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Sensitivity Analyses of Seismic Behavior of Spent Fuel Dry Cask Storage Systems[a]

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ABSTRACT

Sandia National Laboratories is conducting a research project to develop a comprehensive methodology for evaluating the seismic behavior of spent fuel dry cask storage systems (DCSS) for the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). A typical Independent Spent Fuel Storage Installation (ISFSI) consists of arrays of freestanding storage casks resting on concrete pads. In the safety review process of these cask systems, their seismically induced horizontal displacements and angular rotations must be quantified to determine whether casks will overturn or neighboring casks will collide during a seismic event. The ABAQUS/Explicit code is used to analyze three-dimensional coupled finite element models consisting of three submodels, which are a cylindrical cask or a rectangular module, a flexible concrete pad, and an underlying soil foundation. The coupled model includes two sets of contact surfaces between the submodels with prescribed coefficients of friction. The seismic event is described by one vertical and two horizontal components of statistically independent seismic acceleration time histories. A deconvolution procedure is used to adjust the amplitudes and frequency contents of these three-component reference surface motions before applying them simultaneously at the soil foundation base. The research project focused on examining the dynamic and nonlinear seismic behavior of the coupled model of freestanding DCSS including soil-structure-interaction effects.

This paper presents a subset of analysis results for a series of parametric analyses. Input variables in the parametric analyses include: designs of the cask/module, time histories of the seismic accelerations, coefficients of friction at the cask/pad interface, and material properties of the soil foundation. In subsequent research, the analysis results will be compiled and presented in nomograms to highlight the sensitivity of seismic response of DCSS to different input parameters and to facilitate the review of DCSS applications for adequacy under prescribed seismic loads.

KEY WORDS: freestanding dry cask, parametric analyses, nomograms, seismic response, cask collision, cask tipping, coupled finite element models, contact elements, coefficient of friction, deconvolution, seismic accelerations.

INTRODUCTION

One type of Independent Spent Fuel Storage Installations (ISFSI) licensed under 10 CFR Part 72 [1] consists of arrays of freestanding dry cask storage systems resting on concrete pads constructed on a natural sub-grade or engineered fill. In the safety review process of these systems, it is very important to investigate their seismic stability in terms of cask sliding and overturning during a postulated design earthquake. The current guidelines in NUREG-1536 [2] for these systems state that the tip-over and cask-to-cask impact of casks in an earthquake are considered to be accidents and should be analyzed regardless of the likelihood of occurrence. Luk et al [3] developed three-dimensional coupled finite element models, which consist of a cylindrical cask or a rectangular module, a flexible concrete pad, and an underlying soil foundation, to examine their dynamic and nonlinear seismic behavior including soil-structure-interaction effects. Three site-specific seismic analyses [4 and 5] were performed using this coupled modeling approach. Additionally, a number of parametric analyses are performed.

This paper summarizes the scope of parametric analyses using the coupled finite element models to perform analyses of dry cask storage systems in an earthquake event. The parametric analyses use appropriately chosen response spectra and compatible time histories of ground motions to provide a generic prescription of seismic excitation to these dry cask storage systems. The seismic responses of these systems in terms of horizontal sliding displacements and angular rotations generated from parametric analyses will be compiled and presented in nomograms in support of application safety review.

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COUPLED FINITE ELEMENT ANALYSIS MODEL

