Parametric Investigation Of The Effect Of Ground Motion Characteristics On The Response Of A Seismically Isolated Structure

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SUMMARY:
Seismic isolation is an innovative seismic retrofitting strategy which aims to reduce the damaging effects of earthquake ground motions by decoupling the structure from the ground with a flexible layer of seismic isolation bearings. This paper reports the results of a parametric study to investigate the effect of ground motion characteristics (PGA, PGV, PGD, PGV/PGA, PGD/PGV) on the response of a seismically isolated structure using earthquake ground acceleration time-history records. The equations of motions for a two degree of freedom model with friction pendulum isolators are defined using the state-space formulation, where, Bouc-Wen model is used to model the hysteretic behavior of the friction pendulum bearings. Afterwards, the results of the parametric analysis on the effects of the ground motion characteristics on the variation of base shear, floor accelerations and seismic isolation displacements are presented through normalized plots and implications of the results on the design of seismic isolation systems are discussed in the conclusions.

Keywords: Seismic isolation, friction pendulum, characteristics of earthquake, parametric study

1. INTRODUCTION

Seismic isolation is a retrofit strategy which is used to protect buildings, bridges, viaducts and non-building structures such as storage racks and liquid storage tanks from the damaging effects of earthquake ground motions. Although various seismic isolation systems have been developed over the years, all of these systems share two common mechanisms; a mechanism for elongating the natural vibration period of the superstructure and a mechanism for energy dissipation. Elongation of the natural vibration period of the superstructure beyond the predominant period of the seismic base excitation can result in significant reductions in floor accelerations and base shear acting on the structure. However, the period elongation effect provided by the horizontally flexible seismic isolation bearings can lead to large horizontal displacements at the seismic isolation interface. The energy dissipation mechanism of the seismic isolation system is essential for providing the damping to limit the bearing displacements.

This paper reports the results of a parametric study to investigate the effect of ground motion characteristics (PGA, PGV, PGD, PGV/PGA, PGD/PGV) on the response of a seismically isolated structure using earthquake ground acceleration time-history records. The equations of motions for a two degree of freedom model with friction pendulum isolators are defined using the state-space formulation, where, Bouc-Wen model is used to model the hysteretic behavior of the friction pendulum bearings. Afterwards, a parametric analysis was conducted with a script which employs the state-space solvers of MATLAB. The results of the parametric analysis to study the effects of the ground motion characteristics on the variation of base shear, floor accelerations and seismic isolation displacements are presented through normalized plots and implications of the results on the design of seismic isolation systems are discussed in the conclusions.

2. MODELING

2.1. The Friction Pendulum System

The Friction Pendulum System, which was developed by EPS (Earthquake Protection Systems) is one of the widely used systems for seismic isolation. The Friction Pendulum bearings essentially consist of an articulated slider which rests on a concave steel surface with a radius of curvature of R (Figure 1).

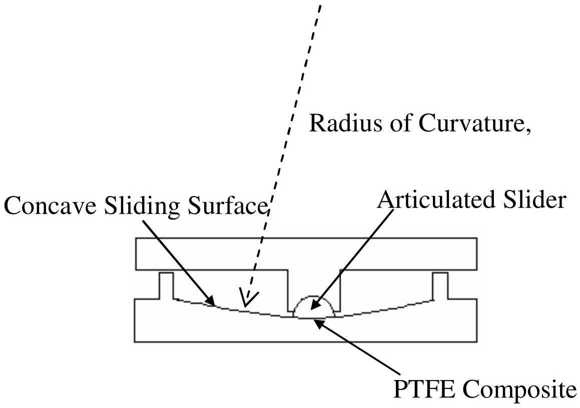

Figure 1. Components of a Friction Pendulum Bearing

The natural vibration period of a structure on Friction Pendulum bearings can be extended by adjusting the radius of curvature of the bearings and the friction at the PTFE composite-steel concave sliding interface essentially provides the mechanism for energy dissipation (Yazici, 2007). Target isolation period for a rigid superstructure resting on a frictionless surface be can be estimated with Equation 2.1. Radii of curvature for various target isolation periods are presented in Table 1 (Zayas, et al., 1990).

