# RESPONSE OF A NUCLEAR POWER PLANT ISOLATED USING SLIDING BEARINGS SUBJECTED TO SEVERE GROUND SHAKING

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## *Abstract*

Nuclear power plants (NPPs) are required to be designed for earthquakes with long return periods (e.g., 100,000 years). Seismic isolation filters a considerable fraction of earthquake input energy, and is a viable strategy to protect the structural system and internal equipment of NPPs from severe ground shaking. This paper presents key response quantities of an NPP seismically isolated using single concave Friction Pendulum™ (FP) bearings subjected to ground motions consistent with the design basis (10,000-year) and extended design basis (100,000-year) shaking at the Diablo Canyon Nuclear Generating Station in California. Two models were developed to simulate the response of the isolated NPP. The structural system, internal equipment and isolation system were explicitly considered in the first model, while the second model comprised a macro sliding bearing. The coefficient of friction at the sliding surface of the FP bearings was updated during the course of earthquake shaking with instantaneous values of sliding velocity, temperature at the sliding surface and axial pressure on the bearing.

Isolation system displacement can be computed using the simplified macro model of the NPP subjected to the two orthogonal horizontal components of ground motions. The temperature dependence of the coefficient of friction at the sliding surface should be considered in the calculation of isolation system displacement; ignoring the heating effects may lead to unconservative estimates. Floor spectral ordinates should be computed using a detailed three-dimensional finite element model of the NPP subjected to the two orthogonal horizontal and vertical components of ground motions. The choice of friction model at the sliding surface does not significantly influence the floor spectral ordinates, especially at a lower elevation.

*Keywords: Seismic isolation; sliding bearings; nuclear power plant; temperature dependence of friction*

# 1. Introduction

Nuclear power plants (NPPs) in the United States are required to be analyzed and designed for extreme seismic events (e.g., those with return periods of 10,000 and 100,000 years; see [1-3]). The internal equipment and the structural system of the NPPs may be vulnerable at such levels of shaking. Seismic isolation is considered a viable technology to reduce the seismic demands. This paper presents a study of an NPP seismically isolated using Friction Pendulum™ (FP) bearings. The NPP is considered to be located at Diablo Canyon, California, a site of high seismic hazard, and is subjected to ground motions corresponding to the design basis (10,000-year) and extended design basis (100,000-year)[1] shaking at the site. This paper attempts to answer how the response estimates, namely, isolation system displacement and floor spectral ordinates, for the NPP are affected when 1) the vertical component of ground motions is not considered in the analysis, 2) the variation of the coefficient of friction with the instantaneous values of axial pressure, velocity and/or temperature at the sliding surface (see [4]) is not accounted for, and 3) a macro model of the NPP is used instead of a detailed three-dimensional (3D) model. The NPP and the two models of the NPP developed using the open source software program OpenSees [5] are explained first. The models to describe the friction at the sliding surface are briefly discussed. Finally, the results of the response-history analyses of the NPP are presented.

# 2. Description of the nuclear power plant

An NPP typically comprises three major components: auxiliary and shield building (ASB), containment internal structure (CIS) and steel containment vessel (SCV). The ASB considered in the present study is a 140,000-ton concrete structure with the plan dimensions of 97 m and 60 m, and a total height of 89 m [6]. The CIS weighs 41,000 tons with a total height of 33 m [7]. The SCV weighs 3,700 tons, which is considered small (see [7-8]). The geometry of the ASB and CIS are presented in the following sections.

## 2.1 Auxiliary and shield building (ASB)

Fig. 1 (Fig. 2) presents plan (elevation) view of the ASB, the dimensions of which were provided by Roche [6]. The interior walls, floors and roof are 0.6 m (2 ft) thick. The exterior walls and the walls along the horizontal axes of symmetry are 0.9 m (3 ft) thick. The concrete used in ASB has a density of 2,400 kg/m$^3$, a characteristic concrete strength of 41 MPa and an elastic modulus of 30 GPa.

## 2.2 Containment internal structure (CIS)

The CIS is considered to be represented by a 33 m-tall vertical stick with masses attached to nodes along the height and outrigger nodes, as shown in Fig. 3 [7]. The total mass of the structure is 41,000 ton.

