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Shaking Table Experiments of Dry Storage Casks

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ABSTRACT
The spent nuclear fuel (SNF) at nuclear power plants is initially stored in pools to control the temperature of the fuel assemblies, and prevent melting of their cladding. Thereafter, the spent fuel is transferred to a Dry Storage Cask (DSC). Some DSCs are designed as free-standing structures resting on a reinforced concrete foundation pad. They are usually licensed for 20 years, although they can be relicensed for operating periods up to 60 years.

The main goal of this study is to evaluate the long-term seismic performance of DSCs. For this purpose, experimental tests on a six-degree-of-freedom (6 DOF) shaking table were performed on 1/2.5 and 1/3.5 scaled specimens that cover the range of commercially available DSCs. According to the similitude law, the scaled DSCs need additional mass to properly reproduce the dynamic response of the original DSCs. This additional mass was provided by adding lead assemblies to the specimens. DSC specimens were designed to sustain handling, sliding and impact during testing. A developed finite element model of the DSC showed good correlation with experimental results obtained from previous literature. This model is used to examine the new experimental data as well as to conduct a parametric study.

KEYWORDS: *Dry Storage Cask, Shaking Table Experiment, Multi-purpose Canister, Scaling and Similitude.*

1. INTRODUCTION

Most DSCs are canisterized casks that include an inner and outer cylindrical shell. The outer shell is the overpack, and is a shield that protects the SNF from damage and prevents any radiation release. The inner part is the Multi-Purpose Canister (MPC), and contains a honeycomb fuel basket to store fuel assemblies in a specific alignment. There are also uncanisterized DSCs that consist of only the overpack. As the main objective of this research is to assess the long-term seismic performance of DSCs, scaling and similitude of such a free rocking structure is a main concern especially under vertical excitation [1]. For this purpose, a selection of representative DSCs was performed to cover a range of commercial DSCs. Subsequently, scaling of the chosen specimens was conducted using the similitude law. Detailed instrumentation was performed to capture the response of the specimens during shaking. Several ground motions were selected for the shaking table experiments based on a parametric study. A finite element model was developed to assess the experimental response of the tested specimens. This model was verified using experimental results obtained by Shirai et al. [2]. Shiari et al. performed biaxial experimental studies of free standing DSC subjected to strong earthquakes. Experimental testing of the DSCs on the shaking table enables the evaluation of the cask for seismic performance.

2. SPECIMEN DESIGN

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 but to minimize the possibility of rocking motion during strong earthquakes [3]. Friction is critical but can significantly changes with time and is difficult to estimate. Slenderness of the cask is a primary governing factor for choosing specimens. The ratio between the cask outer radius and the height from the base to its center of gravity ($r/h_{c.g.}$) is an important factor that represents cask slenderness. In order to fabricate scaled specimens for the shaking table experiments two concerns were considered: the choice of DSC specimens to cover the range of commercial ones; and application of scaling and similitude laws to make sure that the behavior of the scaled specimens is equivalent to the prototype.

2.1. Choice of DSC Specimens

Choice of the specimen dimensions was performed to cover a range of commercial DSCs as presented in NUREG/CR-6865 [4]. Two generic casks and one MPC were chosen according to their $r/h_{c.g.}$ ratio. Cask (I), Cask (II) and MPC have $r/h_{c.g.}$ ratios equal to 0.55, 0.43 and 0.39, respectively. These values of $r/h_{c.g.}$ ratios are compared to the commercial DSCs, as shown in Fig. 2.1.

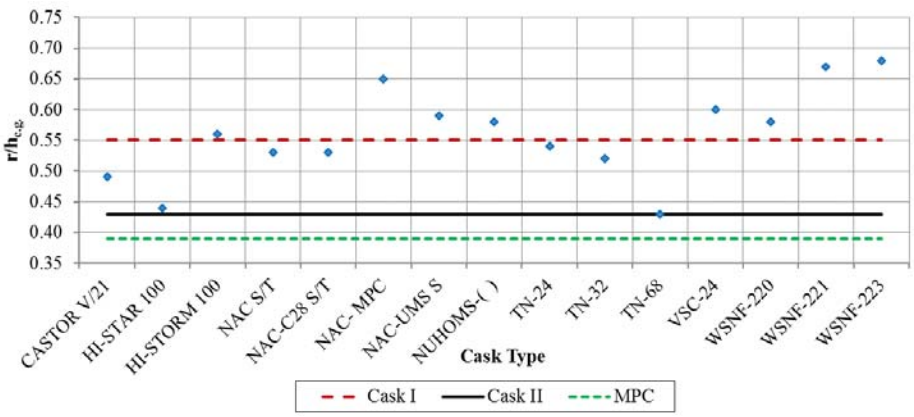


Figure 2.1 Slenderness ratio for commercial DSCs compared to the selected values for different specimens.

