Impact of Slenderness on Dry Storage Cask Seismic Response – 16225

Ahmed Maree[1], Taylor Nielsen[1], David Sanders[2], Sharad Dangol[3], Joel Parks[3], Luis Ibarra[4], and Chris Pantelides[5]
[1] Graduate Student at University of Nevada, Reno
[2] Professor at University of Nevada, Reno
[3] Graduate Student at University of Utah
[4] Assistant Professor at University of Utah
[5] Professor at University of Utah

ABSTRACT

Spent nuclear fuel (SNF) is often transferred to a Dry Storage Cask (DSC), after being stored in pools to control the temperature of the fuel assemblies and prevent melting of their cladding. DSCs are designed as free-standing structures resting on a reinforced concrete foundation pad. Although DSCs are considered as a temporary storage solution, there is a recent interest on assessing the potential use of DSCs as a mid-term solution. Longer compliance periods of hundreds of years increases the seismic hazard, leading to casks exposed to larger seismic accelerations.

The main goal of this study is to evaluate the mid-term seismic performance of DSCs to reach a resilient system resisting earthquakes. To evaluate seismic performance, experiments were conducted using a six degree-of-freedom (6DOF) shake table in the Earthquake Engineering Laboratory at the University of Nevada, Reno. Slenderness of the cask affects its dynamic response, and it is represented as the cask outer radius-to-centroidal height ratio (r/h_{cg}). A finite element model was developed for the cask pad system and results showed good correlation with experimental outcomes. This model was used to extend the investigated parameters to include higher levels of earthquakes that were not applied experimentally due to shake table limitations. Slenderness ratio affects the measured accelerations of DSCs.

INTRODUCTION

Investigating the effect of DSC slenderness on its seismic performance is a part of a research project evaluating seismic response of free-standing DSCs under long-term exposure. In order to obtain a DSC seismic resilient system, several alternatives were investigated in the shake table tests. Three scaled specimens were chosen to cover a range of commercially available DSCs with three different r/h_{cg} ratios of 0.39, 0.43 and 0.55. The first specimen was a Multi-Purpose Canister (MPC) only and the other two were canisterized casks that consist of the outer overpack and MPC. Canisterized casks were investigated to study the effect of pounding between the outer and inner parts. According to the similitude law, the scaled DSCs need additional mass to properly reproduce the dynamic response of the original DSCs. DSC specimens were free standing structures on the shake table; they were instrumented to capture the response during excitation.

Several ground motions were chosen as evaluation earthquakes. The seismic hazard for the evaluation earthquakes has been developed for 1,000-, 10,000-, and 30,000-year return periods. Finite element models were developed to assess the experimental response of the tested specimens. However, assessing the rocking-sliding behavior for free standing DSCs is complex [1] because it is very sensitive to small changes in the size of the tested specimens and its slenderness [2]; acceptable correlation between finite element model results and the experimental results were obtained. Several defining parameters were implemented to obtain a verified model. Also, this model was verified using experimental results obtained by Shirai et al. [3]. Shirai et al. performed biaxial experimental studies of free standing DSC subjected to strong earthquakes. The finite element model developed was used to investigate the effect of higher levels of ground motions. The investigated parameter of slenderness ratio affects the response accelerations of both MPC and overpack. The pounding between the inner MPC and the outer overpack has a significant effect on the amplification of accelerations on the spent fuel assemblies.

EXPERIMENTAL PROGRAM

During an earthquake, the response of the cask could be a sliding motion, a rocking motion or a sliding–rocking motion, depending on cask slenderness and the coefficient of friction (μ) between the cask and the foundation pad. The sliding motion helps to dissipate energy, while the rocking motion brings damaging effects. Accordingly, for seismic stability reasons, it is preferable to allow sliding motion of the cask in order to minimize the possibility of rocking motion during strong earthquakes [4]. Friction is critical but can significantly change with time and is difficult to estimate. Slenderness of the cask is a primary governing factor for selecting specimens. The ratio between the cask outer radius and the height from the base to its center of gravity (r/h_{cg}) is an important factor that represents cask slenderness. In order to fabricate scaled specimens for the shake table experiments two factors were considered: the choice of DSC specimens to cover the range of commercial ones; and application of similitude laws to make sure that the behavior of the scaled specimens is equivalent to the prototype.
The specimens were constructed from Grade 36 steel plates. Lead assemblies and sand were used as additional mass to meet similitude law requirements. Detailed instrumentation plans were prepared to capture the response of the DSC specimens during sliding and rocking. To maintain safety of the specimens, as well as of the shake table, a safety system was developed to prevent damage.

Choice of DSC Specimens

Choice of the specimen dimensions was performed to cover a range of commercial DSCs as presented in NUREG/CR-6865 [5]. Two generic casks and one MPC were chosen according to their r/h_{cg} ratio. Cask (I), Cask (II) and MPC have r/h_{cg} ratios equal to 0.55, 0.43 and 0.39, respectively. For Cask (I), r/h_{cg} ratio represents a common ration that covers a large portion of the current inventory. Cask (II), r/h_{cg} ratio was chosen to represent a minimum practical value, which tends to be less stable and more likely to cause a rocking motion. On the other hand, testing the MPC only to represent a canister is important, as there are types of DSCs that consist of only the canister without a separated outer shield. The theoretical r/h_{cg} ratio of 0.39 can be considered as a critical case for tipping over. The dimension, weight and scale of the chosen DSC specimens are summarized in TABLE I.