$$T = 2\pi\sqrt{\frac{R}{g}} \tag{2.1}$$

Table 1. Radii of curvature for various target isolation periods

T (s)	R (m)
1.50	0.56
2.00	1.00
2.50	1.55
3.00	2.24
5.00	6.21

The bearing force in Friction Pendulum bearings can be calculated by Equation 2.2 where W,R,μ, u_b and Z represent the vertical load, radius of curvature, coefficient of friction at the PTFE composite-steel interface, horizontal bearing displacement and the Bouc-Wen hysteretic variable Z which controls the transition between the stick and slip phases, respectively (Constantinou, et al.,1990).

$$F_{fps} = \frac{W}{R}u_b + \mu WZ \tag{2.2}$$

The value of the hysteretic variable Z can be determined using the Bouc-Wen equation (Equation 2.3), where Y represents the yield displacement whereas, γ, β, A and η are the model parameters which control the shape of the hysteresis loop. The values of η=2, β=0.1, γ=0.9 and A=1 are acceptable values for modeling the hysteresis loops of Friction Pendulum bearings (Park et al., 1986 and Constantinou, et al.,1990).

$$Y\dot{Z} + \gamma|\dot{u}_b|Z|Z|^{\eta-1} + \beta\dot{u}_b|Z|^{\eta} - A\dot{u}_b = 0 \tag{2.4}$$

Extensive information on the Friction Pendulum bearings can obtained from (Constantinou et al., 1990, Constantinou et al., 1999, and Zayas et al., 1990).

2.2. Mechanical Model of Isolated Structure

The 2 DOF model of the isolated structure used in the parametric study is presented in Figure 2. Mass, stiffness and damping of the superstructure are denoted by m,k and c whereas the mass of base plate is denoted by m_b. Horizontal displacement of the ground is denoted by ug and the relative horizontal displacements of bearings and the superstructure are denoted by u_b and u_s,respectively.

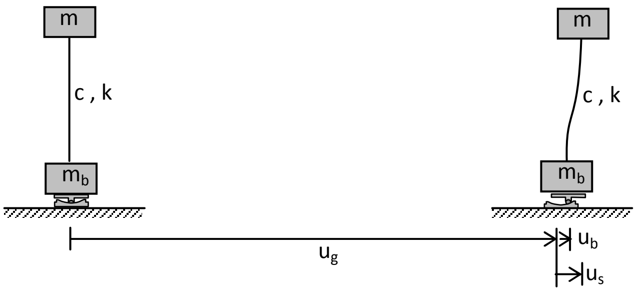

Figure 2. Mechanical Model of the Isolated Structure

The equations of motion for the 2 DOF structure are given by equations (2.5) and (2.6) (Konstantinidis, 2005);

$$m\ddot{u}_s + c(\dot{u}_s - \dot{u}_b) + k(u_s - u_b) = -m\ddot{u}_g \tag{2.5}$$

$$m_b\ddot{u}_b + \left(\frac{W}{R}u_b + \mu WZ\right) - c(\dot{u}_s - \dot{u}_b) - k(u_s - u_b) = -m_b\ddot{u}_g \tag{2.6}$$

3. PARAMETRIC STUDY

A parametric study has been conducted with the 2 DOF model of the seismically isolated structure described in the previous section to investigate the effect of ground motion characteristics (PGA, PGV, PGD, PGV/PGA, and PGD/PGV) on the reductions in base shear, floor accelerations bearing displacements. Five earthquake acceleration time history records used in the study were selected from the PEER Strong Motion Database based on the variation of ground motion parameters. The ground motion properties of these records are outlined in Table 2.

Table 2. Ground Motion Parameters of the Earthquake Acceleration Time History Records Used in the Analyses

Earthquake/Array	PGA(g)	PGV(cm/sec)	PGD(cm)	PGV/PGA	PGD/PGV
Kocaeli/Yarimca/YPT060	0,268	65,7	57,01	245	0,867
Imperial Valley/I_ELC180	0,313	29,8	13,32	95	0,446
Erzincan/ERZ_EW	0,496	64,3	22,78	129	0,354
Duzce/DZC_270	0,535	83,5	51,59	156	0,617
Northridge/RRS228	0,838	166,1	28,78	198	0,173

Mass of the superstructure and the base plate were chosen as 90000 kg whereas the viscous damping coefficient and the stiffness of the superstructure were chosen as 164970 Ns/m and 30240000 N/m, respectively. Coefficient of friction of the Friction Pendulum bearings were assumed to vary between 0.03 and 0.10 and three radii of curvature (R=1.00m, R=1.55m and R=2.24m) were considered in the parametric analysis. The dynamic response of the isolated structure and the fixed base structure were analyzed using a script developed in MATLAB and the results of the parametric study were presented in the form of normalized plots.

