lives in the history. Earthquake is caused "When the surface of the earth get disturbed due to movement of underground along the fault plane".[2] the base isolated structures are much different than the fixed based type. In fixed base structure i.e. conventional structure, the connection between the super structure and sub structure are rigid and in all direction the super structure translation is constrained. This structure has relatively lower time period in which they match with the predominant time period of most of the earthquakes. As a result these structures may experiences large accelerations and seismic forces and even they will be subjected to storey drifts which in turn may leads to damage or even collapse of the structure. Coming to the isolated structure, it almost vibrates like a rigid one with some large displacement due to the presence of isolators at the bottom. In this technique, a flexible interface is introduced between the foundation and superstructure from earthquake ground motion which in turn increases the fundamental time period of the structure and that results in lower acceleration. Consequently at the isolator level the fixed base structure experiences lower displacements and the isolated strictures experiences high displacement because of large displacement at the isolator level. The contents of this study are mainly grouped into four parts which are: (i) Experimental setup of base isolation and fixed case,(ii)study the mechanism of the isolation through equations of motion (iii)Data acquisition of the systems , and (iv) numerical analyses by using the mathematical model proposed in this study. The results from component tests and shaking table tests show that the proposed device is a promising one to upgrade the seismic resistibility of the structures. Furthermore, the numerical study show that the formulations presented in this study can well predict the behavior of the structure isolated with FPS isolator.

Problem definition

In this study performance of structure isolated with Friction Pendulum Isolator subjected to harmonic loading was evaluated. Initially, for better understanding of mechanism the Single storied structure was chosen and when structure is provided with isolation it acts as 2DOF.Modeling for MDoF i.e., storey structure was done for both Fixed and Isolation subjected to harmonic motion on shake table. Further, numerical analysis was done by New mark's Beta method using Mat lab Software. Finally, comparative results were obtained for all the cases.

Table 1:.Parameters used in the formulation

$\ddot{x}$ $\ddot{x} = \ddot{x}_1 + \ddot{x}_r + \ddot{x}_g$	Absolute acceleration of top mass 'm
$\ddot{x}_1$	Absolute acceleration of bottom mass 'm_b'
$\ddot{x}_r$	Acceleration of top mass relative to the ground
$\ddot{x}_s$	Acceleration of base mass relative to the ground
$\dot{x}_r$	Velocity of mass 'm'
$\dot{x}_s$	Velocity of mass 'm_b
X	Absolute displacement of base mass 'm'
x_1	Absolute displacement of base mass 'm_b'
x_r	Relative displacement of top mass 'm' with respect to the

	base mass m_b
x_s	sliding displacement of base mass 'm_b' relative to the ground
x_g	Displacement of the ground
K_o	Stiffness of mass 'm_b'
c_o	Damping coefficient
SDof	Single Degree of freedom
MDof	Multi Degree of freedom

Mathematical formulation

Consider a structure base isolated by Friction Pendulum System subjected to horizontal ground motion ($\ddot{x}_s$). Figure 1 shows the Free Body Diagram of the structure provided by isolator

Equations of motion:-

Generally, the motion consists of two phases, one is Non-sliding phase where the structure is not moving on the sliding surface and the other is sliding phase where the structure is moving on the surface

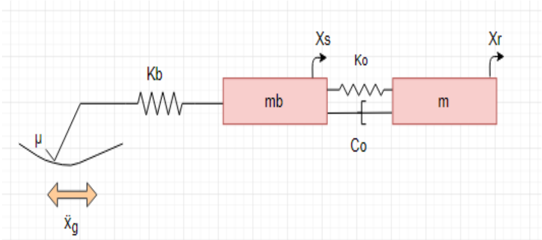


Figure 1: Analytical model of a single storey structure isolated by curved sliding surface isolator