TABLE I. Dimensions, weight, and scale of chosen DSCs

Cask Type	**r / h_{cg}**	**Weight** (ton)	**Diameter** (mm)	**Height** (mm)	**Scale**
Cask (I)	0.55	16.5	1156	2184	1/2.5
Cask (II)	0.43	14.6	1054	2388	1/2.5
MPC	0.39	4.9	660	1767	1/3.5

Similitude Law

According to the similitude law, the fabricated overpacks and MPCs require additional mass to properly reproduce the dynamic response of the scaled prototypes [6]. To reproduce the dynamic motion and bottom stresses, additional mass was placed inside the specimens, as shown in Fig. 1. The additional mass (lead panels) was placed between the inner and outer shells of the overpack and inside the MPC.
After adding the lead panels into the scaled specimens, the cavities between the panels and cylindrical shells of the over pack, and in the MPC, were filled with sand to prevent pounding of the lead units with the cylindrical shells during shaking. The amount of sand used was approximately 10% of the total weight. In addition, the top surface of the lead panels was welded in place. The dimensions of the scaled DSCs were based on generic full-scale casks, and the similitude law.

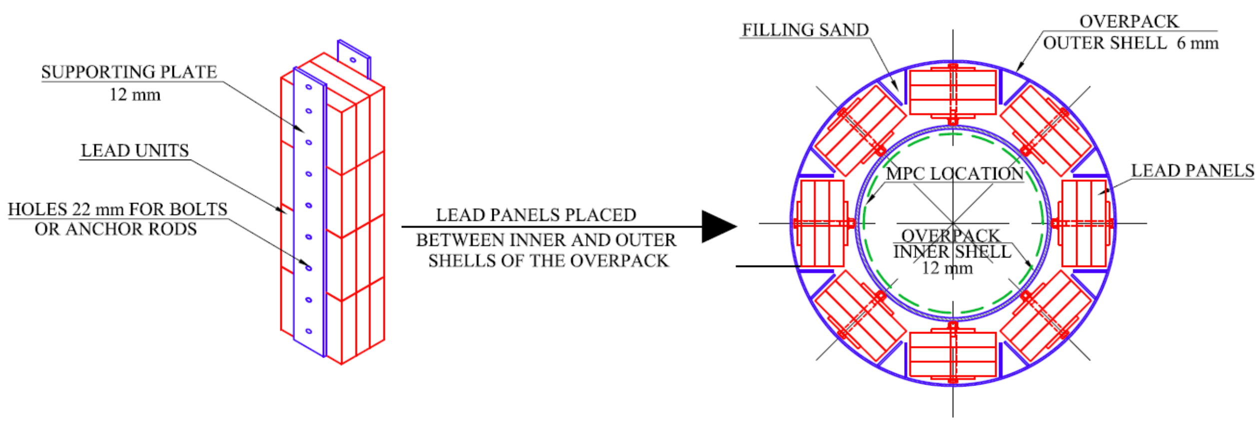


Fig. 1.Lead panels assembled and placed between inner and outer shells of the overpack.

Instrumentation and Safety System

A reinforced concrete pad was fixed to the 6 DOF shake table to represent the footing supporting the DSC in the field. Linear variable displacement transducers (LVDTs), string potentiometers, and accelerometers were used to capture displacements and accelerations of the DSCs and the MPC, as shown in Fig. 2. Accelerometers were placed on the top, bottom and middle of the overpack and MPC. The vertical LVDTs were attached to a space frame to be far enough from the movement zone of the specimens during sliding. In addition, eight rosette strain gauges were attached to the outer surface of the overpack to monitor yielding of the outer shell. Final test setups are illustrated in Fig. 3.

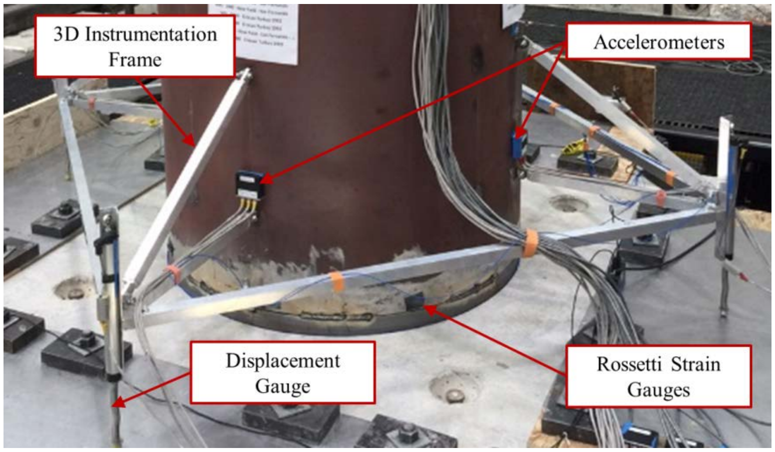


Fig. 2.Bottom instrumentations for Cask II.

(a) Cask I (r/h_{cg} =0.55) (b) Cask II (r/h_{cg} =0.43) (c) MPC (r/h_{cg} =0.39)

Fig. 3.Test setup of shake table experiments.

A safety system was developed for the DSCs on the 6 DOF shake table to prevent excessive sliding or tipping-over of the DSCs. Four cables were connected to the handling plates of the overpack with sufficient sag to allow the cask to slide freely within certain limits.

GROUND MOTION SELECTION

Three earthquake records were chosen for the experiments: San Fernando Pacoima Dam, CA (1971), Erzican, Turkey (1992), and Chi-Chi, Taiwan (1999). These ground motions were obtained from the PEER database [7]. The level of spectral acceleration or seismic hazard at the site has been represented using seismic hazard curves published in NUREG 6728 [8]. The seismic hazard for the evaluation earthquakes was developed for 1,000-, 10,000-, and 30,000-year return periods. Response spectra of the 10,000 year event matched to Western US rock spectra in both horizontal and vertical directions, as shown in Fig. 4.
The selected ground motions were spectrally matched to represent ground shaking of the cask-pad system for: a) Near Field Earthquakes (magnitude M = 6.0 at 2 km), and b) Far Field Earthquakes (magnitude M = 8.0 at 20 km). The response spectra of the original San Fernando Pacoima Dam ground motion showed good correlation with the developed near field response spectrum of the 10,000-year event, without any matching process. This correlation is illustrated in Fig. 5 for the two horizontal components of the original ground motion.