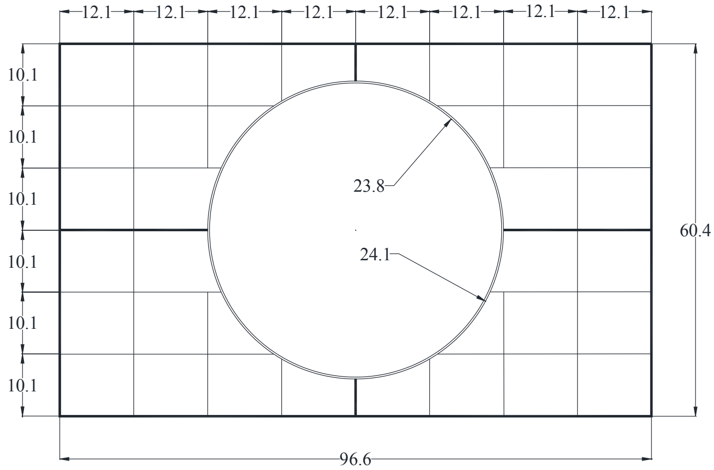
# 3. Numerical models of the nuclear power plant

Two numerical models of the NPP developed using OpenSees are described below.

## 3.1 Model 1: seismically isolated ASB and CIS

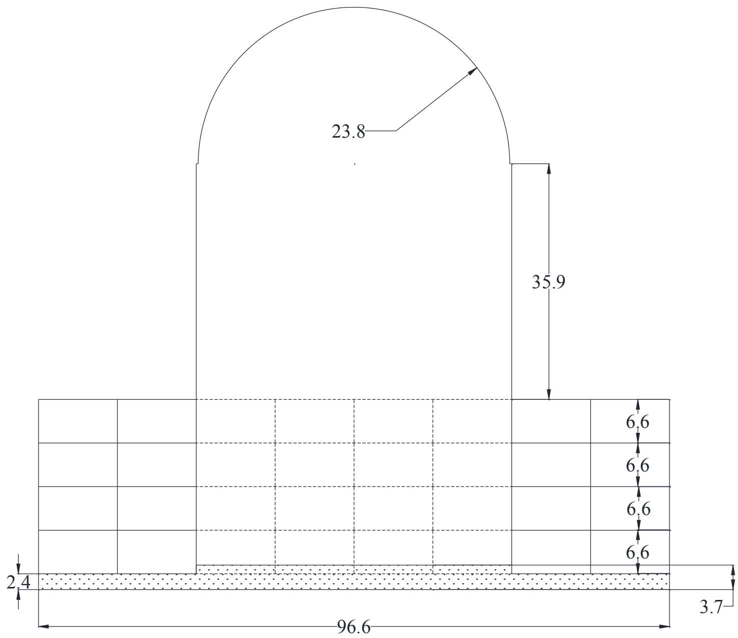
The ASB (Figs. 1 and 2) and CIS (Fig. 3) are joined together and are isolated using the FP bearings in the first model (Model 1). The ASB is discretized using nodes, and the nodes are connected by *elasticBeamColumn* elements [5] as shown in Figs. 4 and 5. The nodes are distributed at nine elevation levels (1.2 m, 9.1 m, 15.8 m, 22.6 m, 29.3 m, 41.5 m, 53.6 m, 65.8 m and 71.3 m). There are 187 nodes at each of the bottom five levels and 99 nodes each at the remaining four levels, making it a total of 1331 nodes. The distance between the adjacent nodes at a level is 6 meters in either of the two principal horizontal directions. The details of masses at the nodes of the ASB are presented in [8].

[1] The definitions of design basis and extended design basis shaking are adopted from [1].




- Dimensions are in meters.
- Exterior walls and the walls along the two horizontal axes of symmetry are 0.9 m (3 ft) thick.
- Other walls are 0.6 m (2 ft) thick.
- The circle of radius 24.1 m (80 ft) indicates the 1.2 m (4 ft) thick cylindrical wall.
- The circle of radius 23.8 m (79 ft) indicates the 0.9 m (3 ft) thick hemispherical dome.

Fig. 1 – Plan view of auxiliary and shield building (adapted from [6])




- Dimensions are in meters.
- Floors and roof are 0.6 m (2 ft) thick.
- Thickness of cylindrical wall is 1.2 m (4 ft).
- Thickness of hemispherical dome is 0.9 m (3 ft).

Fig. 2 – Elevation view of the auxiliary and shield building (adapted from [6])