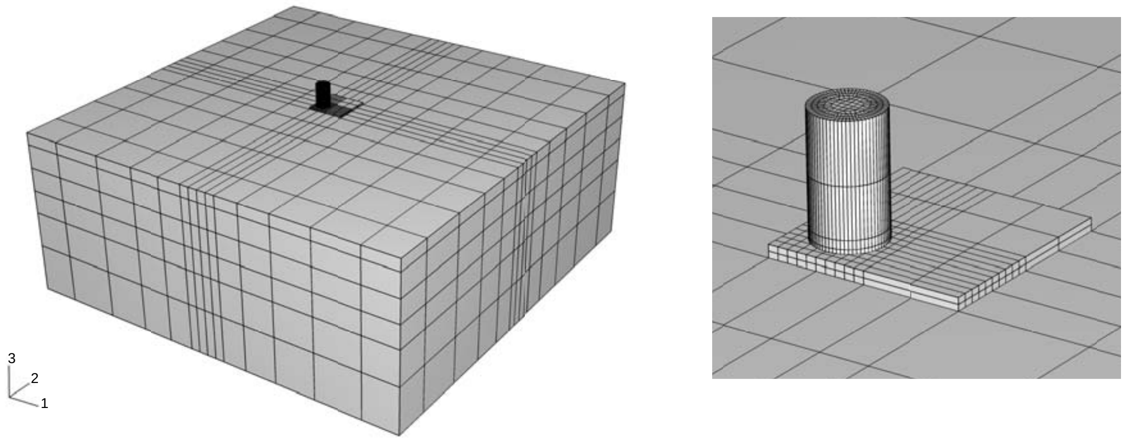
The ABAQUS/Explicit code, Version 6.2-7 [6], is used to analyze three-dimensional coupled finite element models consisting of a module/cask, a flexible concrete pad, and an underlying soil foundation to investigate the seismic response of the module/cask under prescribed earthquake excitations. The coupled modeling approach allows an in-depth evaluation of the nonlinear dynamic seismic behavior of the module/cask and in particular, the soil-structure-interaction (SSI) effect.

Description of Analysis Model

This paper describes the parametric analyses of a cylindrical HI-STORM 100 overpack cask with the MPC-68 canister option only. Figure 1 shows the layout of the entire coupled model that consists of a single cylindrical cask standing on a flexible concrete pad on top of a soil foundation. Experiences accumulated from site-specific analyses of casks indicate that it is adequate to use a concrete pad capable of holding 4 (2x2) casks in the coupled model. All of the finite elements in the model are of the type "C3D8R", which is an 8-node solid, with reduced (one Gauss point) integration and built-in hourglass control. The cask is modeled as a solid cylindrical body partitioned into four horizontal sections with six radial rows of solid elements in each section and 64 elements around the outside perimeter. The center of gravity of the cask is correctly located at its design position. The cask and the concrete pad are modeled as elastic bodies.

In the model, the pad base and the top of the soil foundation are constrained to move together in the two horizontal directions, and contact surfaces are used at the cask/pad interface, where the pad surface is designated as the “master” surface and the cask base is designated as the “slave”. The coefficient of friction at the cask/pad interface is varied in the parametric analyses to investigate the maximum horizontal sliding displacement or angular rotation of the cask.

To simulate semi-infinite boundary conditions, the outside layer of elements on the four vertical sides of the soil foundation submodel are represented by edge columns that allow only horizontal shear deformation. A deconvolution procedure is used to adjust the amplitudes and frequency contents of the three-component reference surface motion before applying them simultaneously to all nodes at the soil foundation base, which along with the edge-column boundary condition, will result in a vertically propagating waveform.



(a) Entire Mesh with Soil Foundation (b) Close-up View of Cask and Pad

Figure 1: Finite Element Mesh of Soil Foundation, Pad, and Cask

Model Geometry

A cylindrical HI-STORM 100 overpack cask with fully loaded MPC-68 canister option has a mass of 163,290 kg. The cylindrical cask has an outside diameter of 3.37 m and an overall height of 5.87 m. The center of gravity of the cask is 3.01 m above the concrete pad. A continuous concrete pad (9.45 m x 9.45 m x 0.61m) holding 2x2 casks is used in the finite element model. The size of the soil foundation submodel (in length, width, and depth) was carefully chosen to adequately simulate the behavior of a semi-infinite soil foundation. The soil foundation submodel is sized with an 103.89 m square and the outside layer of elements on its four vertical sides, with width equal to the pad dimension of 9.45 m, are represented by edge columns. Since the nodes at the inner row of the set of edge columns define the true model size with their degrees of freedom constrained to those at the outside row, the actual geometry of the soil foundation submodel is about nine times the pad dimensions. The adopted dimensions of the soil foundation submodel were based on experience gained from sensitivity studies conducted for previous three site-specific seismic analyses.