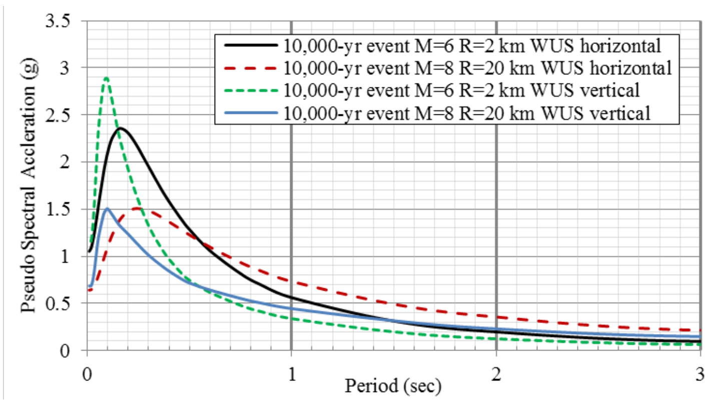


Fig. 4.Response spectra of 10,000-year event matched to western US rock spectra in both horizontal and vertical directions.

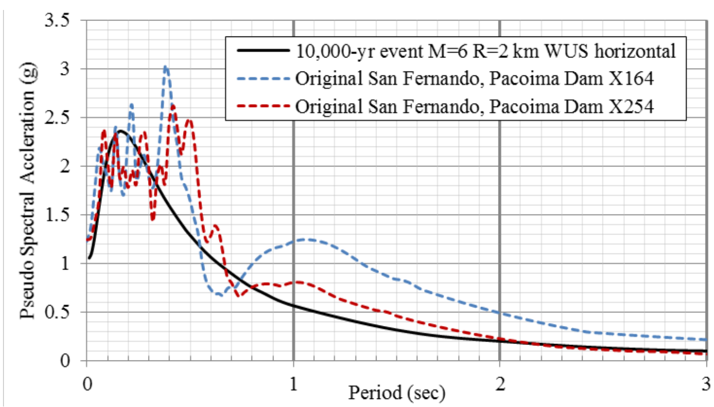


Fig. 5.Comparison between horizontal response spectrum of the developed near field 10,000-year event and the response spectra of the original San Fernando Pacoima Dam ground motion.

This study shows experimental results of the cask subjected to the San Fernando Pacoima Dam, CA (1971) ground motion in three orthogonal directions X, Y and Z. This ground motion was matched to a 1,000 year far field event return period. However, 50% of the original San Fernando ground excitation in three orthogonal directions was used for verification of the finite element model of Cask II. Applying 50% of this ground motion led to the maximum capacity of the shake table, controlled by the high impact forces during DSC rocking. In order to extend the investigated parameters using the developed finite element models to include higher levels of earthquakes, the original San Fernando ground excitation was used in the developed models.

EXPERIMENTAL RESULTS

Experimental results shown in this section are based on San Fernando Pacoima Dam matched to 1,000 year far field event return period. Measured accelerations at mid-height of casks with r/h_{cg} ratio of 0.43 and 0.55 are plotted as shown in Fig. 6 and Fig. 7, respectively for the three orthogonal directions X, Y and Z. The figures illustrate the acceleration on the outer surface of the overpack, as well as the acceleration on the surface of the inner MPC. The acceleration at the inner MPC is always higher than the acceleration on the outer surface of the overpack, due to pounding of the MPC with the overpack during excitation. The sample rate of recorded accelerations was 256 Hz, which can be considered low sample rate to record acceleration values due to impact. This pounding amplifies the acceleration in the MPC which directly affects the stresses on the spent fuel. This amplification of acceleration is higher in both the X-and Y-directions due to pounding, however it is less in the vertical Z-direction. This may be due to the movement of the overpack and the MPC as one unit in the vertical direction, in addition to the nutation motion that was observed during cask rocking.

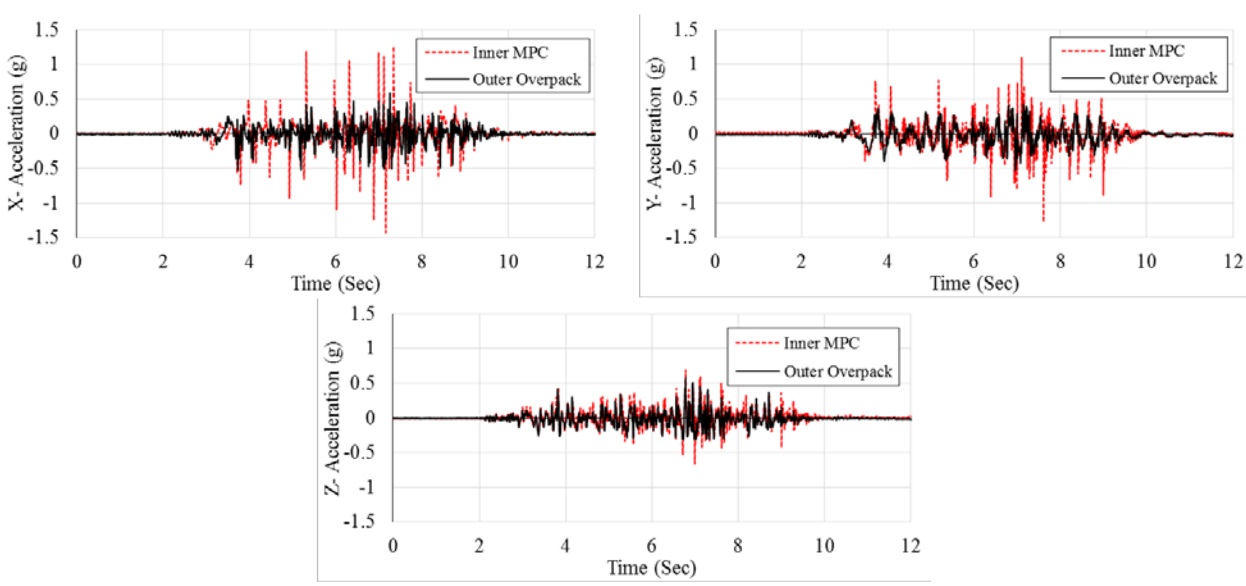


Fig. 6.Accelerations at mid-height of Cask II with r/h_{cg} ratio of 0.43 in X, Y and Z directions.