Non-Sliding phase:-

During this phase the behavior of structure is fixed base. Here, the mass of the body does not move along sliding surface, because, the horizontal forces at the base is less than the frictional resistance

$$\ddot{x}_r + 2\omega_o\xi_o\dot{x}_r + \omega_o^2 x_r = - \ddot{x}_g \ldots\ldots(1)$$

Initiation of sliding phase:-

Sliding motion occurs when the frictional forces are less than the absolute sum of inertia force and restoring force

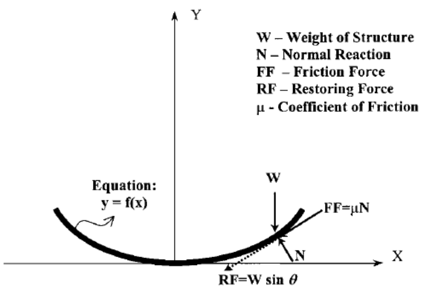


Figure2: FBD of sliding surface of isolator**[9]**

$$\alpha\ddot{x}_r + \ddot{x}_g + \omega_b^2(x_s)\, x_s \geq \mu \ldots\ldots(2)$$

Sliding phase:-

In this phase the static frictional force is overcome and there is relative motion between the sliding surface and the base mass. The equations of motion is as follows

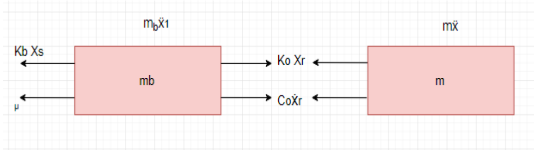


Figure 3: Free Body Diagram for sliding phase

$$\ddot{x}r + 2\omega o\xi o\, \dot{x}r + \omega o2\, xr = - \ddot{x}s - \ddot{x}g\ldots\ldots(3)$$

End of sliding phase

A sliding phase ends when the sliding velocity at the base mass becomes zero i.e.

$$\dot{X}s = 0\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Experimental modeling

The test structure developed for this experiment consists of four three-story building frames materials (Acrylic). One model with fixed base (without base isolation) and other model with base isolated by friction pendulum base isolation system and the floors are made up of aluminium material. In the fixed-base frame structure, the base plate is attached to the shake table. For the friction pendulum, base isolated structure, the 4 wheels are attached to the base plate of the model under the columns and to the base below to the pendulum bearings which moves along the pendulum profile made, which ensures the horizontal motion during the earthquake ground motion. The pendulum profile is attached to the foundation below which is, in turn, rigidly attached to the shaking table. Four accelerometers are attached to the roof of each floor including ground floor to record the lateral accelerations of two structural models.

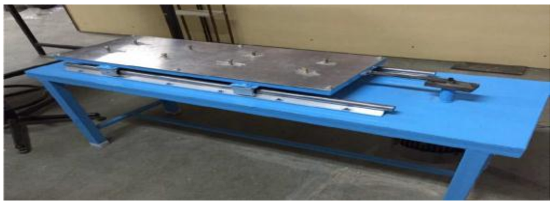


Figure 4: Shake table

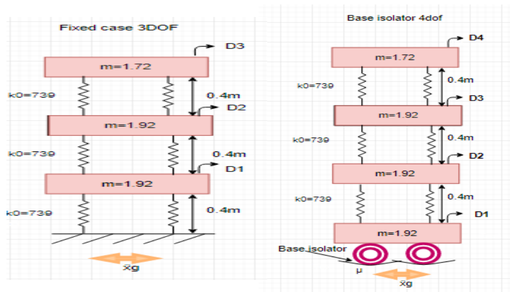


Figure 5: Models for Fixed and base isolated cases

Table2: Physical properties of the model

No	Column	Slab	Screws
Material	Acrylic	Aluminium	Mild Steel
Length, l (mm)	1200	300	
Breadth, b (mm)	35	150	
Depth ,d (mm)	5	12.7	
Young's Modulus(Gpa)	2.7	70	
Mass density(kg/m^3)	1200	2700	
Mass(kg)	M_{col}=0.30 kg	M_{slab} =1.435 kg	M_{screw} = 0.03 kg