For Cask (I), $r/h_{c.g.}$ ratio represents an average value to cover a larger portion of the current inventory. However for Cask (II), $r/h_{c.g.}$ ratio was chosen to represent a minimum 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 $r/h_{c.g.}$ 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 2.1.

Table 2.1 Dimension, weight, and scale of chosen DSC specimens.

Cask Type	$r/h_{c.g.}$	Weight (ton)	Diameter (mm)	Height (mm)	Scale
Cask (I)	0.55	16.5	1,156	2,184	1/2.5
Cask (II)	0.43	14.6	1,054	2,388	1/2.5
MPC	0.39	4.9	660	1,767	1/3.5

2.2. Similitude Law

According to the similitude law [2], the fabricated overpacks and MPCs require additional mass to properly model the actual mass of the prototype. As shaking table experiments included excitation in the three orthogonal directions, having the same bottom stress in both the scaled specimens and the prototype was a main concern in the scaling procedure [5]. The similarity law used for scaling the developed generic DSCs and the tested specimens is summarized in Table 2.2. In order to obtain the same bottom stress additional mass was placed inside the specimens. This additional mass was provided using lead units. The available lead units have typical dimensions of 300 × 300 × 50 mm and each unit weighs 519 N. The typical lead unit also contains two holes of 25 mm diameter, which were used for the units' assembly. In order to assemble the lead units together into panels, two steel plates of 12 mm thickness were used to support them, as shown in Fig. 2.2. These supporting plates were connected together using bolts or anchor rods according to the total width of the lead units. Then, these panels were placed between the inner and the outer shells of the overpack and inside the MPC.

After adding the lead panels into the scaled specimens, the cavity between the panels and the cylindrical shells of the overpack and cavities 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.

Table 2.2 Similarity law for scaled specimens.

Parameter	Notation	Dimension	Similarity Ratio		
			General Form*	N = 2.5	N = 3.5
Length	L	L	$L_s/L_p = 1/N$	1/2.5	1/3.5
Time	T	T	$T_s/T_p = 1/N^{1/2}$	0.6325	0.5345
Acceleration	a	LT^{-2}	$a_s/a_p = 1$	1	1
Angle	θ	---	$\theta_s/\theta_p = 1$	1	1
Mass	M	M	$M_s/M_p = 1/N^3$	0.064	0.023
Mass Moment of Inertia	I	ML^2	$I_s/I_p = M_sL_s^2/M_pL_p^2=1/N^5$	0.01024	0.001904
Equivalent Cross Section	A	L^2	$A_s/A_p = 1/N^2$	0.16	0.0816
Bottom Stress	σ	$ML^{-1}T^{-2}$	$\sigma_s/\sigma_p = (M_sa_s/A_s)/ (M_pa_p/A_p)=1$	1	1
Friction Coefficient	μ	---	$\mu_s/\mu_p = 1$	1	1
(*) Suffix (p) refers to generic prototype, and suffix (s) refers to scaled model specimens					