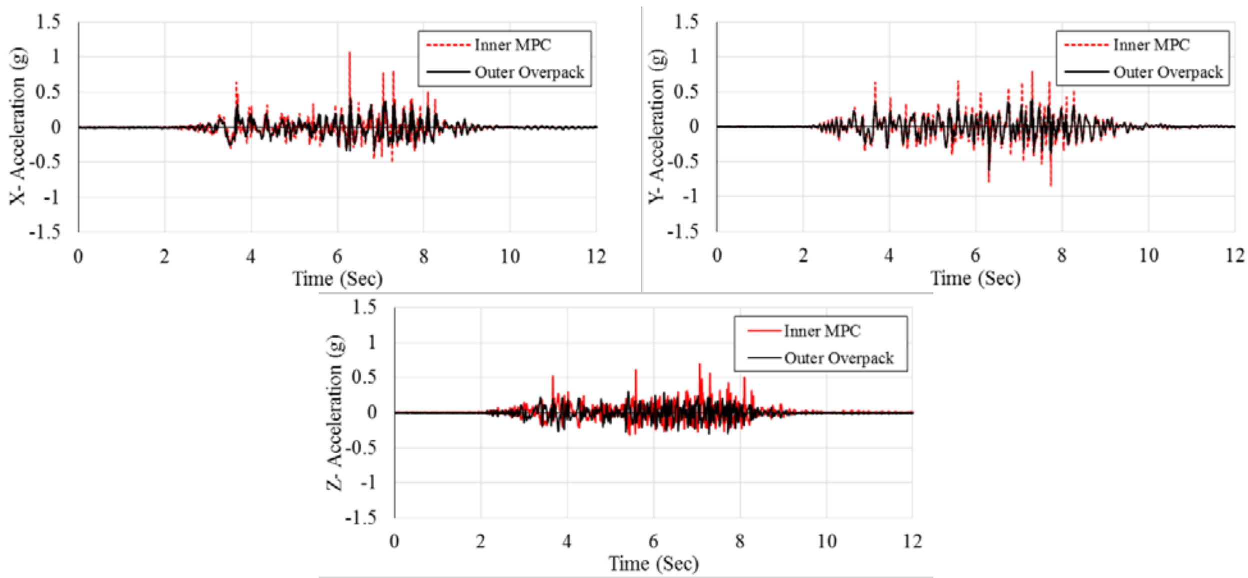


Fig. 7.Accelerations at mid-height of Cask I with r/h_{cg} ratio of 0.55 in X, Y and Z directions.

The vertical displacements at the center of the canister with r/h_{cg} ratio of 0.39, Cask II with r/h_{cg} ratio of 0.43 and Cask I with r/h_{cg} ratio of 0.55 are shown in Fig. 8. The maximum vertical displacements at the center were 3.83 mm, 2.57 mm and 0.43 mm, respectively. These measured vertical displacements in the Z-direction illustrate that the more slender the cask is, the more it tilts up. As the rotation of cask vertical axis depends on the vertical displacement, therefore cask rotation is inversely proportional to r/h_{cg} ratio.

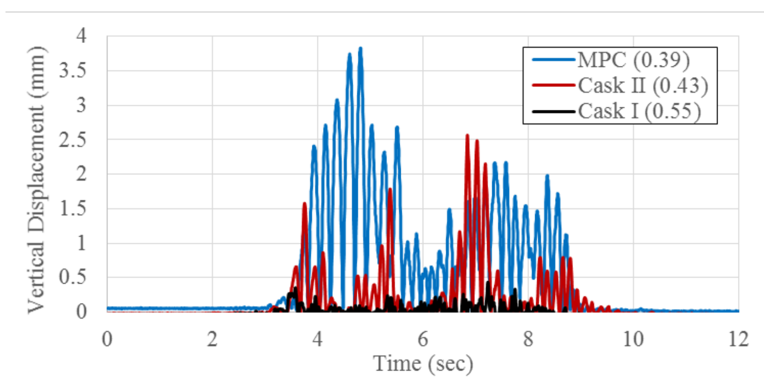
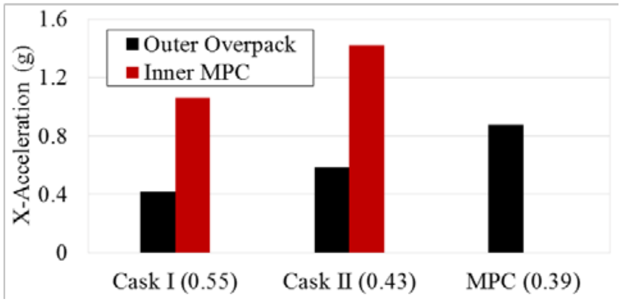
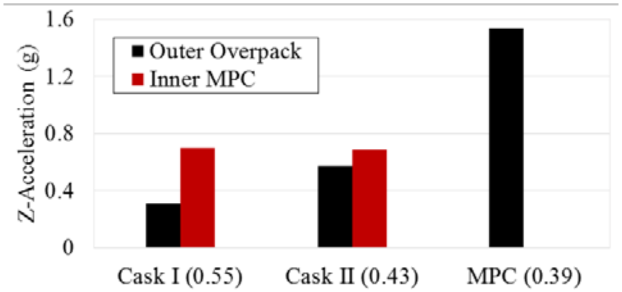


Fig. 8.Vertical displacement at specimens' bottom center due to San Fernando Pacoima Dam matched to 1,000 year far field event return period.