The lateral dimensions of soil foundation submodel exceeds the recommended minimum given in the US Army Corps of Engineers soil-structure-interaction modeling guidelines [7]. The overall depth of the soil foundation submodel was chosen to be 40.71 m, which satisfies the guidelines in American Society of Civil Engineers (ASCE) Standard [8].

PARAMETRIC ANALYSES

An array of input variables was selected for investigation in the parametric analyses to study the seismic response of dry cask systems. These input parameters include cask designs (cylindrical and rectangular), soil profiles (soft and stiff), coefficients of friction at cask/pad interface, response spectrum shapes, and time histories of ground motions. A calculation matrix was developed to provide a roadmap to systematically evaluate the effect of each parameter on the seismic response of dry cask systems. The results of the parametric analyses will provide information to revise the review guidelines in support of the safety review process of these systems.

Calculation Matrix

The calculation matrix of the parametric analyses is summarized in the following:

- 3 spectral shapes (R.G. 1.60 [9], NUREG-0098 [10], and NUREG-6728 [11])
- 5 time histories of ground motion (which are corrected and spectral shape compatible) as listed below, mainly suitable for western U.S. earthquakes, are planned for the R.G. 1.60 and the NUREG-0098 spectral shapes, while 5 additional time histories (to be determined), appropriate for Central and Eastern U.S. seismological conditions, are planned for the NUREG-6728 spectral shape:
  1. 1978 Tabas (Iran) earthquake time history [12]
  2. 1999 Taiwan Chi-Chi earthquake time history [13]
  3. 1992 Landers Joshua Tree earthquake time history [14]
  4. 1994 Northridge earthquake time history [15]
  5. 1979 Imperial Valley Calexico Fire Station earthquake time history [16]
- 3 coefficients of friction, μ, at cask/pad interface (0.20, 0.55, and 0.80)
- 2 cask designs (one cylindrical Holtec HI-STORM 100 cask and one rectangular Transnuclear West module/cask)
- 2 soil profiles (soft and stiff)

The systematic process of executing parametric analyses is described below:

1. Use a selected spectral shape and the set of 5 time histories of ground motions to calculate the seismic response of a HI-STORM 100 cask.

Time histories of ground motions	1	2	3	4	5
μ = 0.55, Peak Ground Acceleration (PGA) = 1.0 g	x	x	x	x	x

2. Select the time history that produces the median cask response in terms of the maximum relative horizontal displacement at cask top and perform the remainder of the analysis series. Scale the ground motion for various PGA levels, and vary the cask/pad friction coefficient. This results in 11 additional analyses. There is no need to re-run the analysis with μ = 0.55 and PGA = 1.0 g because that analysis has already been performed during the ground motion selection process.

		PGA (g)			
		0.25	0.6	1.0	1.25
μ	0.2	x	x	x	x
	0.55	x	x		x
	0.8	x	x	x	x

In summary, there are 16 analyses for a selected combination of spectral shape, cask design, and soil profile. Therefore, the combined total number of parametric analyses is equal to 16x3x2x2=192. If there is a considerable spread between the maximum and median cask responses in these analysis cases, another subset of these parametric analyses will also be performed using the ground motion that yielded the maximum cask response to provide an upper bound of the seismic cask response.

Ground Motion Records

As indicated above, the seismic cask response for each combination of cask design and soil profile is to be investigated under earthquakes conforming to three identified spectral shapes. Five ground motion records have been selected as start-up motions, and are adjusted to conform to the spectral shapes discussed above. The principal axes of start-up motions are first identified to minimize the cross correlation between the three-component motions. Then each component of the rotated motions (that is, start-up motions rotated to their principal axes) are modified to match the intended design spectrum, and finally corrected to form the reference target ground surface motion. A deconvolution procedure is then conduced for each soil profile to generate ground motion records that can be applied to the soil foundation base. It has been concluded that the above-discussed procedure, along with assigning the appropriate soil properties (such as secant soil moduli and damping parameters) that are compatible with the deconvolution analyses, will result in a ground motion that closely approximates the original reference ground motion at the surface of the soil mass if the cask and pad are not present. The principal horizontal components of the deconvoluted ground motion are applied to the nodes at the soil foundation base in the directions designated as 1 and 2 in Figure 1. The vertical motion is also fitted to the appropriate spectral shape, deconvoluted, and applied to the soil foundation base in the vertical (3) direction.