Variation of bearing displacements for the three curvature radii considered in the study are presented in Figures 3 through 5.

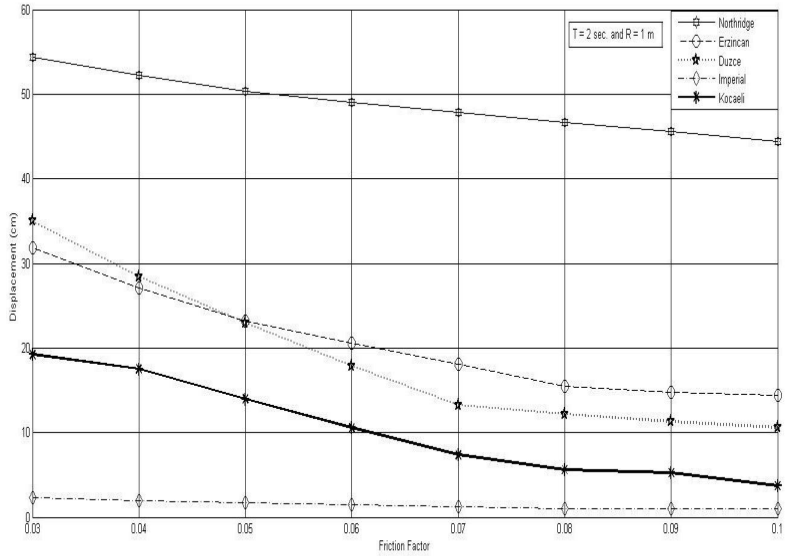

Figure 3. Bearing displacements for R = 1 m (T=2s)

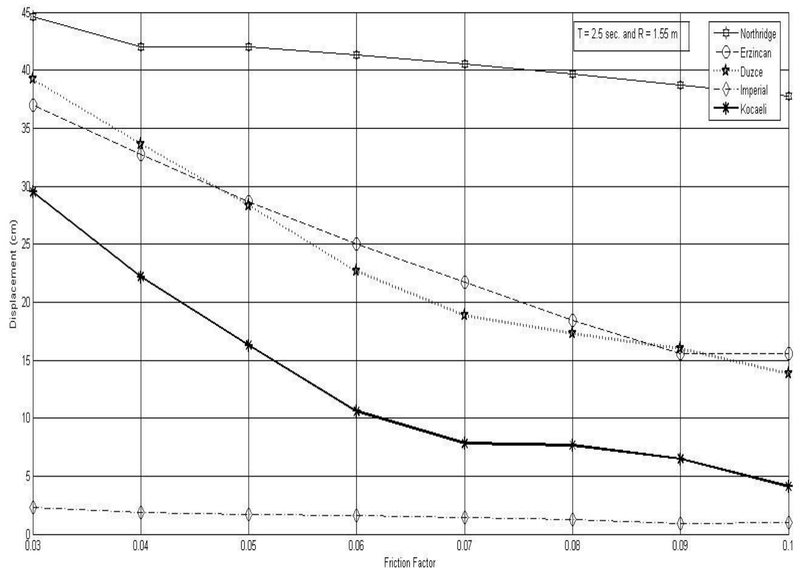

Figure 4. Bearing displacements for R = 1.55 m (T=2.5s)

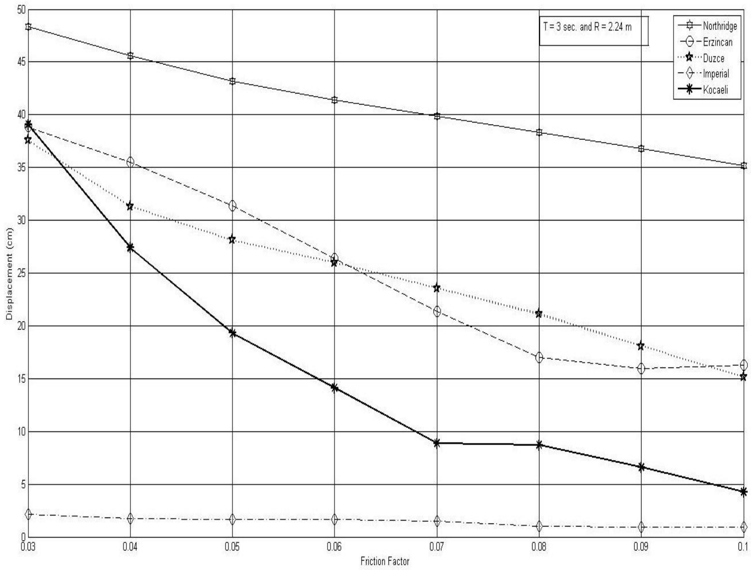

Figure 5. Bearing displacements for R = 2.24 m (T=3s)