Figure 6 shows the natural frequencies of the model represented with mode shapes

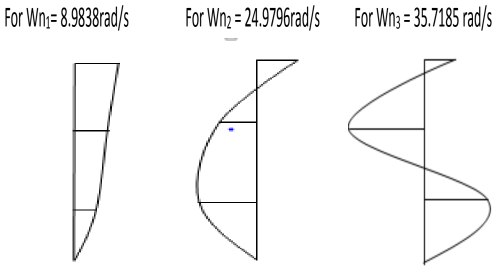


Figure 6: Mode shapes

Data acquisition system

Data acquisition is the process of measuring the physical phenomenon and converting the results into digital values or digital signals that can be manipulated by a computer. Following are the instruments used for data acquisition. This is having many components as follows

➢ **Accelerometer:**

The accelerometer ADXL335 has been selected for measuring the structural response of a three storey structural model during earthquake excitation

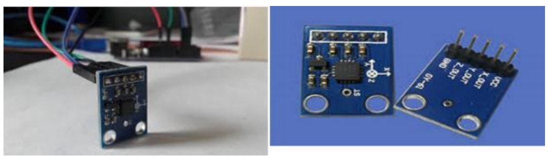


Figure 7: ADXL335 Accelerometer sensor

➢ **Arduino-Uno Board:**

The Arduino-Uno board is microcontroller board based on the ATmega328, it has 14 digital input or output pins and 6 analog inputs, which has everything which supports the microcontroller, can be simply connected to the computer source with a USB cable.

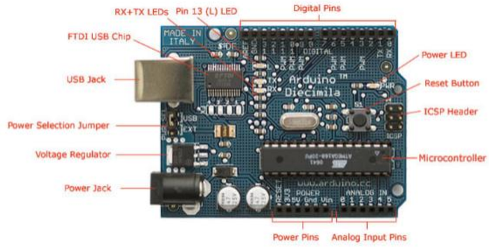


Figure 8: Arduino UNO board

➢ **Telemetry**

It is an automated communication process for sensing and measuring the data between remote points and receiving equipment and helps to monitor and controls the happening process at the instrumentation place

➢ **System Identification:**

Sinusoidal harmonic motion test

The sinusoidal harmonic motion test can be performed as follows:

1) With AC circuit driver speed controller, set up a control panel that generates shaking table motion in the form of a sine sweep from 0 to 25 Hz and with a fixed displacement amplitude of 12.5mm.

2) Generate the sinusoidal harmonic motion of the shaking table. Be particularly careful about avoiding excessive response when the excitation frequency passes through the resonant frequency.

3) Throughout the duration of the test, the acceleration response should be measured at the each storeys including ground floor.

4) During the test, observe the structural response, watching for the development of mode shapes as the sinusoidal harmonic excitation passes through the natural frequencies.

5) The acceleration data are stored in log.xls file format in the system, raw data of acceleration of all floors are stored in excel file and the unit of the stored raw data is milli volts.

6) Convert the stored raw data in to required data units by dividing the sensitivity value of the accelerometer.

7) The converted data units will be of time domain results. Carry out the FFT function in excel to obtain the frequency. The frequency chart (frequency v/s magnitude) is plotted for each floor from the obtained FFT results shown in Figure 11