The parametric analyses started using the NUREG-0098 spectral shape and a selected soft soil profile whose material properties are described in a later section. Preliminary analysis results indicate that the surface ground motion record for the Northridge earthquake (motion case 4) fitted to the NUREG-0098 spectral shape yields the median cask response. Therefore, the rest of this paper is devoted to discussion of cask response subject to this input combination. Figure 2 shows the surface ground motion record for the Northridge earthquake in terms of displacement, velocity and acceleration resolved in the principal direction labeled as “1” direction in Figure 1. Figure 3 shows the pseudo-spectral accelerations and relative displacements of the three components of the Northridge earthquake fitted to the NUREG-0098 spectral shapes, along with the target horizontal and vertical spectral shapes for reference.

Cask/Pad Friction Coefficient

A number of researchers (such as [17], [18], [19]) have investigated the friction coefficient between steel and

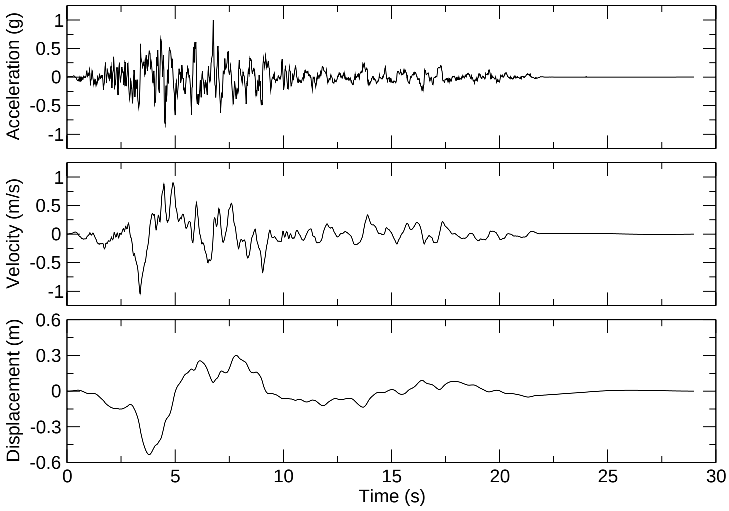


Figure 2: Principal Components of Surface Ground Motion Record for Northridge Earthquake Fitted to NUREG-0098 Spectral Shape

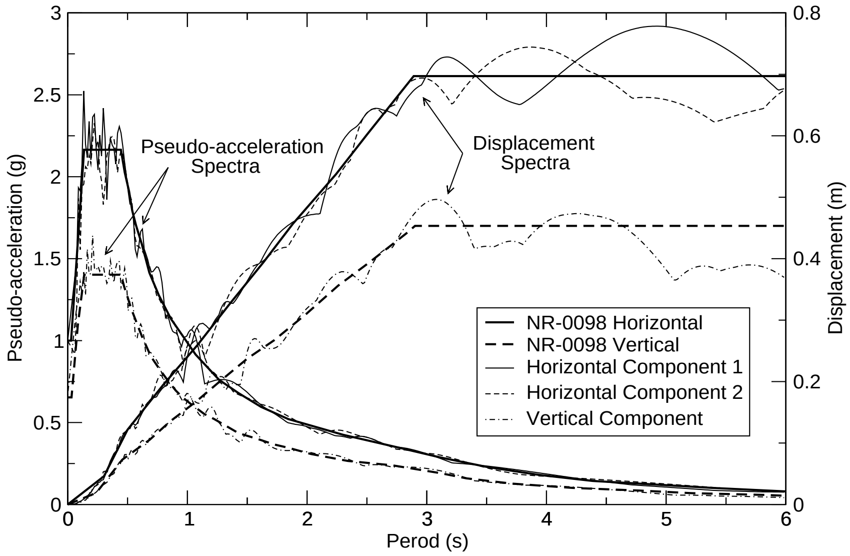


Figure 3: Pseudo-Spectral Accelerations and Relative Displacements for Northridge Earthquake Fitted to NUREG-0098 Spectral Shape

concrete surfaces under various conditions. The friction coefficient can vary depending on the normal force, the relative velocity of the two surfaces, and the wetness of the interface. The referenced studies report friction coefficients ranging from 0.2 to 0.7, depending on the conditions. The coefficient of 0.2 was reported in [19] for an isolated case where the steel surface was covered with mill scale and the normal stress was very low. For conditions applicable to the present work, it appears that the friction coefficient can vary between 0.3 and 0.7. For this study, a coefficient of 0.55 was chosen as a "best estimate" value, and values of 0.2 and 0.8 were chosen as extreme lower and upper bounds for use in the analyses.