The bearing displacements for the Northridge earthquake acceleration record are higher compared to the bearing displacements from other earthquake acceleration records. The bearing displacements naturally decrease with the increase in the friction coefficient and increase with the increases in the curvature radius of the bearings. Although, the large bearing displacements obtained from the Northridge earthquake acceleration record could be attributed to the large PGA of the event, the results obtained from other earthquake acceleration records indicate that the parameters of PGV and PGV/PGA are also effective on the bearing displacements. As the target isolation period is increased, the bearing displacements tend to increase more for the earthquake acceleration records with a high PGV/PGA ratio.

Variation of the reduction of floor accelerations for the three curvature radii considered in the study are presented in Figures 6 through 9.

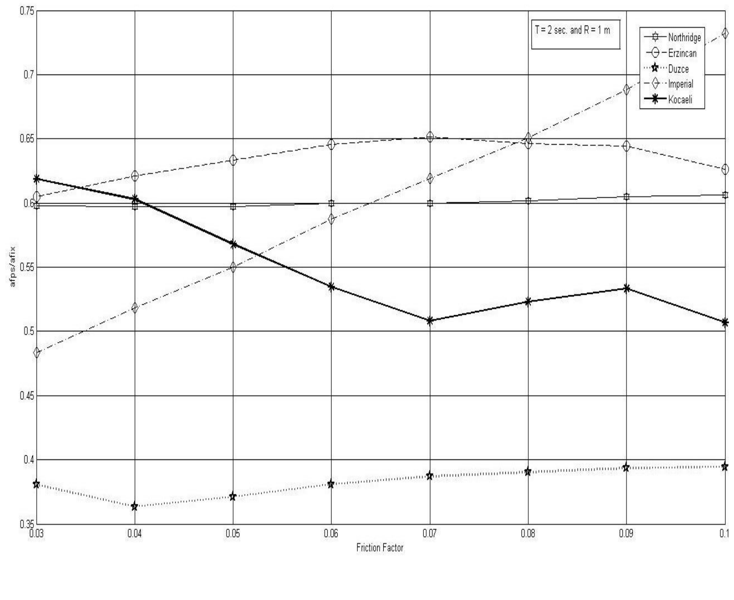

Figure 6. Floor acceleration ratio (a_{fps}/a_{fix}) for R = 1 m (T=2s)

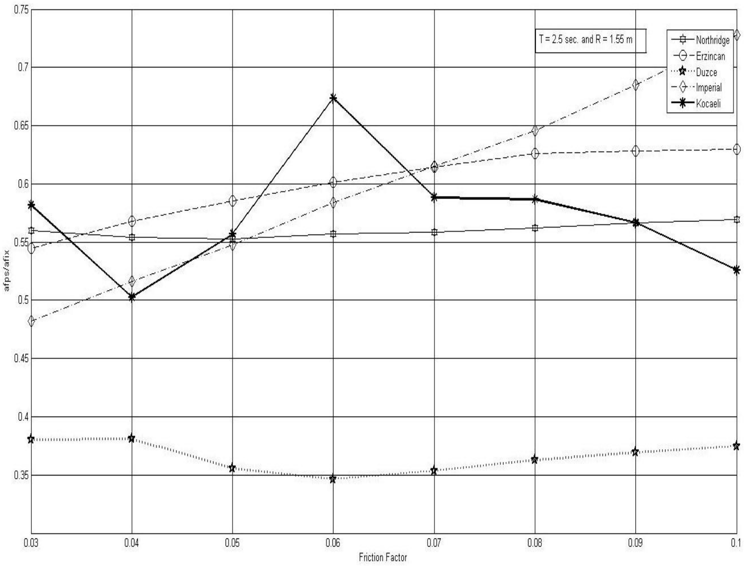

Figure 7. Floor acceleration ratio (a_{fps}/a_{fix}) for R = 1.55 m (T=2.5s)

