INFLUENCE OF FRICTION PENDULUM SYSTEM ON THE RESPONSE OF BASE ISOLATED STRUCTURES

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ABSTRACT :

The analytical and experimental seismic response analysis of 7 storey reinforced concrete shear type building structure isolated by friction pendulum system (FPS) are presented herein. The superstructure is idealized as a linear shear type building. Nonlinearity is located in the base in the bearings for base isolation. Real earthquake records with equal maximum acceleration were used. The identification results are verified by numerical simulations and the accuracy of the identified parameters is verified by comparing with the experimentally measured results. The response of seismically isolated structure by FPS with different friction coefficients is also investigated and it is found that a small variation of the friction coefficient produces significant difference of the response for all earthquake excitation.

KEYWORDS: Friction pendulum system, seismic isolation, dynamic response of structure

1. INTRODUCTION

In recent years, the Friction Pendulum System (FPS) has become a widely accepted device for seismic isolation of structures. The concept is to isolate the structure from ground shaking during strong earthquake. Seismic isolation systems like the FPS are designed to lengthen the structural period far from the dominant frequency of the ground motion and to dissipate vibration energy during an earthquake. The FPS consists of a spherical stainless steel surface and a slider, covered by a Teflon-based composite material. During ground motion, the slider moves on the spherical surface lifting the structure and dissipating energy by friction between the spherical surface and the slider. Advantages of this type of system for base isolation are practically identified and approved in this thesis through analytical and experimental analysis. Numerical model of real reinforced concrete structure is defined and verified by comparing with the experimentally measured results. The same model is used for analysis of base isolated structure with system of friction pendulum bearings in the base and comparison of the results of these two analytical models was done.
Investigation was done in two phases:
I phase - Basic theoretical concept analysis for modeling the behavior of isolated structures and
II phase - Application of the proposed methodology for analysis of seismic isolated structures.

2. THEORETICAL BACKGROUND

Figure 1 shows the structural system under consideration which is an idealized N-story shear type building mounted on the FPS system. The unique feature of the FPS is that movement of one part of the bearing with respect to others resembles pendulum motion in the presence of friction. The lateral force needed to induce a lateral displacement of the building–bearing system depends primarily upon the curvature of the spherical sliding surface, and the vertical load on the bearing [5].

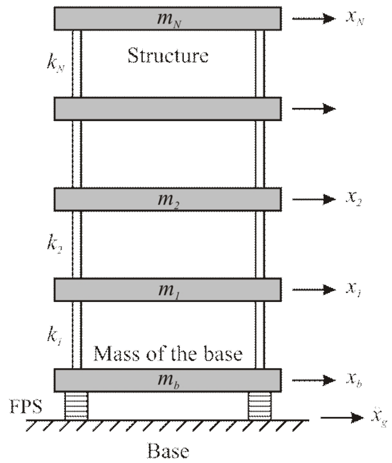

Figure 1. Flexible superstructure with FPS

The lateral force is proportional to the vertical load, a property which minimizes adverse torsion motions in structures with asymmetric mass distribution. One lateral dynamic degree of freedom is considered at each floor and base mass. Therefore, for the N-story superstructure the dynamic degrees of freedom are N + 1. The governing equations of motion for the fixed-base N-story superstructure model are expressed in matrix form as:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\} \quad [\cancel{M}]\{1\}\{\ddot{x}_g+\ddot{x}_b\} \tag{1}$$

where [M], [K] and [C] are the mass, stiffness and damping matrices of the fixed base structure of the order N x N; $\{x\}=\{x_1,x_2,\ldots,x_N\}^T$ is the displacement vector of the superstructure; x_j (j = 1, 2,......, N) is the lateral displacement of the j-th floor relative to the base mass; $\{1\} = \{1, 1, 1,\ldots\ldots, 1\}^T$ is the influence coefficient vector, $\ddot{x}_b$ is the acceleration of base mass relative to the ground; $\ddot{x}_b$ is the acceleration of earthquake ground motion. Note that the damping matrix of the superstructure, [C] is not known explicitly. It is constructed by assuming the modal damping ratio which is kept constant in each mode of vibration.

