State of Knowledge: Theory and Design for Vertical Ground Shaking Effects on Seismically Isolated Bridges and Other Structures

PEER Transportation Systems Research Program

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Introduction

Several numerical and experimental studies suggest that in structures isolated with friction bearings, base shear and floor accelerations are amplified during combined horizontal and vertical shaking. Specifically, a full-scale shake table test of a 5-story steel moment frame building isolated with triple pendulum bearings showed that vertical motion induced high frequency variation in the axial force of the bearing. Which led to surge in base shear. However, many studies have concluded negligible influence of vertical motion ([5-6]), while only a few have noticed considerable increase. As a result, a new PEER project focuses on better quantifying the influence of vertical shaking on the design base shear in bridges.

Objectives

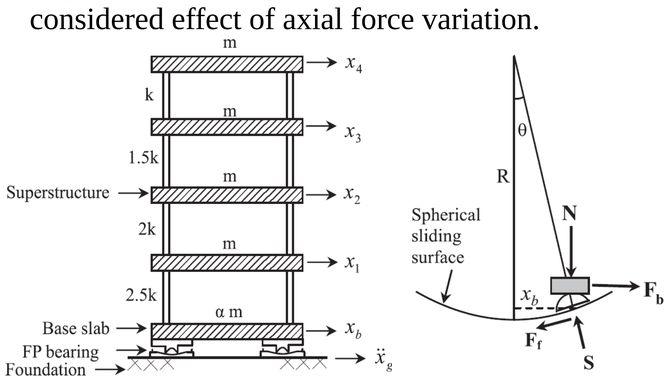
- The primary objective is to review current literature on amplification of base shear and related effects in structures with friction bearings, focusing on bridges. Studies that have found a significant effect will be reviewed in detail, and data quantified whenever possible.

Detailed Review of Selected studies

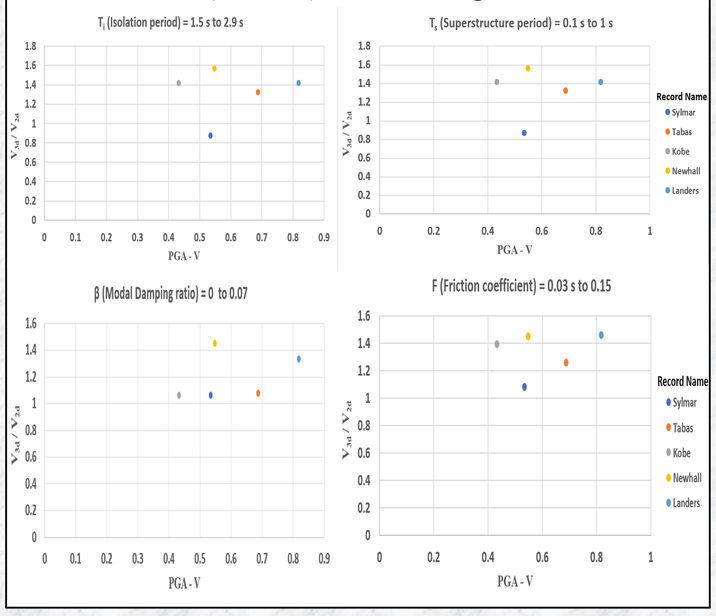
✓ Some important findings and data from available research literature are presented below.

Rabiei and Khoshnudian (2011)

- The main objective of this study was to identify the effects of vertical ground motion on response of multistory buildings isolated with friction pendulum bearings.
- A 4-story building isolated with friction bearing was modelled as a shear type structure with one lateral degree of freedom at each floor.
- Vertical dynamics of the system were neglected.
- FP bearing was modelled assuming small displacement as per Zayas et al. (1987) that considered effect of axial force variation.

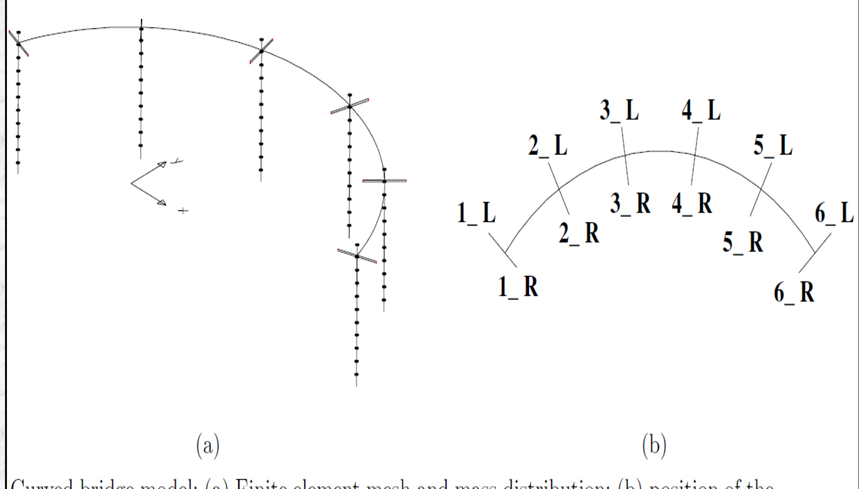


- Parameters varied were: Superstructure period, Isolation period, Coefficient of friction, Modal damping ratio. The following figures plot base shear amplification factor vs vertical peak ground acceleration(PGA-V) for various ground motions.