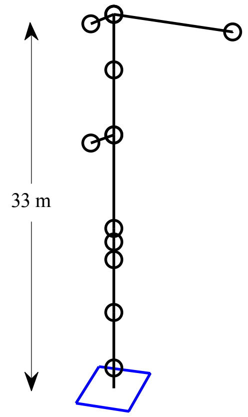
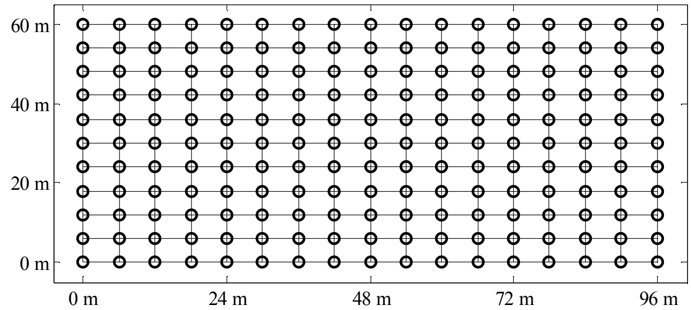
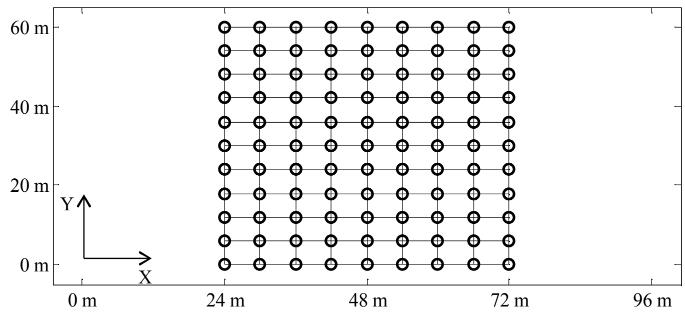



Fig. 3 – Containment internal structure (adapted from [7])




(a) Levels 1 through 5




(b) Levels 6 through 9

Fig. 4 – Locations of nodes (indicated by circles) in the ASB in plan [8]

The nodes of the ASB are connected by the vertical and horizontal members as indicated in Figs. 4 and 5. These members are modeled using *elasticBeamColumn* element available with OpenSees [5]. The geometric and material properties of the vertical and horizontal members are presented in [8]. The longest natural period of the fixed-base ASB in the two orthogonal horizontal directions, Y and X (see Fig. 5), is 0.15 s and 0.15 s, respectively.

The CIS is modeled as a vertical stick with three outrigger nodes as shown in Fig. 3. Details of the masses and moments of inertia associated with the nodes, and the properties of the members between two nodes (modeled using *forceBeamColumn* element [5]) are presented in [8]. The 13 nodes in the CIS are located at elevations of 1.2 m, 3.1 m, 7.9 m, 12.7 m, 14.2 m, 15.5 m, 23.7 m, 29.4 m and 34.3 m. About 70% of the total translational mass of the CIS is associated with nodes at 3.1 m, 7.9 m and 12.7 m. The natural periods of the fixed-base CIS in the first two modes are 0.082 s and 0.078 s, respectively [8].

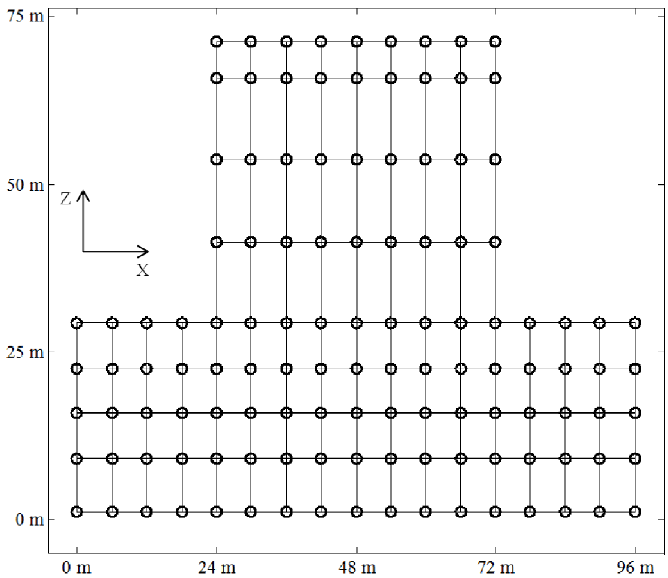



Fig. 5 – Locations of nodes (indicated by circles) in the ASB in elevation [8]

The ASB and the CIS are joined at one point. The ASB and CIS joined together are seismically isolated using single FP bearings: the sliders of the 187 bearings are connected to the bottommost 187 nodes of the ASB-CIS segment and the sliding surfaces are connected to the ground. The sliding period of the bearings is 3 s, reference coefficient of friction[2] is 0.06 and the static axial pressure is 50 MPa [8].

### 3.2 Model 2: macro model (single FP bearing)

The second model of the NPP (Model 2) comprises a single FP bearing, wherein the mass of the superstructure is assigned to the slider. The bearing is identical to those considered in Model 1, so far as sliding period, reference coefficient of friction and the static axial pressure are concerned (see [8]).

The response quantities computed using the two models of the NPP are listed in Table 1.