Material Properties of Soils

The parametric analyses are performed for generic "soft" and "stiff" soil profiles. These soil profiles were generated based on the recommendations given in [20] for generic structural response studies at nuclear power plant sites. Both of these soil profiles consist of six horizontal layers, the properties of which are tabulated in Table 1 for the soft soil profile and Table 2 for the stiff soil profile. The discussion in this paper focuses on the seismic cask response with the soft soil profile.

Table 1: Soft Soil Profile

Layer	Thickness (m)	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio	Horizontal Motion Damping Ratio (%)
1	3.05	2000	132.9	0.3	4.94
2	6.10	2000	180.9	0.3	7.90
3	6.10	2000	341.3	0.3	5.49
4	6.10	2000	450.6	0.3	4.24
5	9.14	2000	576.6	0.3	3.21
6	10.22	2000	673.4	0.3	3.26

Table 2: Stiff Soil Profile

Layer	Thickness (m)	Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio	Horizontal Motion Damping Ratio (%)
1	3.05	2000	715.2	0.3	2.35
2	6.10	2000	864.7	0.3	3.89
3	6.10	2000	1096	0.3	3.31
4	6.10	2000	1332	0.3	2.64
5	9.14	2000	1552	0.3	2.21
6	10.22	2000	1896	0.3	1.69

ANALYSIS RESULTS

The seismic responses of the cask are characterized in terms of three components of translational displacements with reference to the top surface of the concrete pad and three components of angular rotation with respect to the coordinate system of the model. The pure sliding movements of the cask are described by the two horizontal components of translational displacement at the cask base. Combining the sliding displacement with the displacement caused by cask rotations yields the total displacement at the cask top. The two horizontal components of translational displacement are combined vectorially to produce the resultant cask displacement, which is used to check for the possibility of collision with neighboring casks. The vertical component of displacement provides a measure of potential uplifting of casks. The possibility of cask tipping over is investigated by monitoring the cask angular rotation.

A broad array of input variables is used in the parametric analyses to investigate the seismic response of casks under prescribed earthquake events. This paper presents a portion of the parametric analyses related to a cylindrical HI-STORM 100 cask and the soft soil profile, subjected to five selected earthquake records conforming to the spectra in the NUREG-0098 guidelines. Figure 4 shows the time histories of the resultant horizontal displacement at the cask top relative to concrete pad for a coefficient of friction of 0.55 at cask/pad interface and five ground motion records with peak ground acceleration (PGA) of 1.0 g fitted to the NUREG-0098 spectra. Based on these results, as well as the time histories of the angular rotations for each ground motion record, it was determined that Case 4, or the Northridge earthquake record, yields the median cask displacement. Figure 5 shows the displacement trajectories of the top and base of cask relative to the concrete pad subjected to this earthquake record. It is evident from this figure that the cask undergoes a rocking or precessing motion in this particular case. The horizontal displacements at the cask top are significantly larger than those at the cask base, indicating that the cask experiences considerable angular rotations and relatively little sliding at its base in this case.