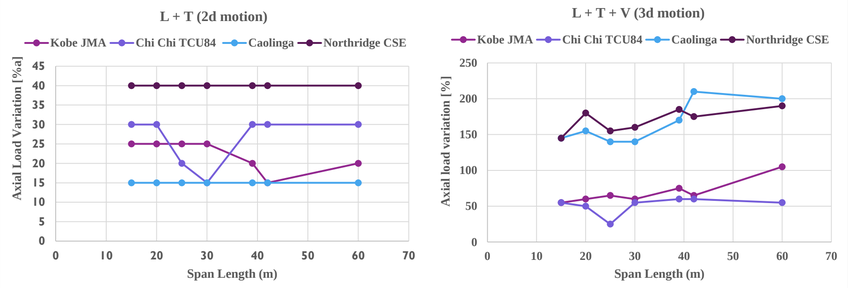
Calvi et al. (2004)

- The main objective of this study was to evaluate effect of axial force variation on response of bridges isolated with friction pendulum bearings.
- Straight and curved bridge model was developed to test effect of axial force variation on bridges isolated with FPS.
- Parameters varied were: span length, pier height, deck aspect ratio, Acceleration components, FPS models.
- Vertical dynamics of bridge do not appear to be considered.



Curved bridge model: (a) Finite element mesh and mass distribution; (b) position of the FPS devices.

- Graphs below show axial force variation on isolators under 2d (longitudinal and transverse) motion and 3d(longitudinal, transverse and vertical) motion according to span length.
- Since base shear is related to axial forces acting on isolators, shear demand on bridge pier will increase as axial force variation is high when vertical shaking is included. However, the effect could not be quantified from data in the paper.