The restoring force of the FPS is expressed by:

$$F_b=F_x+k_b \cdot x_b \tag{2}$$

where F_x is the frictional force in the FPS; and k_b is the stiffness of the FPS provided by the curvature of the spherical surface through inward gravity action.

The limiting value of the frictional force, Q, to which the FPS can be subjected (before sliding) is expressed as:

$$Q=\mu W \tag{3}$$

where μ is the friction coefficient of the FPS; $W=Mg$ is the total weight of the isolated building; $M=\left(m_b+\sum_{j=1}^{n} m_j\right)$ is the total mass of the base-isolated building; m_j is the mass of the j-th floor; and g is the acceleration due to gravity. The stiffness k_b of the FPS is designed such a way to provide the specific value of the isolated period, T_b expressed as:

$$T_b=2\pi\sqrt{\frac{M}{k_b}}T_b \tag{4}$$

Thus, the modeling of FPS requires specification of two parameters, namely the isolation period (T_b) and the friction coefficient (μ).

The governing equations of motion of the base isolated structure cannot be solved using the classical modal superposition technique due to non-linear force–deformation behavior of the FPS. The system remains in the non-sliding phase $(\dot{x}_b = \ddot{x}_b = 0)$ the frictional force mobilized at the interface of FPS is less than the limiting frictional force ($|F_x| < Q$). The system starts sliding $(\dot{x}_b \neq 0$ and $\ddot{x}_b \neq 0)$ as soon as the frictional force attains the limiting frictional force ($|F_x| = Q$). The governing equation of motion of the base mass is also included for the solution during the sliding phase of motion. Whenever the relative velocity of the base mass becomes zero $(\dot{x}_b = 0)$, the phase of the motion is checked in order to determine whether the system remains in the sliding phase or sticks to the foundation.

3. EXPERIMENTAL AND NUMERICL INVESTIGATION

Object of analysis of this research is real residential building with 7 floors located in Skopje. The main constructive system of this building consists of reinforced concrete walls and plates. Building layout is almost symmetric with dimensions 22.85 *m* x 21.65 *m*. Total high of the structure is 28.8 *m*. Till now, no bearings for base isolation are installed on the structure.

3.1. Experimental investigations

Experimental investigation of this structure encloses measuring of ambient vibration of the real structure on site. Ambient vibrations measuring are done in all floors of the building with two types of equipment: wireless TROMINO instruments and system of seismometers, amplifier and recorder. During the experimental investigations, 10 min. records in two horizontal orthogonal directions east-west and north-south were done.
Two of the TROMINO instruments were referent and located on the top floor of the structure. Another 4 instruments were placed on every floor of the structure.
One of the seismometer of another type of the equipment was used as referent for measuring the vibrations in two different directions of the top floor of the structure, and another two seismometers were placed on every floor of the structure at the same locations like the TROMINO instruments.
To identify the results obtained by the measurements, the computer program ARTeMIS was used. Obtained amplitude spectra are shown in Figure 2.