Fig. 9 shows the effect of the slenderness ratio (r/h_{cg}) on the measured horizontal and vertical acceleration for Cask I, Cask II and MPC. As observed, the acceleration decreases as the r/h_{cg} ratio increases, an effect more pronounced in the vertical direction. This figure also illustrates the effect of pounding between the inner MPC and the outer overpack on the amplification of acceleration in case of Cask I and Cask II.



(a)



(b)

Fig. 9.Comparison between resulted acceleration for Cask I, Cask II and MPC for both (a) X-direction and (b) Z-direction.

FINITE ELEMENT MODEL VERIFICATION

Finite element models were verified using Shirai et al. [3] experimental results, as well as the experimental shake table results for Cask (II). The finite element models were developed using LS-DYNA version R7.0.0 [9]. Several modeling parameters were used to verify the models. Verified models showed satisfactory correlation with experimental results.

For the Shirai et al. specimen, the thickness of the reinforced concrete pad supporting the cask was 300 mm with horizontal dimensions of 2600 mm × 2600 mm. The cask overpack has 1230 mm outer diameter, 1921 mm height and 8.17 ton mass. The canister had an outer diameter of 559 mm, 1543 mm height and 1.95 ton mass. A three dimensional view of the developed Shirai et al. model is shown in Fig. 10. The JMA Kobe ground motion excitation was applied to the node set of concrete pad lower surface in both the X and Z directions. This was the same excitation used by Shirai et al. in their test.

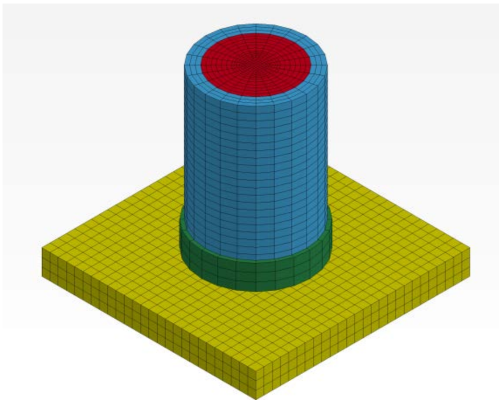


Fig. 10.Extruded view of the verification model of Shirai et al. specimen using LS-DYNA.

To verify Shirai et al. model, several parameters have been compared with the experimental results, as well as other verifications performed by Ko et al. [4] using ABAQUS [10]. Fig. 11 presents the response angle of rotation for the cask vertical axis compared to experimental results and the verification by Ko et al. The results show good correlation compared to the experimental results. The response angular velocity was compared to Shirai et al. experimental results, as shown in Fig. 12. This relation shows satisfactory correlation between the finite element verification and the Shirai et al. experimental results.

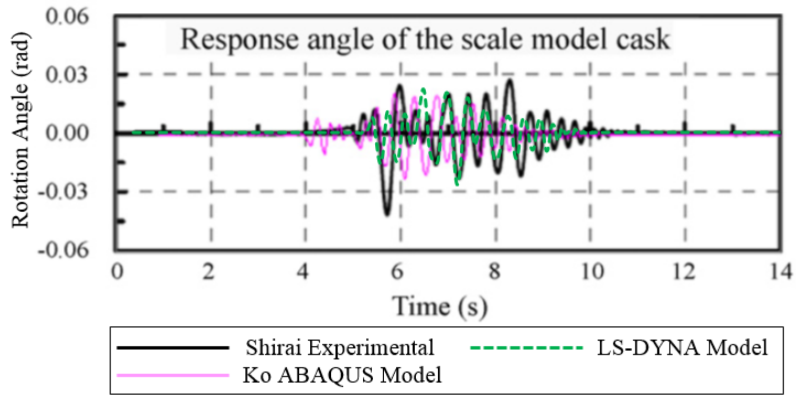


Fig. 11.Response angle of rotation for the cask vertical axis for verified model compared to Shirai et al. experimental results and Ko et al. verification using ABAQUS.

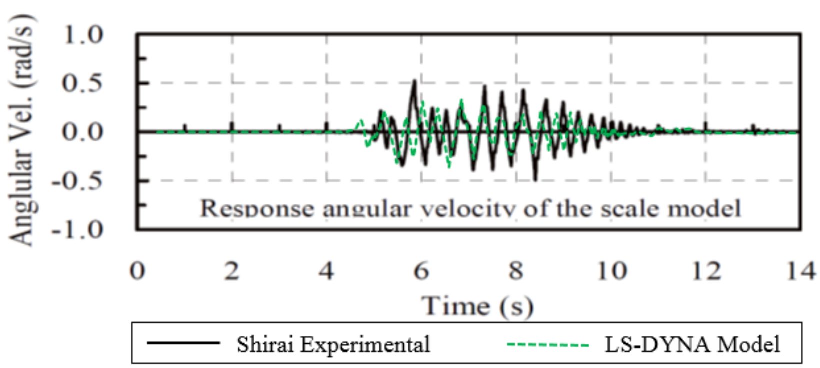
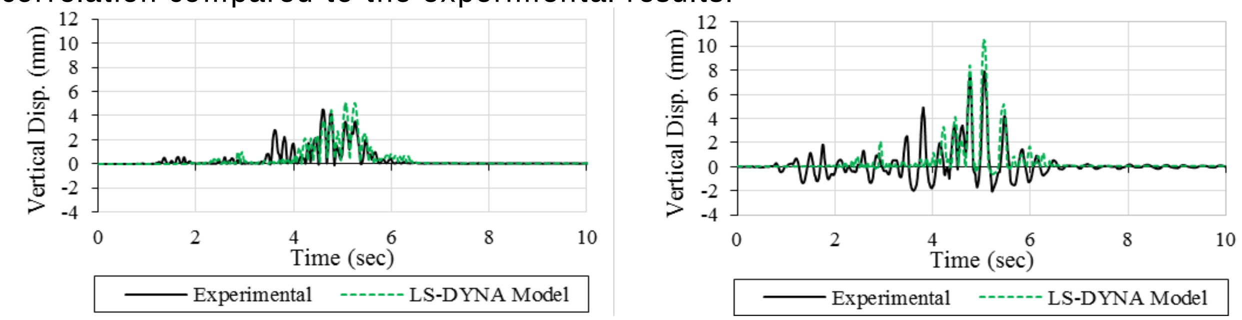