Table 1 – Response quantities computed using the two models of the NPP

| **Model** | **Description** | **Response quantity** | | |
|---|---|---|---|---|
| | | Isolation-system displacement | Acceleration of basemat | Acceleration of nodes of CIS |
| 1 | Isolated ASB-CIS | Y | Y | Y |
| 2 | Macro model | Y | Y | N |

## 4. Friction at the sliding surface of FP bearings

The sliding in an FP bearing involves motion of a PTFE-type composite material against the polished stainless steel (see [4], [8-9]). The coefficient of sliding friction varies with the instantaneous values of sliding velocity, axial pressure on the bearing and temperature at the sliding surface[3] [9]. Five friction models listed in Table 2 are

[2] The reference coefficient of friction at the sliding surface of an FP bearing is defined as the coefficient of friction measured at a given static axial pressure (or reference axial pressure), ambient temperature of 20°C and a high velocity of sliding (e.g., 1000 mm/s) (see [4] for details).

[3] It is demonstrated in [4] that the coefficient of friction can be considered to vary with velocity, temperature, and pressure independently.

considered in the present study, which facilitates the understanding of the influence of changes in pressure, temperature and velocity on the coefficient of friction, and in turn on the response quantities.

Table 2 – Models to describe coefficient of friction at the sliding surface (see [4], [8])

| Model | Description |
|---|---|
| 1 | Coulomb |
| 2 | Pressure dependent |
| 3 | Temperature dependent |
| 4 | Velocity dependent |
| 5 | Pressure, temperature and velocity dependent |

## 5. Ground motions

Ground motions consistent with 10,000- and 100,000-year shaking at the Diablo Canyon Nuclear Generating Station (DCNGS) are considered in this study. The uniform hazard spectrum (UHS) in a horizontal direction[4] for the 10,000-year shaking at Diablo Canyon is presented in Fig. 6. The UHS for the vertical direction was computed (see [8]) by multiplying the horizontal UHS with the ratios of vertical to horizontal (V/H) spectral ordinates suggested in [10]. The V/H ratios plotted in Fig. 7 are considered in the present study.

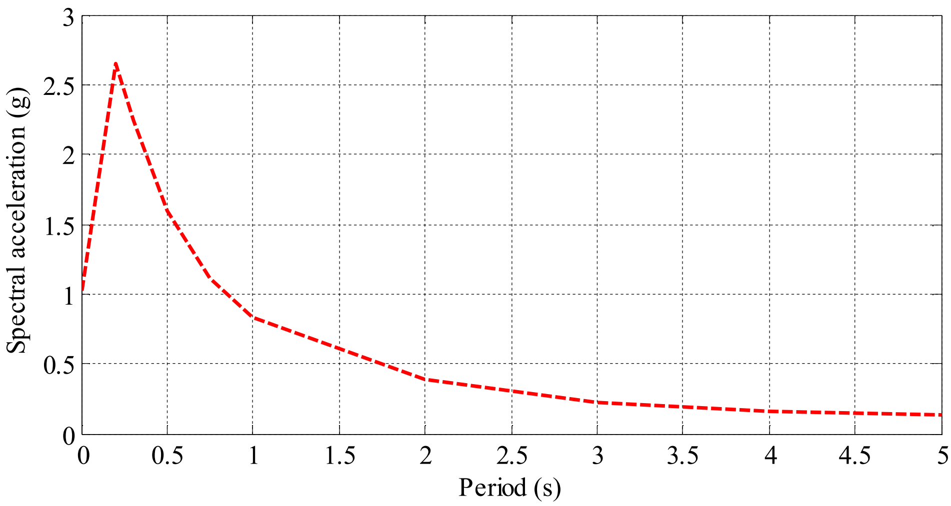



Fig. 6 – Uniform hazard spectrum for 10,000-year horizontal shaking at Diablo Canyon [8]

A set of 30 three-component seed motions (listed in [8]) were spectrally matched to the 10,000-year horizontal[5] and vertical UHS for the Diablo Canyon site using the software program RSPMatch [11].