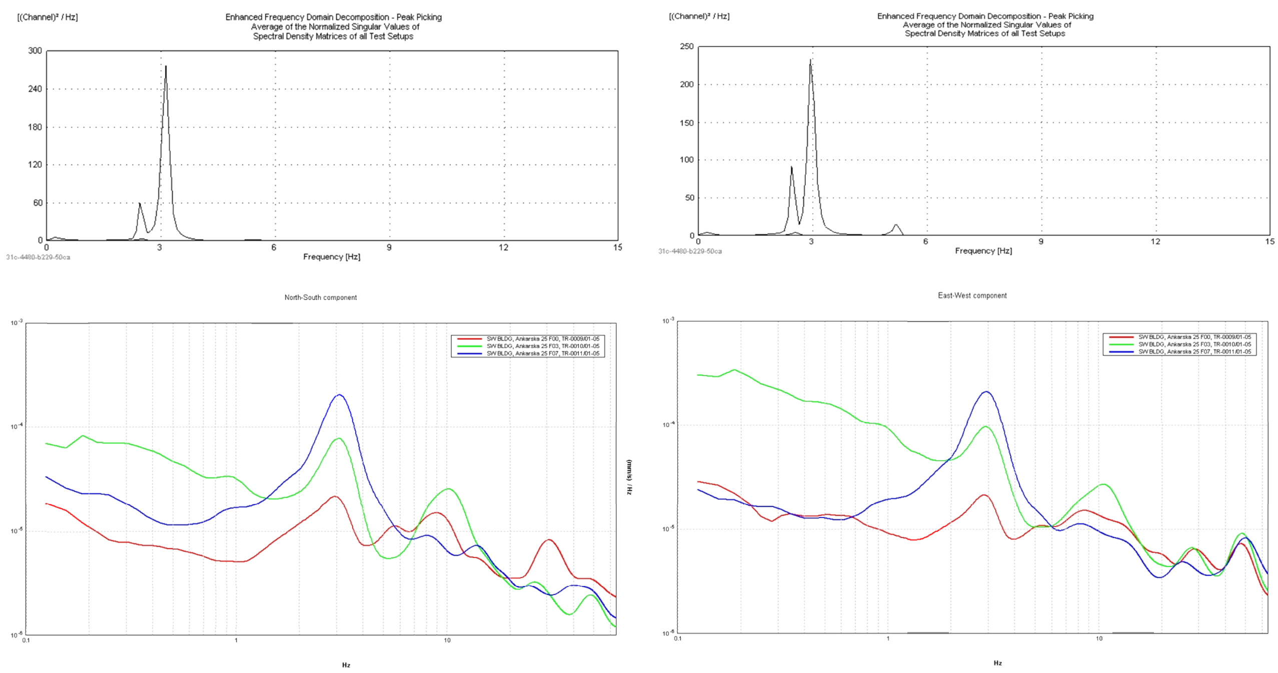

Figure 2. Amplitude spectra by system of seismometers and TROMINO instruments

3.2. Numerical analysis of real reinforced concrete residential building

The structure is modeled as a three dimensional, and the characteristics of the structural members are adopted as they were in the design documentation. For the dynamic analysis of the structure, original time history records in two horizontal directions are used. Time history from El Centro earthquake is taken as referent, but Parkfield, San Francisco and Loma Prieta are scaled to get maximal acceleration of the referent 0.3417 m/sec^2 (0.348 g). Material properties, loading intensity and foundation conditions were adopted assumptions when modeling the real (non-isolated) reinforced concrete structure. The main assumptions in modeling of the fixed structure are linear behavior of the model and fixed base. The behavior of the based isolated structure is also linear with local nonlinearity in the elements modeled as bearings of the friction pendulum system. The total number of bearings used for base isolation is 44. Every element is modeled with two joints with same coordinates. All six degrees of freedom are restrained on the "bottom" joints, but all "top" joints are constrained in moving together (as in the reality).

3.2.1 Results

All attained results from these complex analysis show that installation of FP bearings has direct influence on lengthening of the structural natural vibration period and change the mode of vibration as a result of nonlinear bearing behavior (Table 1 and Figure 3). Due to nonlinear behavior of the bearings, larger displacement in the base were obtained, but significant reduction of base shear, relative displacement and relative acceleration was also acquired. Top level acceleration of the base isolated structure influenced by all earthquake records is reduced around 3 times compared with the fixed structure. The most exclusive property for a FPS type of bearing is that they have low sensitivity to the frequency and amplitude of the excitation and lateral restoring force is proportional to the weight carried by the bearing.
The numerical results show that using the friction pendulum system for base isolation leads to increase of the seismic resistance of this type of structure.