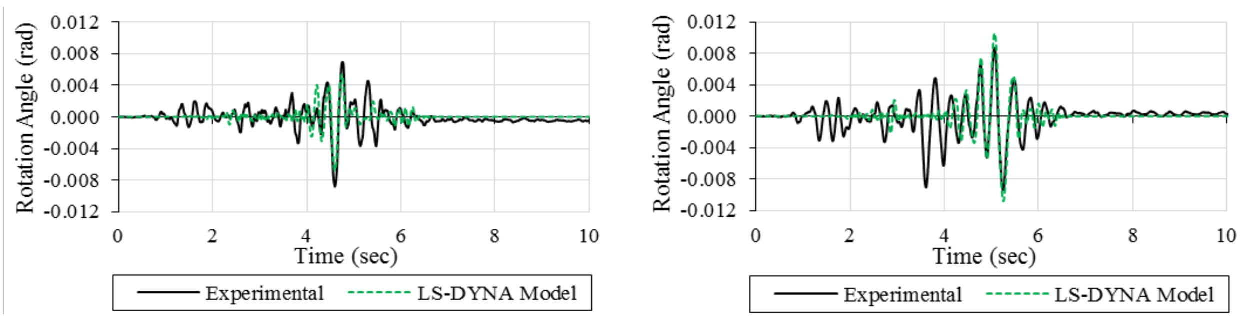
Fig. 12.Response angular velocity for verified model compared to Shirai et al. experimental results.

The details of the specimen used to model Cask (II) were illustrated previously in TABLE I. The applied verified shake table motion was 50% of original San Fernando Pacoima Dam ground motion. For the Cask (II) model verification, several results were compared to the experimental results. Comparison between LS-DYNA model results and experimental results for Cask (II) center and north edge are illustrated in Fig. 13 (a) and (b), respectively. Note that there is a negative vertical displacement in Cask (II) north edge, which was not captured in the model. This negative value of vertical displacement may represent the uneven surface of the concrete pad, where the maximum difference in the level between different points on the concrete surface was only 2 mm. Also, Fig. 14 (a) and (b) present the response angle of rotation for Cask (II) about the vertical axis compared to experimental results for the X and Y direction, respectively. The results show good correlation compared to the experimental results.



(a) (b)

Fig. 13.Cask (II) vertical displacement response experimental results compared to LS-DYNA model results: for both (a) cask center and (b) north edge.

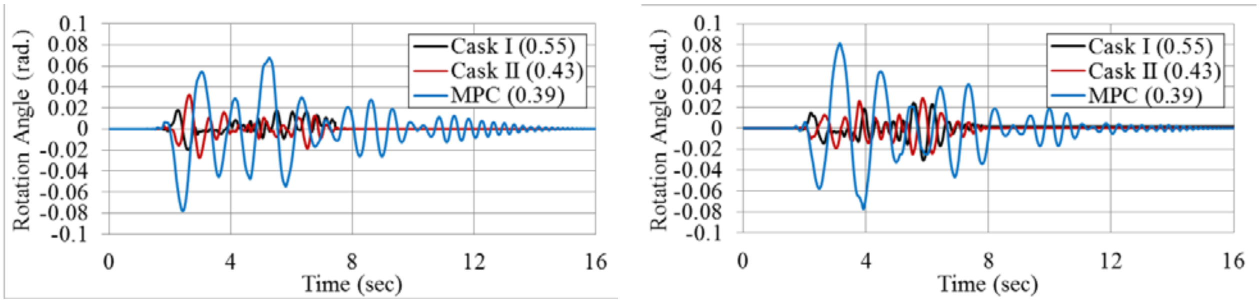


(a) (b)

Fig. 14.Cask (II) vertical axis rotation angle response experimental results compared to LS-DYNA model results for both (a) X-direction and (b) Y-direction.

FINITE ELEMENT MODEL RESULTS

The developed verified model was used to extend the investigated parameters to include higher levels of earthquakes that were not applied experimentally due to shake table limitations. Original San Fernando Pacoima Dam (1971) ground excitation was used in the developed models. Three finite element models were developed for Cask I, Cask II and MPC. The details of Cask I and Cask II specimens are illustrated in Table I. However the details of the MPC were changed to have the same scale of Cask I and Cask II, which is 1/2.5. The developed MPC specimen was 1054 mm outer diameter, 2705 mm height and 14.7 ton mass, but its r/h_{cg} remains the same equal to 0.39. Comparison between the response rotation angle for the specimens' vertical axes are shown in Fig. 15 (a) and (b) in X and Y directions, respectively. This figure illustrates the effect of slenderness ratio on the rotation angle. As the r/h_{cg} ratio increases the rocking angle decreases. The figure also presents the change of the phase angle as well as the change in the natural period of the specimens with the change of slenderness.



(a) (b)

Fig. 15.Response angle of rotation for developed models for both (a) X-direction and (b) Y-direction.