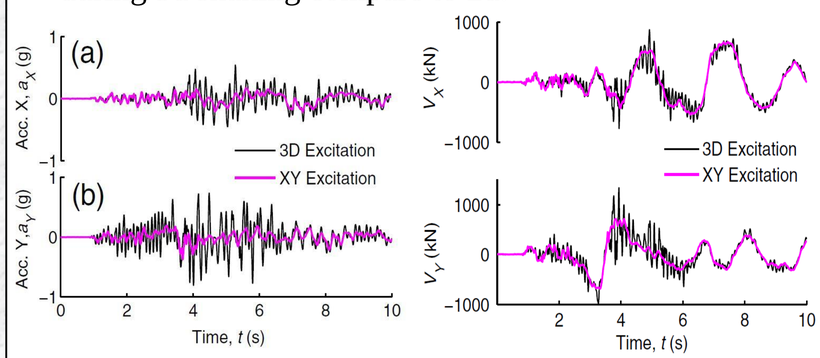
References

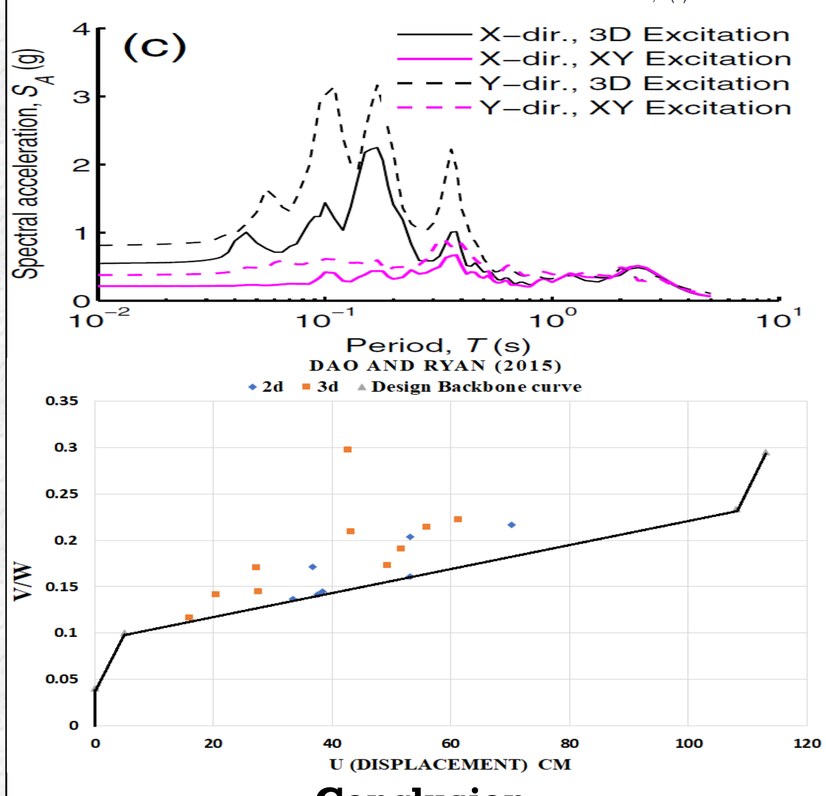
1. Shakib, H., and Fuladgar, A. (2003). "Effect of vertical component of earthquake on the response of pure-friction base-isolated asymmetric buildings." Eng. Struct., 25(14), 1841–1850.
2. Politopoulos, I., and Moussallam, N. (2012). "Horizontal floor response spectra of base-isolated buildings due to vertical excitation." Earthquake Eng. Struct. Dyn., 41(3), 587–592.
3. Mosqueda, G., Whittaker, A. S., and Fenves, G. L. (2004). "Characterization and modeling of friction pendulum bearings subjected to multiple components of excitation." J. Struct. Eng., 10.1061/(ASCE)0733-9445 (2004)130:3(433), 433–442.
4. Rabiei, M., and Khoshnoudian, F. (2011). "Response of multistory friction pendulum base-isolated buildings including the vertical component of earthquakes." Can. J. Civ. Eng., 38(10), 1045–1059.
5. Morgan, T. A., and Mahin, S. A. (2011). "The use of innovative base isolation systems to achieve complex seismic performance objectives." Rep. No. PEER-2011/06, Pacific Earthquake Engineering Research Center, Univ. of California, Berkeley, CA.
6. Fenz, D. M., and Constantinou, M. C. (2008). "Development, implementation and verification of dynamic analysis models for multi-spherical sliding bearings." Technical Rep. MCEER-08-0018, Multidisciplinary Center for Earthquake Engineering Research, State Univ. of New York at Buffalo, Buffalo, NY.
7. Eroz, M., and DesRoches, R. (2008). "Bridge seismic response as a function of friction pendulum system (FPS) modeling assumptions." Eng. Struct., 30(11), 3204–3212.
8. Dao, N. D., and Ryan, K. L. (2015). "Seismic response of a full-scale 5-story steel frame building isolated by with triple pendulum bearings under 3D excitations." Rep. No. CCEER-15-01, Center for Civil Engineering Earthquake Research, Univ. of Nevada, Reno, NV.
9. Calvi, G. M., Ceresa, P., Casarotti, C., Bolognini, D., and Auricchio, F. (2004). "Effects of axial force variation in the seismic response of bridges isolated with friction pendulum systems." J. Earthquake Eng., 8(1), 187–224.
10. Iemura, H., Taghikhani, T., Yoshikazu, T., and Jain, S.K. (2005). "Effect of Variation of normal force variation on seismic performance of resilient sliding isolation systems in highway bridges". Earthquake Engineering and Structural Dynamics, 8(1): 187–224.
11. Tsopelas, P., Constantinou, M.C., Kim, Y.S., and Okamoto, S. (1996). " Experimental study of FPS system in bridges seismic isolation." Earthquake Engineering and Structural Dynamics, 25(1): 65–78.
12. Lin, B. C., and Tadjbakhsh, I. (1986). "Effect of vertical motion on friction-driven isolation systems." Earthquake Eng. Struct. Dyn., 14(4), 609–622.
13. Ryan, K. L., & Dao, N. D. (2015). Influence of vertical ground shaking on horizontal response of seismically isolated building with friction bearings. Journal of structural engineering,142(1), 04015089.`

E-Defense Test

- Full scale steel moment resisting frame isolated with TPB was shaken in Japan to evaluate effectiveness of base isolation to protect building structure and nonstructural components.
- Specimen tested: Full scale 2 x 2 bay 5-story steel moment resisting frame (10 x 12 m in plan and 16 m high) isolated with triple friction pendulum bearing.

- Following figures show increase in base shear and recorded floor acceleration at roof during 3d 88RRS motion.
- Calculated spectral acceleration for recorded roof acceleration shows higher structural modes were excited during 3d shaking compare to 2d.





Conclusion

- A few studies agree that vertical shaking signinficantly increases base shear in FPS isolated structures. There is almost no work on effect of vertical shaking in isolated bridges, which shows need for the project.

Scope of project

- A parametric study will be conducted on bridge model to perform computational simulations to understand influence of vertical ground motion on bridge base shear.
- Different parameters varied will be: span length, number of spans, period of isolation system, pier height, different deck cross-sections, pier support conditions etc.
- Isolation bearings will be modelled using Triple Friction Pendulum element, that can simulate the interaction of bearing axial force and lateral force. Vertical dynamics will be considered. For instance distributed stiffness and mass along the superstructure spans to capture the vertical dynamics of the system, which is usually not considered.
- Opensees will be used for evaluating bridge seismic response carrying response history analysis.
- As bridges are comparably simple structures, base shear escalation will be main effect of vertical shaking, making bridges ideal starting point to find out increase in base shear due to vertical shaking. Base shear will be quantified for 3d shaking corresponding to 2d shaking to identify impact of vertical ground motion.

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