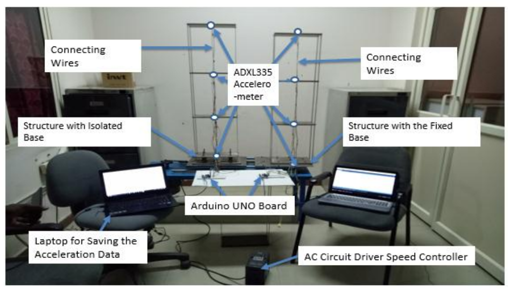


Figure 9: Experimental setup of DAS

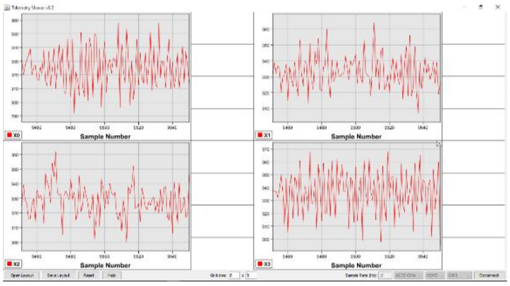


Figure 10: Fixed base model acceleration graph of each storey for 3.99Hz

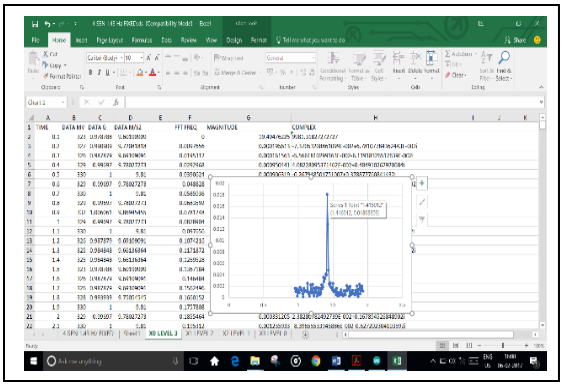


Figure 11: Obtaining Natural frequency from the raw data using FFT analysis in Excel

Table3: Frequencies for fixed case (3Dof)

From the history curves	Frequencies (Hz)
Feeding frequency	3.92
3Dof	1.42
2Dof	1.41
1Dof	1.40
AVERAGE	1.41

Table.4. Frequencies for isolation case (4Dof)

From the history curves	Frequencies (Hz)
4Dof	0.5
3Dof	0.49
2Dof	0.47
1Dof	0.47
AVERAGE	0.48

Analysis

Theoretical analysis to find displacements by Modal superposition method for MDof for fixed case. The Figure.12 gives displacement curves for each storey

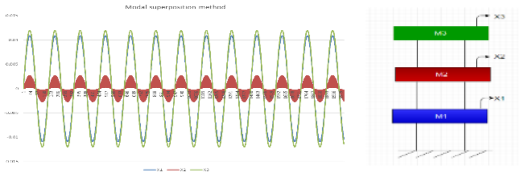


Figure 12: Displacements v/s Time for each floor

Obtaining Frequencies from the Time history curves using MAT LAB software

Frequency is defines as number on oscillation per unit time. It is inverse of time (T).So, from figure vibration is obtained from mat lab where time period for u nit cycle is noted.

Frequency, f = $^1/_T$

➢ **For Fixed case 3 DoF**

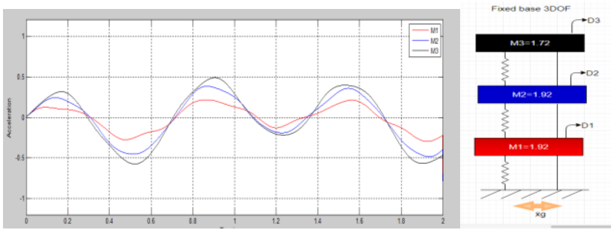


Figure 13: Time history curves for fixed case

Acceleration (m/sec^2) V/s Time(sec)

Time difference from graph (Figure.13.),

T = 0.7 sec

Frequency, f = $\frac{1}{0.7}$

= 1.42 Hz

Similarly, from time history curves obtained 4dof for isolation case are shown table 3

Results and Discussions

Mat lab results for response of SDof fixed case using Newmark's method subjected to sinusoidal loading

Pq=Pont*sin (w*t)