Table 1. Natural periods and frequencies

Period	Fixed structure		Isolated structure	
	[sec]	Direction of vibration	[sec]	Direction of vibration
T_1	0.497199	first mode, torsion	2.1987191	first mode, x-direction
T_2	0.319407	first mode, x-direction	2.1542015	first mode, y-direction
T_3	0.283233	first mode, y-direction	2.0227555	first mode, torsion
T_4	0.124677	second mode, torsion	0.3929018	second mode, x-direction
T_5	0.088260	second mode, y-direction	0.3517677	second mode, y-direction

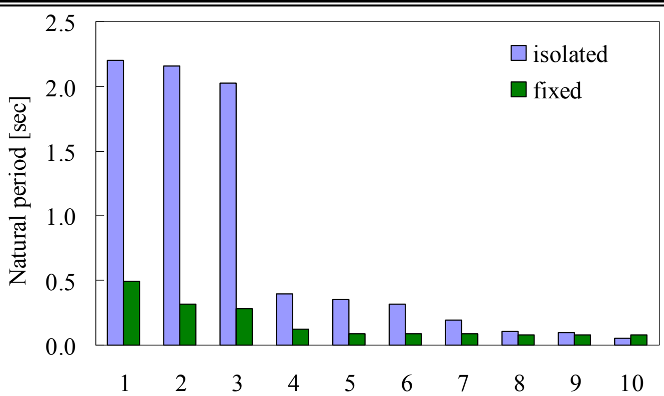

Figure 3. Natural periods

Figure 4 shows the compared displacement, velocity and acceleration diagrams in all joints by the height of the model at the time when peak value during El Centro time history at the top level has occurred. Maximum displacement is much bigger than in isolated structure, but more important parameter for base isolated structure is relative displacement which is insignificant in comparison with the fixed structure.
Figure 5 shows compared time history of total base shear in fixed and isolated models where obvious significant reduction of base shear is in the isolated structure. This reduction occurs in the results of all of the earthquakes inputs analyzed.

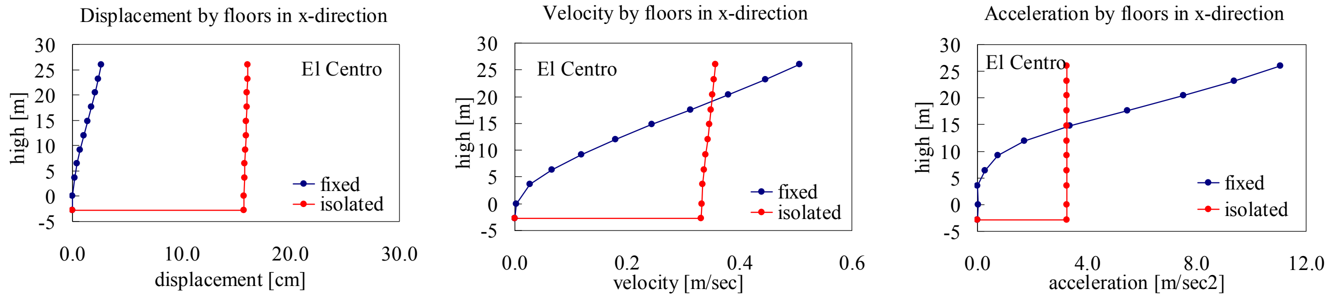

Figure 4. Compared displacement, velocity and acceleration for fixed and isolated structure

The hysteretic loop on Figure 5 illustrates the dissipation of energy.