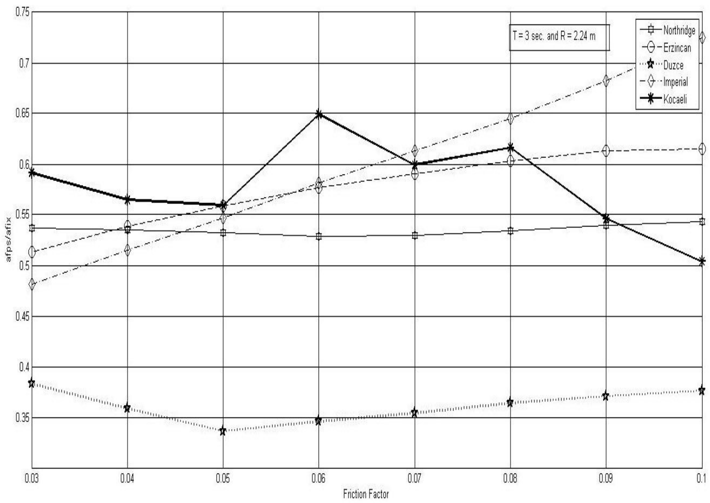

Figure 8. Floor acceleration ratio (a_{fps}/a_{fix}) for R = 2.24 m (T=3s)

The reductions in the floor accelerations generally decreased with the increase in the radius of curvature of the Friction Pendulum bearings. Greatest reductions in floor accelerations were achieved for the analyses conducted with the Duzce earthquake acceleration record. Although, there seems to be an increase in the floor accelerations beyond a certain coefficient for certain earthquake acceleration records, it is hard to make any generalizations from the available results.

Variation of the reduction of base shears for the three curvature radii considered in the study are presented in Figures 9 through 11.

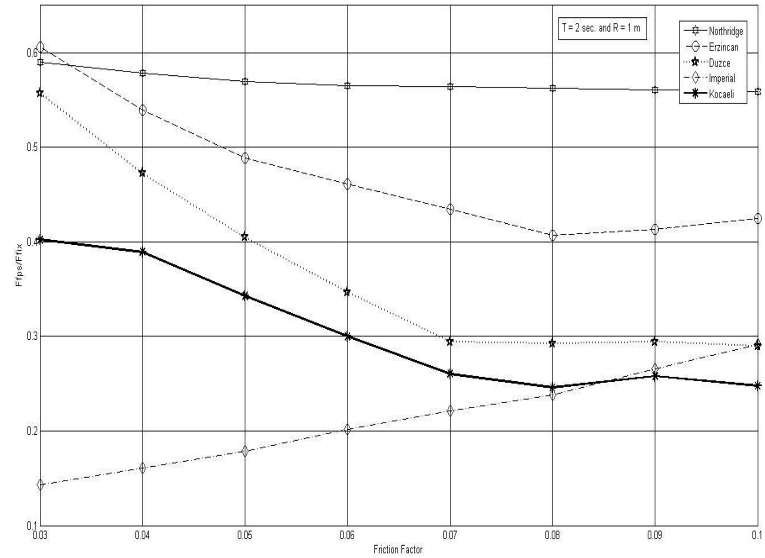

Figure 9. Base shear ratio F_{fps}/F_{fix} for R = 1 m (T=2s)

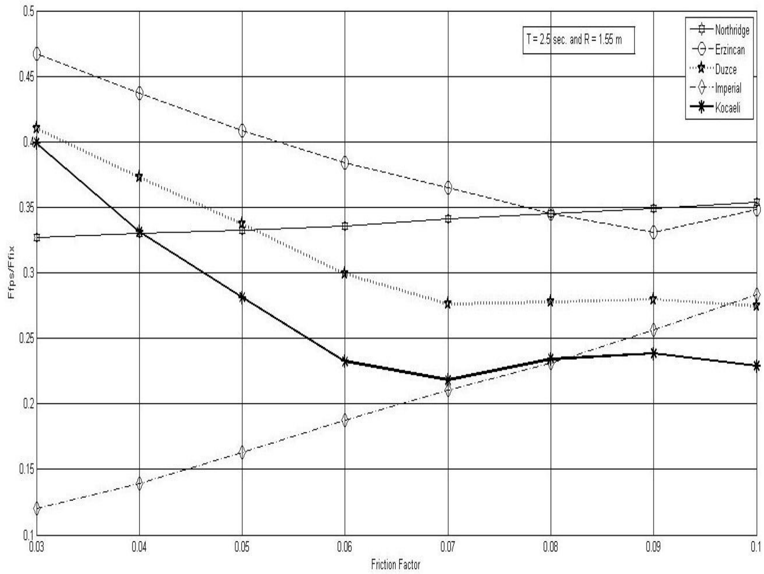

Figure 10. Base shear ratio F_{fps}/F_{fix} for R = 1.55 m (T=2.5s)