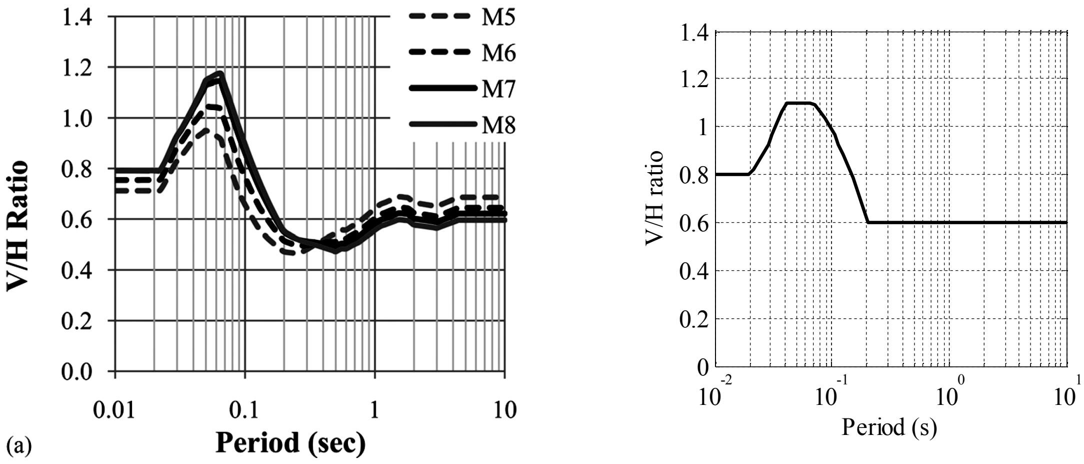
The 100,000-year ground motions were obtained by amplitude scaling the 10,000-year ground motions for the DCNGS by a factor of 2.0, based on the data presented in Fig. 8.

## 6. Results

This section presents the results of the response-history analysis of the NPP using the two models described earlier. Each model was subjected to 30 sets of ground motions in the two orthogonal horizontal directions (no vertical component) consistent with the two levels of shaking. Each of these analyses were repeated for the five friction models (see Table 2) making it a total of 600 ( = 2 × 30 × 2 × 5) response-history analyses. In addition,

[4] The UHS was obtained from http://geohazards.usgs.gov/hazardtool/application.php (accessed on July 15, 2014).
[5] Identical UHS was considered in the two orthogonal horizontal directions.

Model 1 of the NPP was subjected to all three components of ground motions – a total of 300 ( = 30 × 2 × 5) analyses.




(a) Model proposed by [10]    (b) Assumed V/H ratio

Figure 7 – Median ratio of vertical to horizontal spectral response on a rock site with a source-to-site distance of 5 km [8]

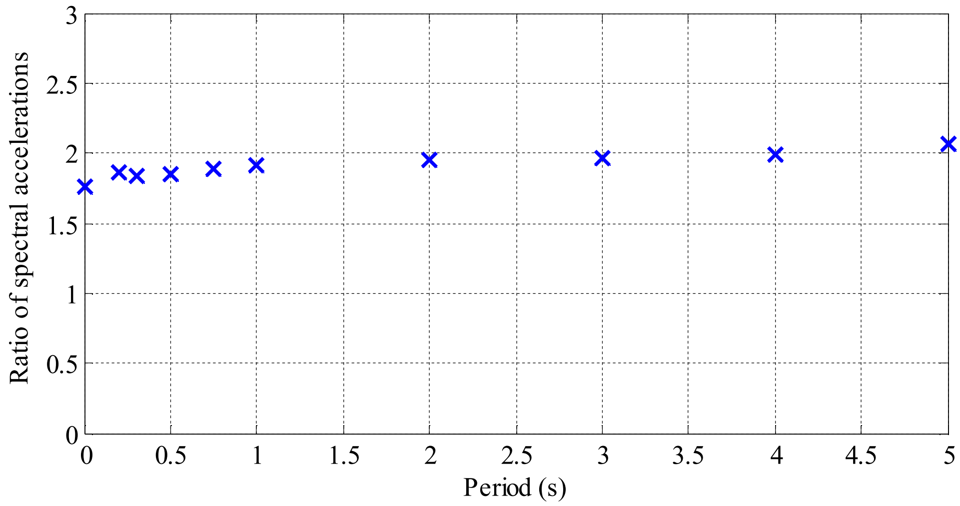



Fig. 8 – Ratio of UHRS spectral ordinates for 100,000 years to 10,000 years shaking at the Diablo Canyon site [8]

## 6.1 Isolation system displacement

Fig. 9(a) presents the 16th, 50th, 84th and 99th percentiles[6] of the peak isolation system displacements computed using the two NPP models subjected to the extended design basis (100,000-year) shaking. Friction at the sliding surface of the FP bearings is defined using the Coulomb model. Not including the vertical component of ground motion or considering a macro model of the NPP instead of the detailed 3D model in the response-history analyses does not alter the estimates of isolation system displacements materially. Panel (b) of Fig. 9 presents the results when the friction at the sliding surface is considered to vary with the axial pressure. Panels (c), (d) and (e)

[6] The percentiles in this study are computed assuming that the response quantity distributes lognormally. The assumptions have been verified in [8].

present the results for temperature-dependent, velocity-dependent, and pressure-, temperature- and velocity-dependent coefficient of friction, respectively. The observations for panel (a) also apply for panels (b) through (e). The displacements at a given percentile are almost identical for panels (a), (b) and (d) (Coulomb-type, pressure-dependent, and velocity-dependent friction, respectively). These values are smaller compared to when the friction is considered to vary with temperature (panels (c) and (e)).