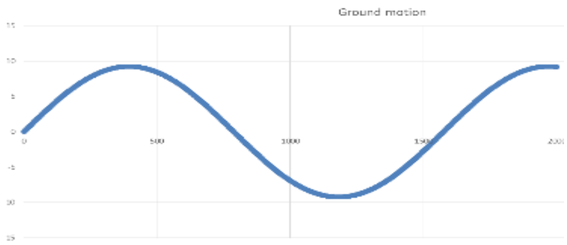


Figure 14: Graph for Applied ground motion

Comparison of Frequencies for isolation (4Dof) and fixed case (3Dof) experimentally

From figure.15&16, it was experimentally and seen that Frequencies are significantly reduced in isolated structure

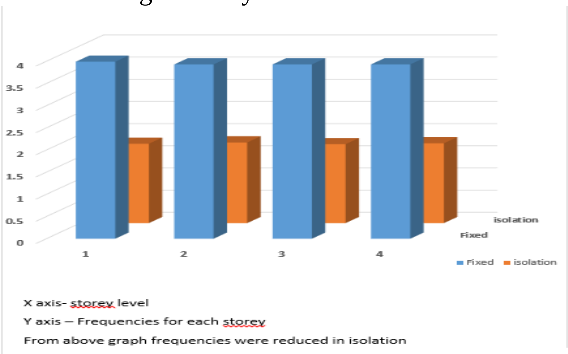


Figure 15: Comparisons of frequencies for fixed and isolation subjected to sinusoidal loading from experimental

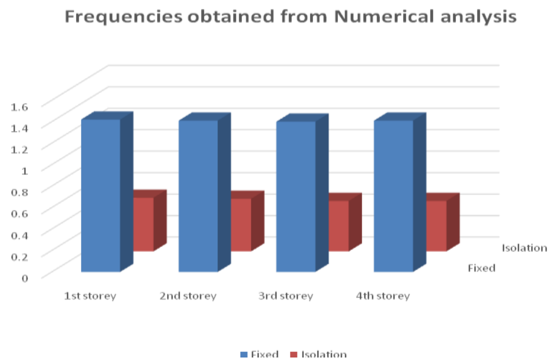
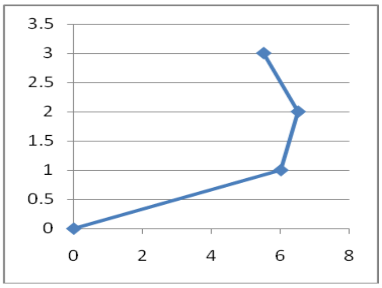


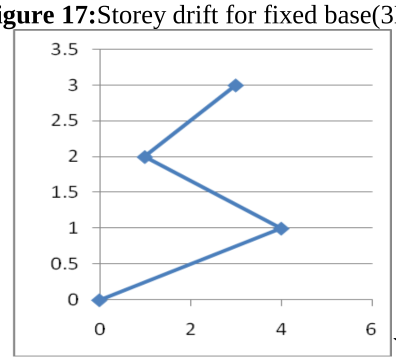
Figure 16: Comparisons of frequencies for fixed and isolation subjected to sinusoidal loading from numerical analysis

Comparison of Storey drift of fixed (3DoF) and isolation (4DoF) experimentally



Storey drift(mm)

Figure 17: Storey drift for fixed base(3Dof)



Storey drift(mm)

Figure 18: Storey drift for base isolator(4Dof)

Time History Analysis

Response of the structure subjected to EL Centro earthquake

The El Centro earthquake occurred on 19th May 1940 at Southern California near border of Mexico and United states. On Mercalli intensity scale the maximum intensity was found to be 6.9 magnitude .The structure is analyzed for ground motions. The data obtained are a from the historical recordings. The time history analysis was carried out for base isolated structure and fixed cases.