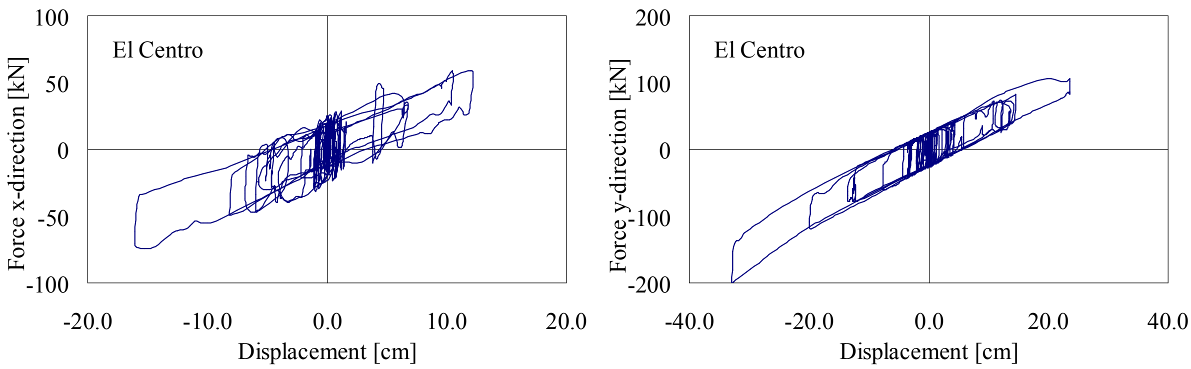

Figure 5. Force-displacement relationship in Friction Pendulum Bearing System

More than 50% of input energy was dissipated in the base isolation system (Figure 6).

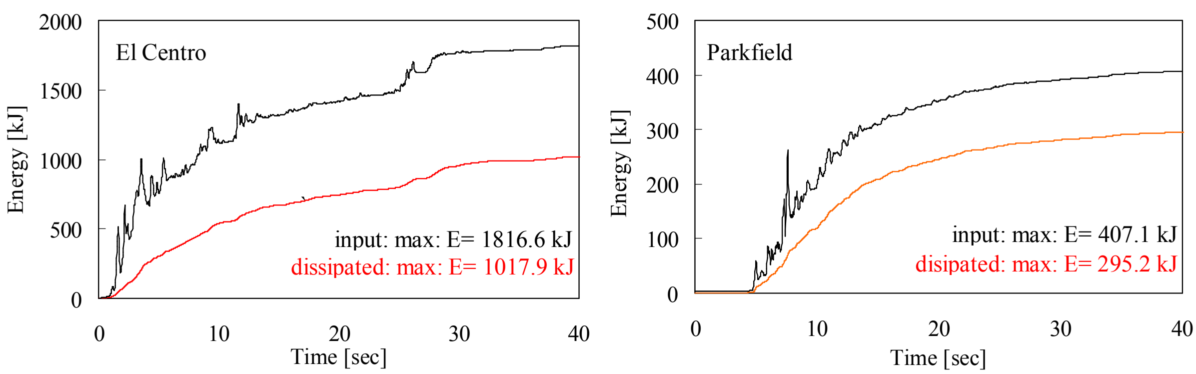

Figure 6. Energy time history comparison

A small variation of the friction coefficient value has high influence on the base shear force (Table 3). This friction coefficient depends on the bearings producers.

Table 2. Influence of friction coefficient of base shear

Friction coefficient at fast velocities	Max. displacement in bearings in horizontal direction [cm]	Max. base shear [kN]	% W_T
0.06	21.16	1200.01	2.9
0.10	15.77	1358.00	3.3
0.15	14.75	1451.00	3.5
0.20	12.54	2085.00	5.1
0.25	10.47	2837.00	6.9
0.30	8.53	3347.00	8.1

4. CONCLUSIONS

The main objective of this research is analytical and experimental earthquake response investigation of 7 storey building structure isolated by friction pendulum system. The analysis used in these investigations gave solution with satisfied accuracy which shows:

1. Increase of the fundamental structural period from 0.49 sec to 2.19 sec after the application of the base isolation, far away from earthquakes dominant frequencies;
2. Significant energy dissipation and reduced displacement to acceptable level had occurred;
3. Significant reduction of base shear in isolated structure;
4. Maximal accelerations at all levels of the isolated structure are almost the same and isolated structure behaves like rigid body;
5. Relative displacements of the base isolated structure are negligible;
6. The earthquake load transmitted to this particular test model was effectively reduced by using FPS type base isolation devices.

FPS is considered to be essential especially in the design of structures that need immediate occupancy and that should remain fully serviceable after an earthquake, such as hospitals and fire departments.

Generally, base isolation introduces about 0-5% of the original total cost but the reduced cost may be more dramatic in both the structural and nonstructural items and the contents of the structure. Of course one should not deduce that base isolation is a must, but it could be applied when it provides a more effective and economical alternative than other methods of providing for earthquake safety.

These investigations present part of development strategy for frequent use of seismic isolation as a protection from earthquake damage in our country.

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