The observations from the results for the design basis shaking (10,000-year) are similar to that presented in this section (see [8]).

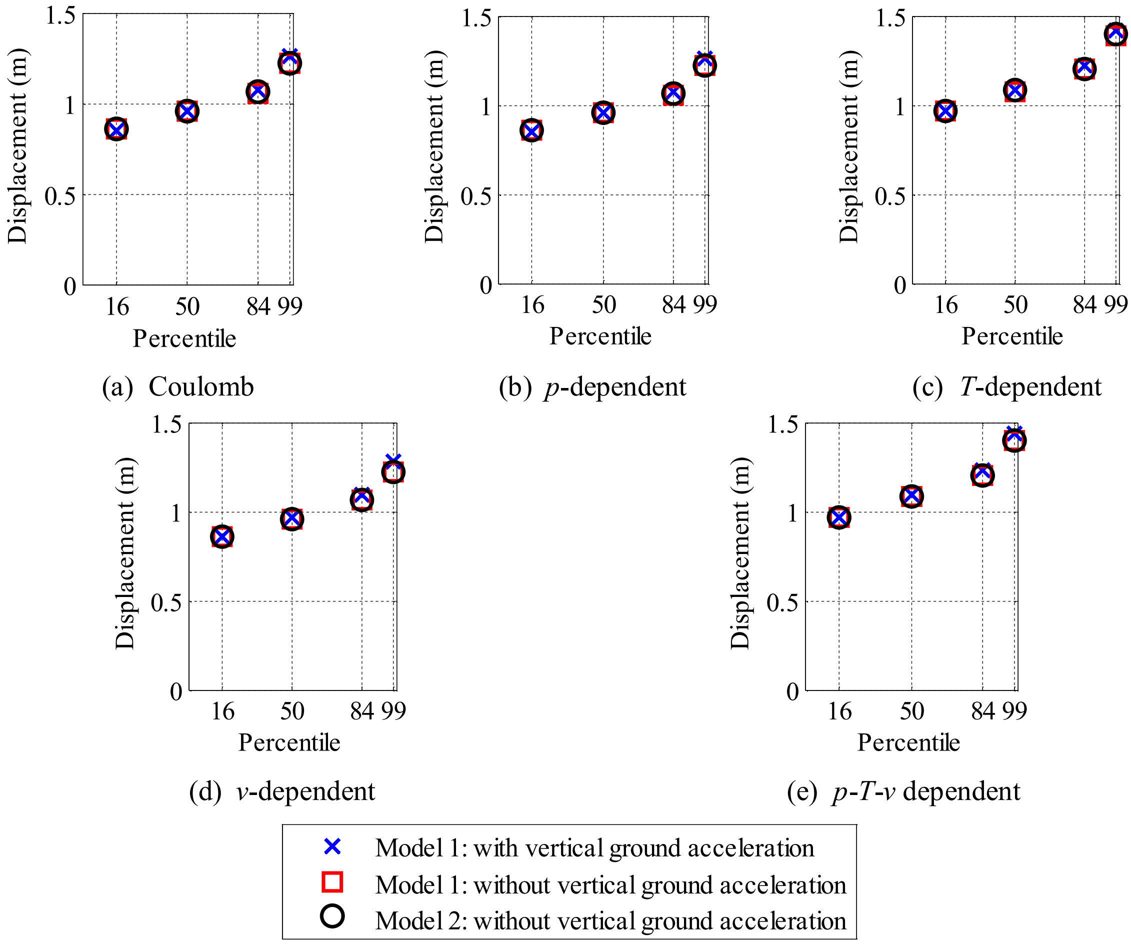



Figure 9 – Distributions of isolation-system displacement for the three models subjected to the extended design basis shaking [8]

## 6.2 Floor response spectra

Fig. 10 presents the median spectral acceleration ordinates in X direction at nodes 109060 (basemat level), 532 (height of 13 m), 5351 (height of 24 m) and 5382 (height of 34 m) of the CIS. Nodes 5351 and 5382 are outrigger nodes (see Fig. 3). Friction at the sliding surface of the FP bearings was considered to be Coulomb-type. Panel (a) of the figure shows the ordinates at the basemat level computed using the two NPP models. The results obtained using the two models are almost identical when the vertical component of the ground motion is not considered in the analysis. Including the vertical component of ground motion considerably alters the spectral ordinates at periods between 0.02 s and 0.08 s. The differences increase as the nodes at greater elevations are considered (panels (b) through (d)). Similar observations are made for other percentiles (e.g., 90$^{th}$), friction model and intensity of shaking (see [8]).