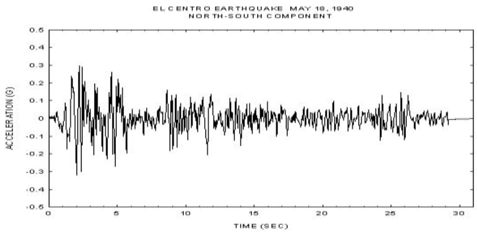


Figure 19: Acceleration data for El Centro

(Source: EL Centro data.com)

Response of the base isolated and fixed case structures subjected to EL Centro earthquake

Displacements of the structures subjected to EL Centro

The following graphs gives the displacements of the structure subjected to EL Centro.

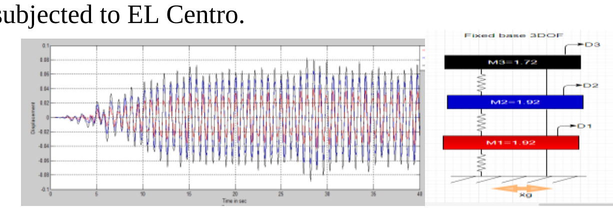


Figure 18: Displacements at each storey of the fixed based structure subjected to EL Centro

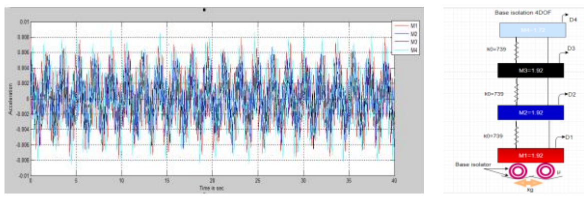


Figure 19:.Displacements at each storey of the isolated structure subjected to EL Centro

The graph in Figure.19,indicate how little a difference there is between the base and top story displacement. Peak value for fixed case is 0.06m and isolation is 0.0004m.

Vibrations of the structures subjected to EL Centro

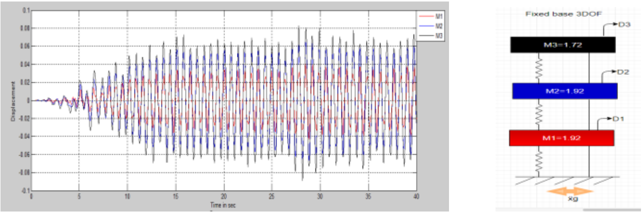


Figure 20: Vibrations at each storey of the fixed based structure subjected to EL Centro

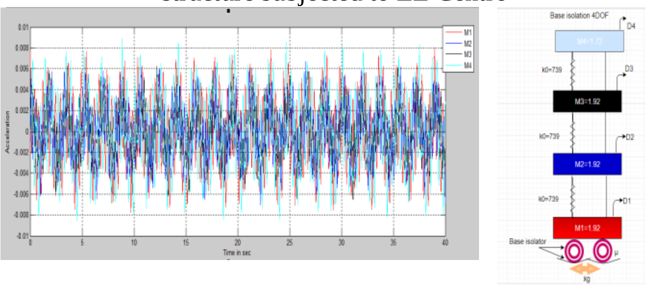


Figure.21: Vibrations at each storey of the isolated structure subjected to EL Centro

From Figure 20 & 21, Vibrations for fixed is 10m/sec^2 and for isolation is 0.08m/sec^2.

Conclusion

- The results of the project shows that the response of the structure can be reduced by the use of Friction Pendulum System
- From Figure 15, Experimentally, comparing the frequency obtained for the fixed base model and an isolated base model, we can observe there is a reduction of frequency up to 50% in isolated base model
- Numerically from Figure 16, the time period of the structure has increased from 0.7sec to 2.083sec of the isolated structure.
- From Figure 17 &18, Experimentally ,Storey drift was reduced up to 86.66%, so FPS has been effective in reducing the deformations
- From Figure 20 & 21, considering peak values for structure subjected to EL Centro , its seen there is 99% reduction in the deformations and vibrations in the isolated structure.

Thus, we can conclude that base isolation is an effective measure for substantially improving earthquake resistance of buildings.

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