Resulted accelerations from the developed models at mid-height of casks with r/h_{cg} ratio of 0.43 and 0.55 are plotted in Fig. 16 and Fig. 17, respectively for the three orthogonal directions X, Y and Z. These figures show the acceleration on the outer surface of the overpack, as well as the acceleration on the surface of the inner MPC. The acceleration at the inner MPC is always higher than the acceleration on the outer surface of the overpack, which is due to the pounding of the MPC with the overpack during excitation. These are the same observations from the experimental tests under low level of ground excitation, but the amplification values are higher.

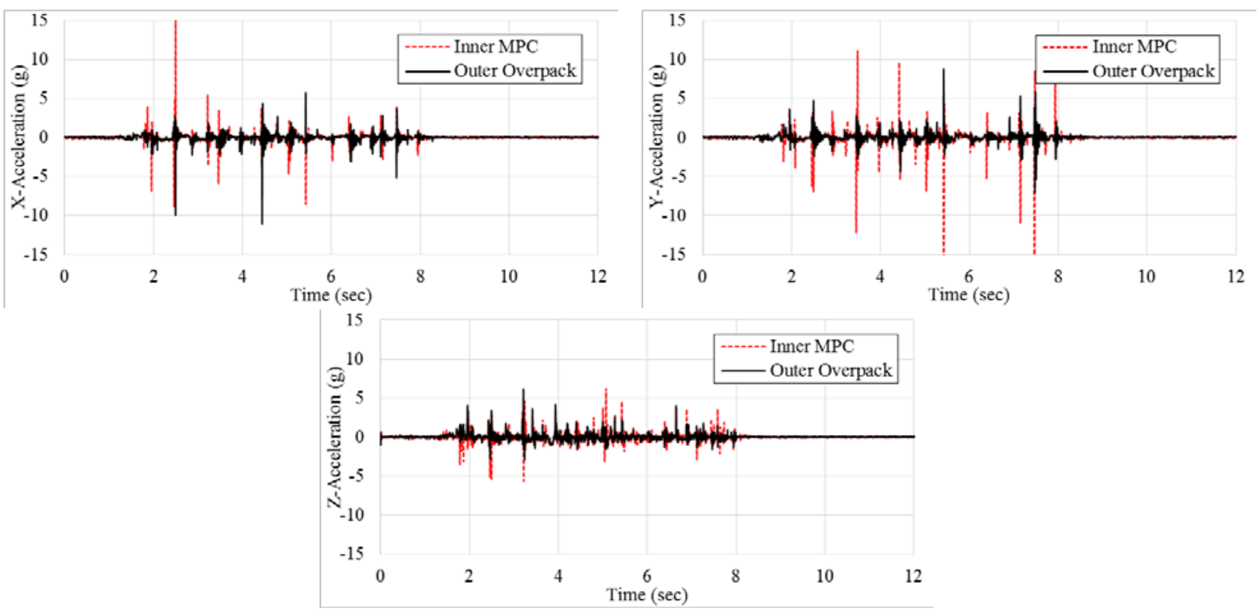


Fig. 16. Accelerations at mid-height of Cask II model with r/h_{cg} ratio of 0.43 in X, Y and Z directions

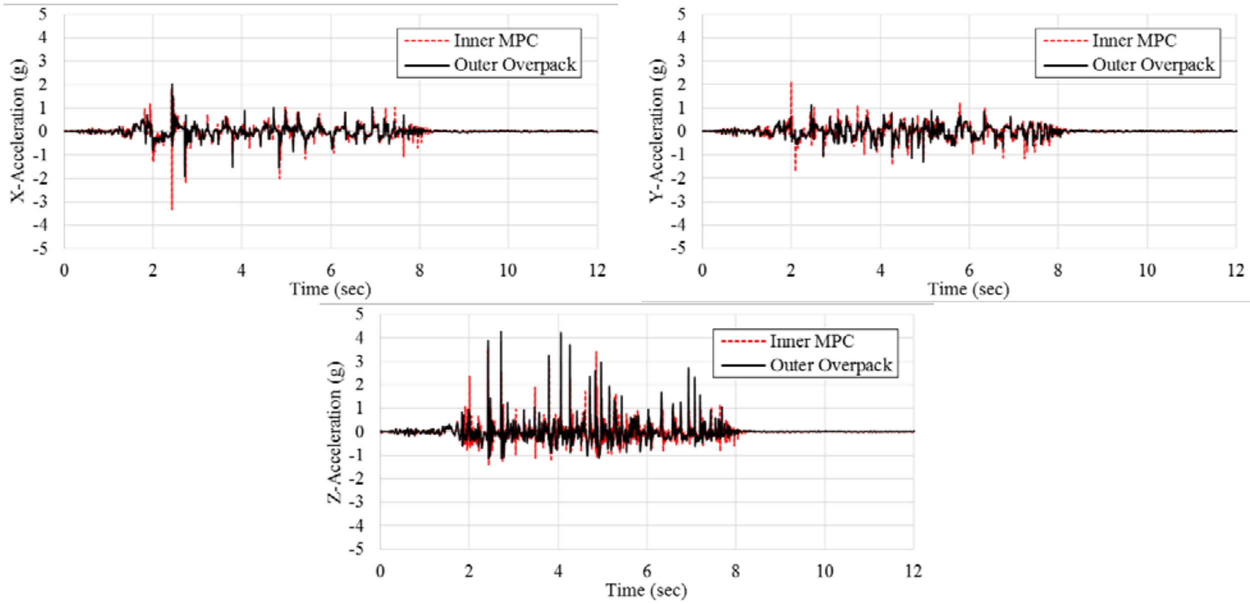


Fig. 17. Accelerations at mid-height of Cask I model with r/h_{cg} ratio of 0.55 in X, Y and Z directions

The vertical displacement resulted from the models at the center of the canister with r/h_{cg} ratio of 0.39, Cask II with r/h_{cg} ratio of 0.43 and Cask I with r/h_{cg} ratio of 0.55 are shown in Fig. 18. For MPC the nutation motion was governing during earthquake excitation resulting in a vertical displacement at the center of the cask that did not reach zero until the end of the motion. The maximum vertical displacements at the center were 49.9 mm, 16.1 mm and 3.8 mm for the MPC, Cask II and Cask I, respectively. Accordingly, the vertical displacements increase for slender casks. Fig. 19 compares the vertical displacements of the developed models at different locations.