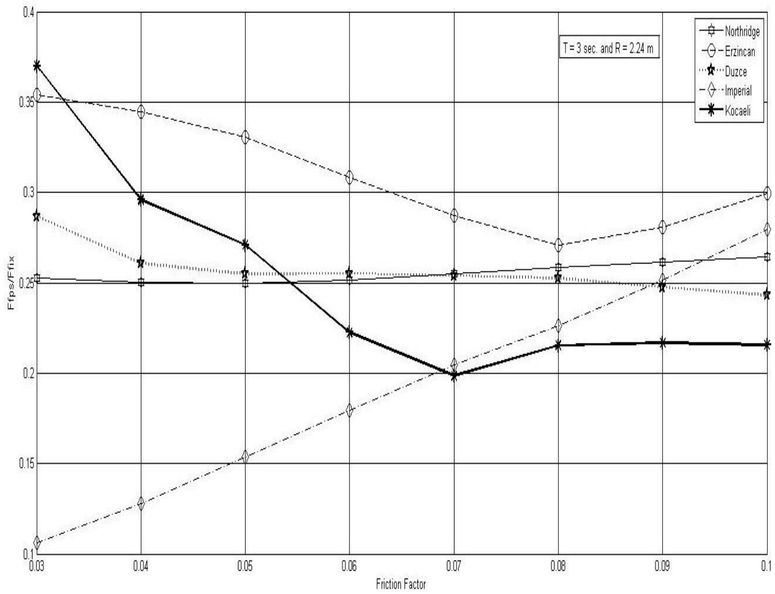

Figure 11. Base shear ratio F_{fps}/F_{fix} for R = 2.24 m (T=3s)

Seismic isolation system proved to be quite useful for all the configurations used in the study. The reductions naturally increased with increases in the target seismic isolation periods. Similar to the case of floor accelerations, the reduction in base shear decreased after a certain coefficient of friction for some of the earthquake acceleration records.

4. CONCLUSIONS

Seismic isolation is an effective strategy for protecting structures from the damaging effects of earthquakes. The significant reductions in floor accelerations and seismic base shear can be achieved with the selection of appropriate parameters for the mechanical properties of the seismic isolation system components. The displacements are mainly concentrated on the seismic isolation system interface and can be reduced by increasing the damping provided by the seismic isolation system. However, increasing damping can decrease the effectiveness of the seismic isolation system in reducing the base shear and the floor accelerations. The effectiveness of the seismic isolation increases as the gap widens between the predominant period of the earthquake ground motion and the target isolation period. Therefore, the use of seismic isolation systems may prove to be relatively ineffective at sites where ground motions with long predominant periods are to be expected. Although, it is quite hard to make any certain generalizations with the available data, the parameters of PGV and PGV/PGA can have significant implications on the bearing displacements.

REFERENCES

Constantinou, M. C., Tsopelas, P., Kasalanati, A., and Wolff, E., (1999) Property modification factors for seismic isolation bearings, *Report MCEER-99-0012*, State University of New York at Buffalo, New York.

Park, Y.J., Wen, Y.K., and Ang, A.H.S., (1986) Random Vibration of Hysteretic Systems Under Bidirectional Ground Motions, Earthquake Engineering and Structural Dynamics, 14:543–557.

Zayas, V.A., Low, D.S., and Mahin, S.A., (1990) A Simple Pendulum Technique for Achieving Seismic Isolation, Earthquake Spectra, 6:317-314.

Yazıcı, G., (2007), Dynamic Behaviour of Liquid Storage tanks isolated with friction pendulum bearings, 10th World Conference on Seismic Isolation.

Constantinou, M.C., Mokha, A., and Reinhorn, A.M., (1990). Teflon bearings in base isolation II: Modelling. *Journal of Structural Engineering*, *ASCE*, **116**, 455–474.

Konstantinidis, D.,(2005). Dynamic Analysis of Base-Isolated Structures with MATLAB, CE 290D Notes, University of California,Berkeley..