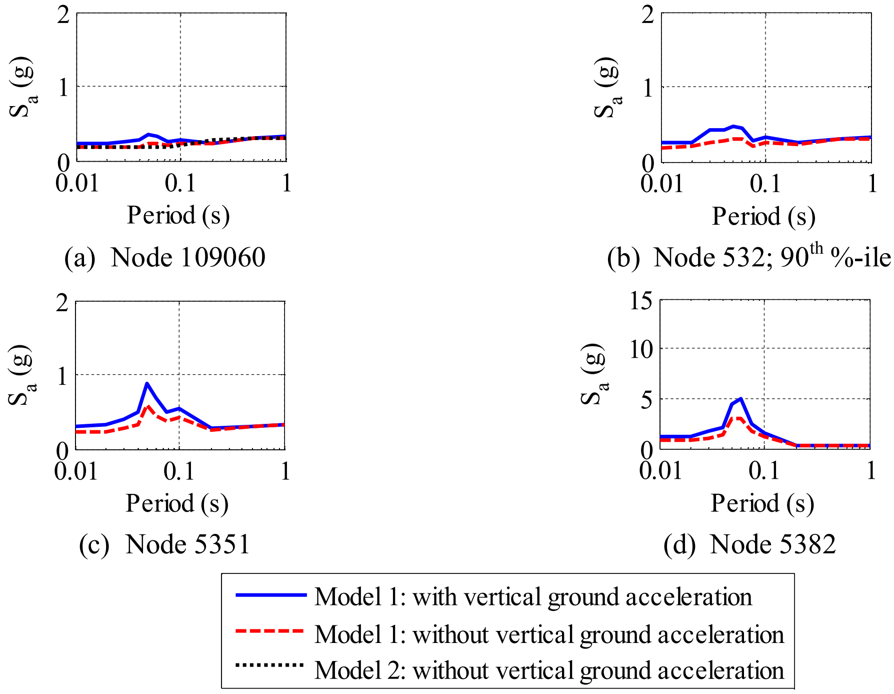



Fig. 10 – Median floor spectral ordinates at the nodes of the CIS subjected to the design basis shaking

Median spectral acceleration in the X direction at 0.01 s for Node 109060 is plotted against the friction model (see Table 2) in Fig. 11(a). As noted previously, the effect of the choice of the NPP model or the inclusion of vertical ground motion in the response-history analysis is small. In addition, the choice of friction model does not affect the spectral ordinates materially. Figs. 11(b), 11(c) and 11(d) present results at 0.05 s, 0.1 s and 1.0 s, respectively, and the observations for Fig. 11(a) apply also for the three panels. Figs. 11(e) through 11(h) present the spectral ordinates for Node 532, Figs. 11(i) through 11(l) present the ordinates for Node 5351, and Figs. 11(m) through 11(p) present the ordinates for Node 5382. The spectral ordinates at short periods (e.g., 0.05 s and 0.1 s) are considerably influenced by whether the vertical ground motions are considered in the analysis (also seen in Fig. 10). The choice of friction model does not significantly influence the spectral ordinates, except for Node 5382, which is located on top in the CIS.

Observations on the spectral ordinates of the NPP subjected to the extended design basis shaking are similar to those presented in this section (see [8] for details).

## 7. Summary and conclusions

This paper presents results of the response-history analyses of an NPP seismically isolated using FP bearings. Two models of the NPP are developed using OpenSees: Model 1 considers the structural system, internal equipment and isolation system explicitly, while the structural system and the internal equipment are merged with the slider of a macro FP bearing in Model 2. Friction at the sliding surfaces of the FP bearing was defined using five models that account for the influence of the axial pressure on the bearing, temperature at the sliding surface and sliding velocity on the coefficient of friction. The NPP is considered to be located at Diablo Canyon, California – a site of high seismicity. The seismic hazard in the vertical and horizontal directions are defined using UHS. The UHS in the two principal horizontal directions are considered identical. The UHS in the vertical direction is obtained by multiplying the horizontal UHS by the V/H ratios, a function of the seismic parameters (e.g., magnitude, source-to-site distance) and the natural period. The two NPP models are subjected to the design basis (10,000-year) and extended design basis (100,000-year) shaking, and two response quantities, namely, isolation system displacement and floor response spectra, are calculated.