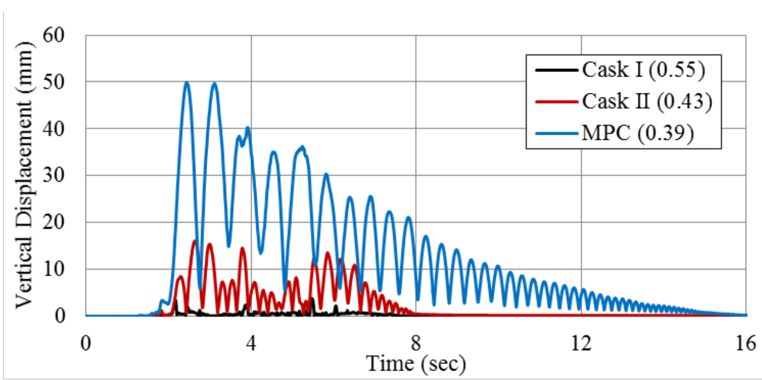


Fig. 18.Vertical displacement at specimens' bottom center for the developed models.

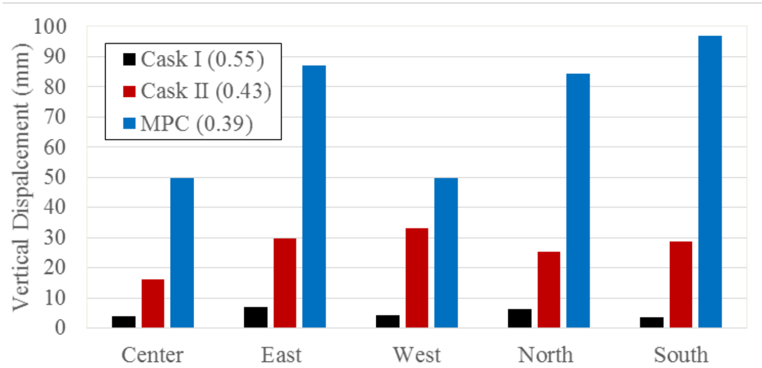


Fig. 19.Comparison between vertical displacements of the developed models.

CONCLUSIONS

This study investigates the seismic performance of free standing DSCs. Experimental tests were performed on a 6 DOF shake table. A three dimensional model of a cask-pad system was developed using LS-DYNA. Experiments performed on a 6 DOF shaking table were used to validate the finite element model. The LS-DYNA Model showed satisfactory correlation compared to the experimental results. The effect of DSC slenderness was investigated through a low level ground motion from the experimental results (San Fernando Pacoima Dam matched to 1,000 year far field event return period), as well as a high level ground motion from finite element models (Original San Fernando Pacoima Dam). The slenderness effect is described as follows:

i. Slenderness ratio affects the measured accelerations of DSCs. As the r/h_{cg} ratio increases the acceleration decreases.
ii. The pounding between the inner MPC and the outer overpack has a significant effect on the amplification of accelerations on the MPC, and potentially on the spent fuel assemblies.
iii. The vertical displacements in Z-direction increase with the increase of cask slenderness.
iv. The rotation of cask vertical axis depends on the vertical displacement, therefore cask rotation is inversely proportional to r/h_{cg} ratio.

NOMENCLATURE

r = outer radius of the DSC
h_{cg} = height from the DSC base to its center of gravity
μ = coefficient of friction

REFERENCES

1. Y. KO, H. YANG and C. HUANG, “An Investigation of the Seismic Response of Free-Standing Dry Storage Cask for Spent Fuel Using the Finite-Element Method,” Nuclear Engineering and Design, 261, 33-43 (2013).
2. C.-S. YIM, A. K. CHOPRA, and J. PENZIEN, “Rocking response of rigid blocks to earthquakes,” Earthquake Engineering and Structural Dynamics, 8, 565-587 (1980).

3. K. SHIRAI, K. HIRATA and T. SAEGUSA, “Experimental Studies of Free-Standing Spent Fuel Cask subjected to Strong Earthquakes,” Transaction in SMiRT 17, Prague, Czech Republic, August 17-22 (2003).
4. Y. KO, S. HSU and C. CHEN, “Analysis for seismic response of dry storage facility for spent fuel,” Journal of Nuclear Engineering and Design, 239, 158-168 (2009).
5. V. K. LUK, B. W. SPENCER, I. P. LAM, and R. A. DAMERON, “Parametric Evaluation of Seismic Behavior of Freestanding Spent Fuel Dry Cask Storage Systems,” NUREG/CR-6865, Sandia National Laboratories, Albuquerque, NM (2005).
6. A. MAREE and D. SANDERS, “Dry Storage Cask Shake Table Experiments.” Transactions of the American Nuclear Society, Anaheim, California, USA, November 9–13, Vol. 111, P. 366-368 (2013).
7. PEER Ground Motion Database (2014), http://peer.berkeley.edu/peer_ground_motion_database.
8. R. K. MCGUIRE, W. J. SILVA, and C. J. COSTANTINO, “Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-consistent Ground Motion Spectra Guidelines,” NUREG/CR-6728, Nuclear Regulatory Commission, Washington DC (2001).
9. LS-DYNA Livermore Software Technology Corporation (LSTC) (2013). LS-DYNA Keyword User’s Manual, Version R7.0.
10. ABAQUS Inc. (2003). ABAQUS User’s Manual, Version 6.4.

AKCNOWLEDGEMENTS

This material is based upon work supported under the Department of Energy Nuclear Energy University Programs. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the Department of Energy Office of Nuclear Energy.