**Template** (2 pages maximum, Times New Roman 11 pt, formatting same as PEER report)

**Motivation**: Isolation devices incorporate energy-dissipation mechanisms designed to limit the displacements demands to a reasonable level. Figure 1.3 shows a bilinear force-displacement curve, which is generally representative of several types of energy-dissipating isolation devices. The area under the closed curve represents the energy dissipated during each cycle of motion of the isolators.

**Objectives**: As outlined above, although quite a few previous experimental studies reported no significant influence of vertical motion on the horizontal response isolated structures, the experimental test on a full-scale five-story steel moment frame building isolated with TPBs at E-defense demonstrated that vertical shaking can increase the base shear and horizontal acceleration. This observation is supported by a number of analytical studies that predict that horizontal responses can be increased by 3D excitation. These effects are anticipated to have direct significance to bridges, wherein the amplified horizontal force of the TPBs will lead to increased base-shear demand on bridge piers. Furthermore, potential coupling between vertical and horizontal vibration modes might occur, which can increase horizontal acceleration and associated spectra due to the activation of a higher structural mode.

**Methodology**: Figure 2.1 shows the target median (m) and median plus/minus ± one standard deviation (m ± s) spectral acceleration. The procedure used to scale the ground motions to best fit the target spectrum was as follows [Carlton 2014]: first, motions were rotated to the direction that maximized the spectral acceleration at a period T = 1 sec. The code SigmaSpectra [IICGE 2019] was used to select the best suite of ground motions from a larger pool of rotated motions. Table 2.2 indicates the scaled PGA in the vertical direction and in the two horizontal directions (PGAT and PGAL to be applied in the bridge transverse and longitudinal directions, respectively), as well as the final scale factors and adjustment factors for horizontal and vertical components. Figures 2.4 and 2.5 show acceleration spectra for individual scaled motions plotted against the target spectrum for horizontal and vertical components, respectively. In each plot, the Group 1, Group 2, and Group 3 spectra are identified by color. Relative to the standard column height (20 ft), Bridge 8 has a reduced column height of 15 ft. Isolation system parameter variations were also applied to the Base Model bridge to investigate the influence of friction coefficient and isolation period on bridge response to combined horizontal and vertical ground motions. Table 3.3 lists the isolator parameter variations considered for Base Model bridge. Due to multiple sliding surfaces, TPBs are more compact than other types of friction pendulum bearings. The bridges in this study were isolated with TPBs, although the observations regarding the influence of vertical shaking are expected to apply generally to any type of spherical sliding bearing. Figure 3.7 presents a general configuration of a TPB, which consists of an inner slider, two articulated sliders, and two main concave surfaces. Figure 3.7 presents a general configuration of a TPB, which consists of an inner slider, two articulated sliders, and two main concave surfaces. The radii of these curved surfaces, R1, R2, and R3, and the friction coefficients of the sliding interfaces, µ1, µ2, and µ3, determine the hysteretic response of the TPBs. Parameters d1, d2, and d3 represent displacement limits of the pendulum mechanisms, and h1, h2, and h3 are slider heights; see Figure 3.7. The radii of these curved surfaces, R1, R2, and R3, and the friction coefficients of the sliding interfaces, µ1, µ2, and µ3, determine the hysteretic response of the TPBs. Parameters d1, d2, and d3 represent displacement limits of the pendulum mechanisms, and h1, h2, and h3 are slider heights; see Figure 3.7. A TPB provides different pendulum mechanisms under different levels of shaking intensity.

**Results**: Thus, for this example, a lower amplification factor underestimates the amplification of the base shear, but including an amplification factor based on the vertical spectral response leads to a slightly conservative estimate of the base-shear amplification. Figures 5.1 and 5.2 present the simulated base-shear coefficients for 2D and 3D motions, along with base-shear coefficient for 3D motions estimated with different amplification factors in the transverse and longitudinal directions, respectively. In the transverse direction, the estimated base-shear values are conservative for almost all motions, except for two Group 1 motions. The signs and their interpretations (negative = underestimated, positive = overestimated) are consistent with AE, but the magnitude of the error has decreased relative to AE as BSNE represents an error in the full base-shear coefficient, rather than just the amplification term. Figures 5.5 and 5.6 compare BSNE for the base-shear estimates in the transverse and longitudinal directions, respectively, for different values of the amplification factor ν. The trends are similar as those observed for AE, except that the error magnitudes are smaller. For ν = Sa(Tv)/PGAV, the estimated base-shear amplification differs for different bridge models only due to changes in the period of the dominant vertical mode. Under the Group 1 motion SFPU, the base-shear amplification is high for all bridge models in both longitudinal and transverse directions [Figure 6.5(a) and (b)]. Of the three motions considered, SFPU produces the greatest variation in base-shear amplification for different models. Differences in spectral amplification due to vertical period shifts that affect the estimated base-shear coefficients are not consistent with simulated response. The base-shear coefficient and its amplification due to vertical shaking is least sensitive to bridge modeling parameters for the Group 2 moderate-intensity motion LGP [Figure 6.5(c) and (d)]. The amplification factor ν = 0.5 is quite accurate for this motion.

**Conclusions**: Thus, the method is applicable for bridge design based on equivalent static analysis. The theory predicts that the amplification of base shear is proportional to (uo/Reff + m), where uo is peak isolator displacement, Reff is the radius and m the friction coefficient of the effective pendulum mechanism, as well as PGAV, thus accounting for any variation of isolation system parameters in the estimate. Three different amplification factors, ν, were considered: ν = 0.5, ν = 1.0, and ν = Sa(Tv)/PGAV. The average BSNE was essentially independent of the variation in isolation system parameters. Differences in base-shear amplification for bridge superstructure parameter variations were insignificant, and the simplified method also estimated base shear for 3D shaking accurately across the range of bridge model variations. Large dispersion of the BSNE was observed over the suite of ground motions.