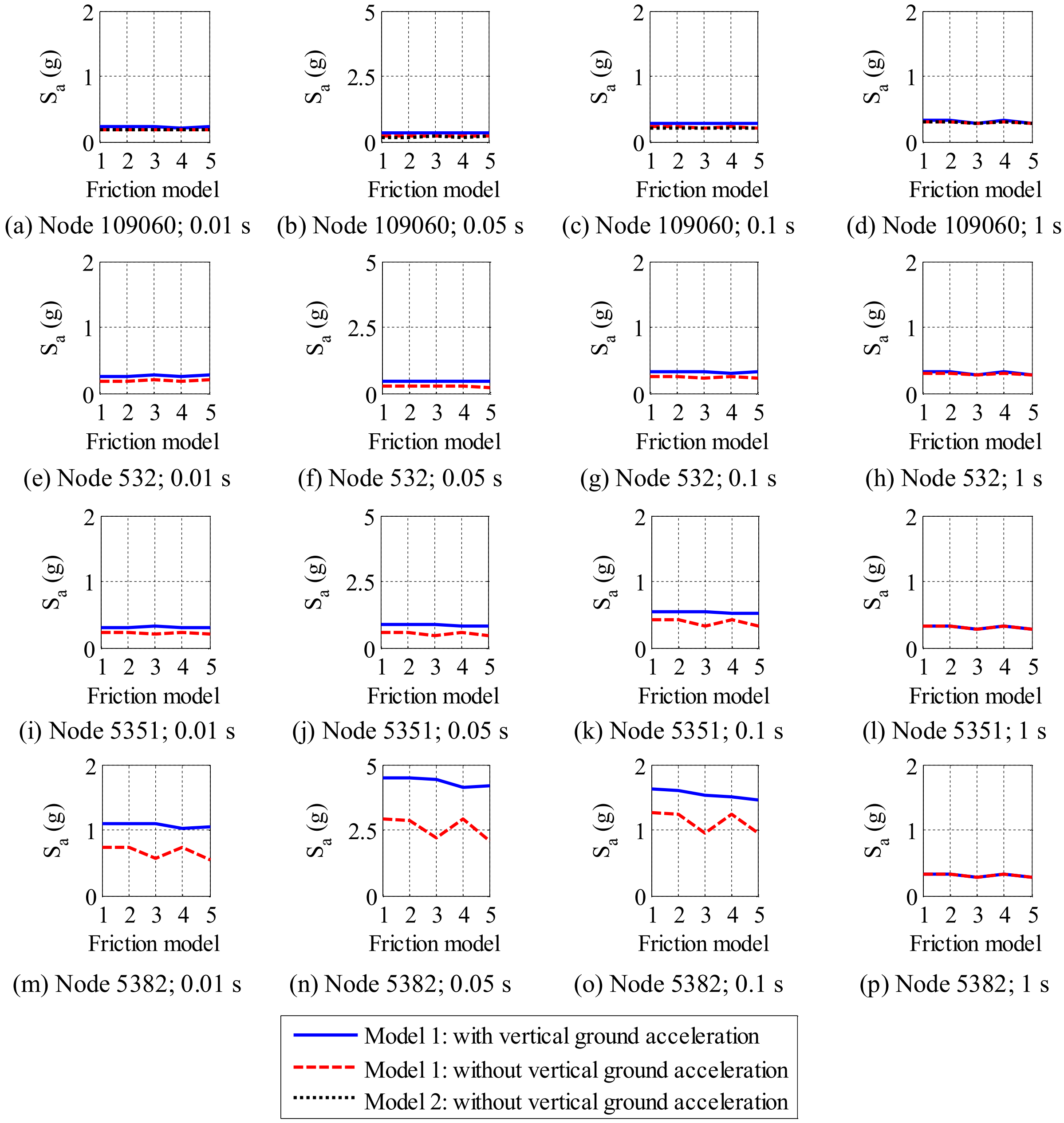



Figure 11 – Median spectral accelerations in the X direction at four nodes of the CIS subjected to 30 ground motions amplitude scaled by 1.0; friction models 1 through 5, respectively, denote Coulomb, pressure-dependent, temperature-dependent, velocity-dependent and *p*-*T*-*v* models

The peak lateral displacement of a macro bearing subjected to horizontal ground motions in the two principal directions provides a reasonable estimate of the isolation system displacement of an NPP. The definition of the coefficient of friction should include the heating effects in the displacement calculations. The floor spectral ordinates should be computed by subjecting a detailed three-dimensional model of the NPP to all three components of ground motions. The ordinates are not considerably affected by the definition of coefficient of friction at the sliding surface, particularly at small heights (e.g., less than 25 m).

## 8. Acknowledgements

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## 9. Copyrights



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