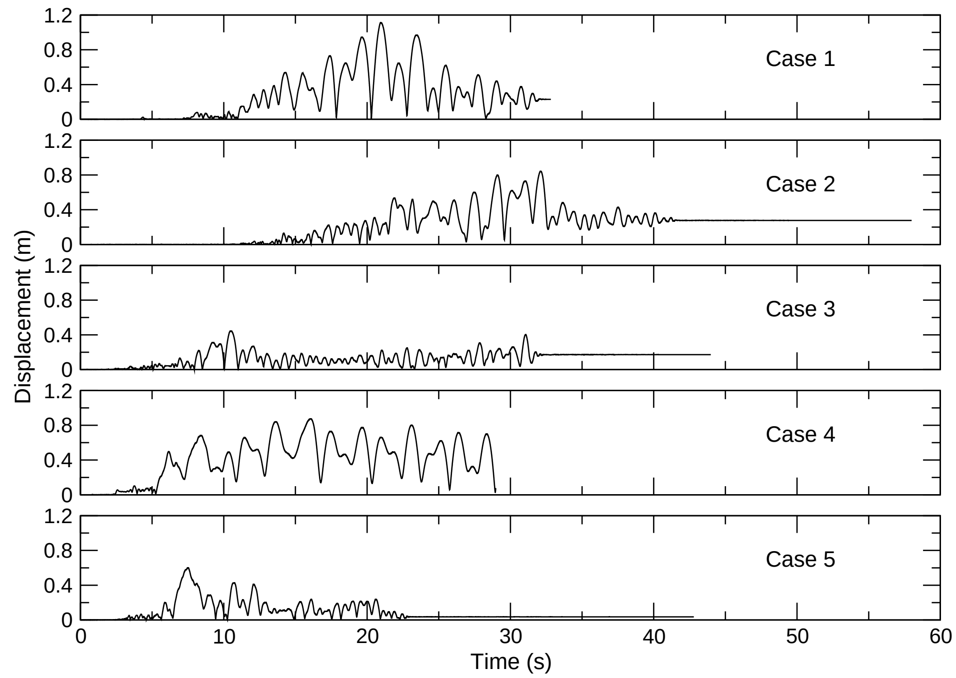


Figure 4: Time Histories of Cask Top Displacement Relative to Concrete Pad for Ground Motions of 5 Earthquake Cases, HI-STORM 100 Cask, Soft Soil Profile, Coefficient of Friction = 0.55 (Cask/Pad)

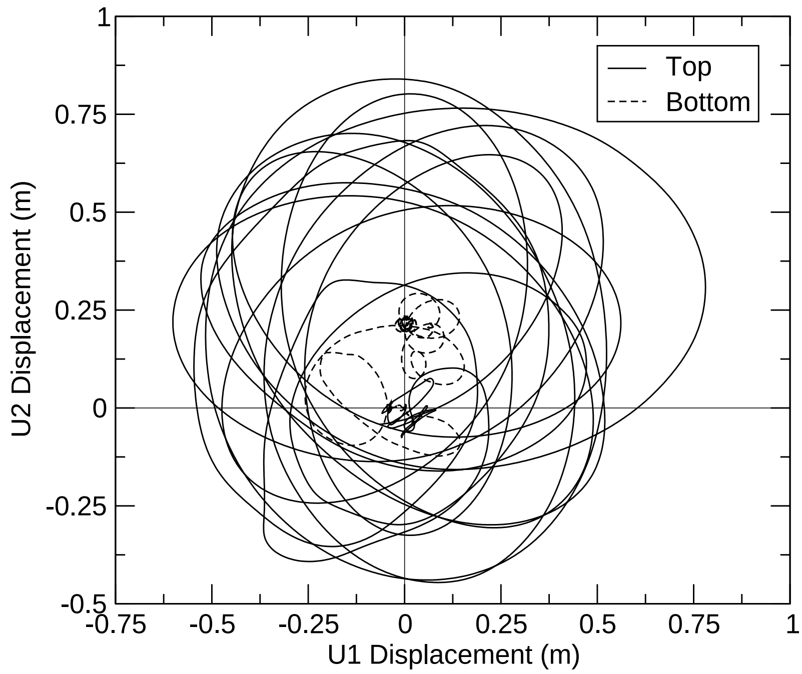


Figure 5: Displacement Trajectories of HI-STORM 100 Cask Top and Bottom Relative to Concrete Pad Subjected to Northridge Earthquake, Soft Soil Profile, Coefficient of Friction = 0.55 (Cask/Pad)

After evaluating the analysis results from the set of five selected earthquake records, it was determined that the Northridge earthquake record yields the median cask response. Therefore, this earthquake record was used as input excitation to the coupled model with the same cask/soil combination to analyze the remaining 11 parametric cases with varying cask/pad interfacial coefficient of friction and PGA. A small subset of parametric analysis results is plotted in Figure 6, which shows the maximum horizontal displacements of the cask top relative to the concrete pad for the case with $\mu = 0.55$ at the cask/pad interface. In this figure, the cask top undergoes greater relative horizontal displacements when subjected to ground motions of higher peak ground accelerations, which are usually associated with increased levels of excitation energy.

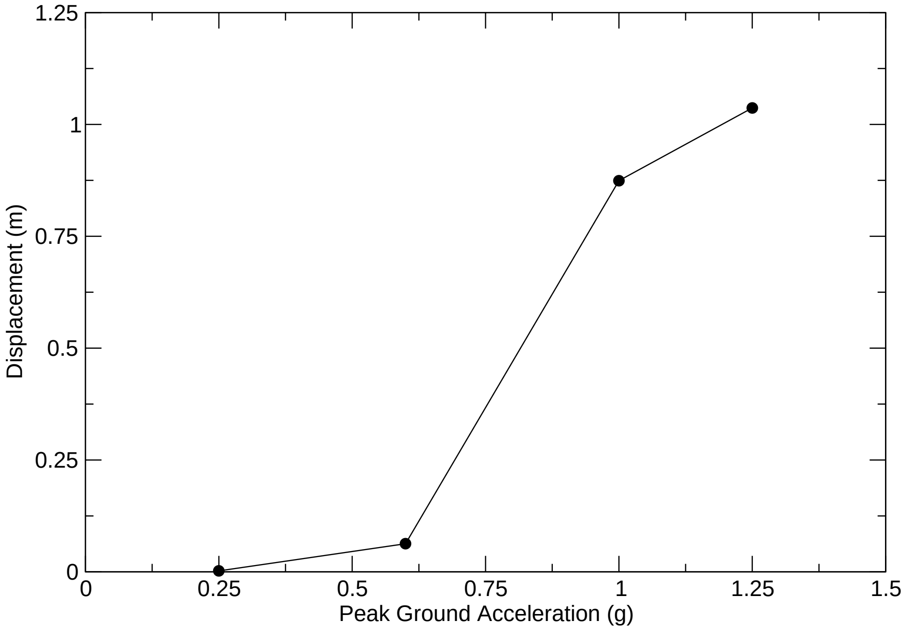


Figure 6: Maximum Displacements of Cask Top Relative to Pad for Northridge Earthquake, HI-STORM 100 Cask, Soft Soil, Coefficient of Friction = 0.55 (Cask/Pad)

SUMMARY

This research project investigates the seismic response of freestanding dry cask storage systems. Coupled finite element models consisting of a module or cask standing on a flexible concrete pad on top of a soil foundation have been developed to examine the nonlinear and dynamic behavior of these systems subjected to prescribed earthquake excitations. Three different site-specific seismic analyses of these systems have been performed, providing insight to the relative importance of various input parameters on the seismic responses of these systems. The current phase of the project focuses on defining and identifying a finite set of input variables involved in the parametric analyses of these systems. Later in the project, the cask displacements and angular rotations obtained from these analyses will be compiled and presented systematically in nomograms to provide information in support of the safety review of applications to use these systems.

This paper presents a subset of the parametric analyses of seismic response of dry cask storage systems. This subset of analyses involves a cylindrical HI-STORM 100 cask standing on a concrete pad on top of a foundation with a soft soil profile. The input seismic excitations are generated from a set of five selected earthquake records baseline corrected and shape compatible to the NUREG-0098 spectra. Results from this set of parametric analyses indicate that the methodology developed in this project may be a reasonable approach to performing such parametric analyses. However, caution must be exercised in interpreting the results of this highly dynamic problem simulated with nonlinear contact algorithms, particularly, for cases involving earthquake records with high peak ground accelerations. The input earthquake time history has been identified as an important parameter governing the cask response. Future effort will also be devoted to evaluate whether ground motion parameters, other than peak ground acceleration, such as peak ground velocity and peak ground displacement, could be substituted as the measurement of ground shaking intensity to reduce the degree of scatter in the computed cask response.

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