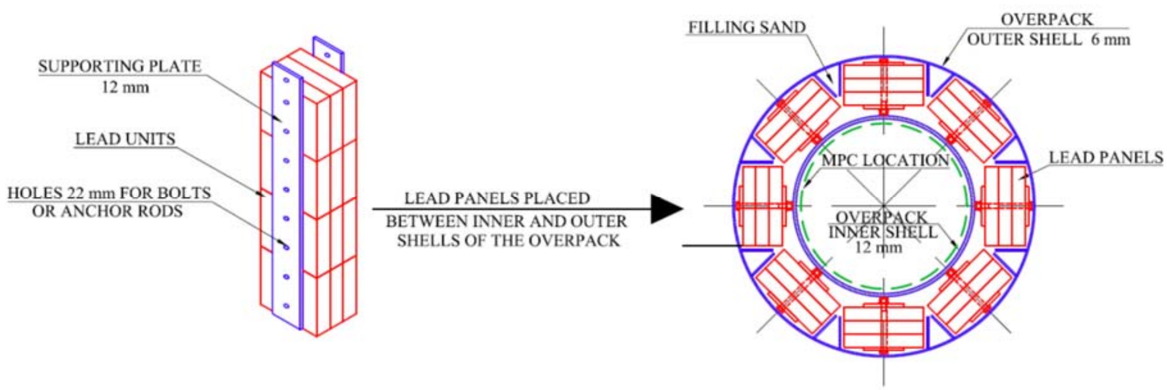
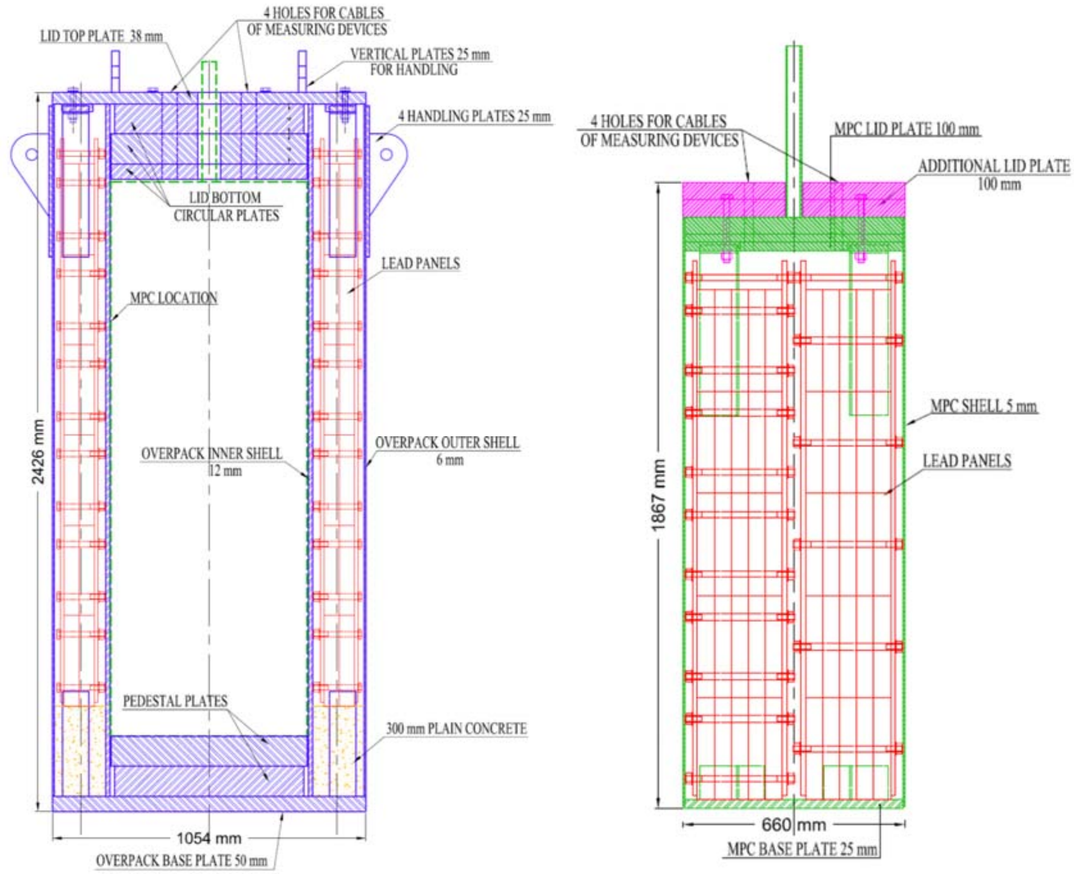


Figure 2.2 Lead panels assembled and placed between inner and outer shells of the overpack.

2.3. Design to Sustain Handling and Impact

As these chosen DSC specimens are not conventional structures, design of the scaled specimen was performed by developing finite element analysis models using LS-DYNA [6]. One model was used to check the stresses on different elements of the overpack and the MPC during handling. Handling is a critical issue due to the additional mass added by the lead assemblies. Another model was used to check the impact of the scaled cask on the shaking table during the experiments. The impact causes stress concentrations at the bottom part of the overpack outer shell, so the adequacy of the thickness of the overpack outer shell was checked to minimize the effect of such stresses. The final fabrication drawings were developed for each element of the overpack and MPC. For example, the sectional elevation of the overpack of Cask (II) and MPC are shown in Fig. 2.3 (a) and (b), respectively.



(a) (b)

Figure 2.3 Sectional elevation for (a) overpack of Cask (II) and (b) MPC.

3. EXPERIMENTAL WORK

The specimens were constructed from Grade 36 steel plates. Lead assemblies and sand were used as mass to meet scaling and similitude law requirements. Detailed instrumentation plans were prepared to capture the response of the DSC specimens during sliding and rocking. In order to maintain safety of the specimens as well as of the shaking table, an adequate safety system was developed to prevent any damage.

3.1 Instrumentation

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. 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 setup of the experiment before testing can be seen in Fig. 3.1.

3.2 Safety system for the DSCs during shaking

A safety system was developed for the DSCs on the 6 DOF shaking table to prevent excessive sliding or tipping-over of the DSCs. Four cables were connected to the handling plates of the overpack. Two cables were connected to the side reaction walls from the south and east sides, and the other two cables were connected to vertical steel columns at the north and west sides. Along each direction, the cask specimen was connected to the reaction wall from one side and to the steel column from the other side. These safety cables were designed to prevent the specimens from tipping over and damaging adjacent equipment. Also, they had sufficient sag to allow the cask to slide freely within certain limits.

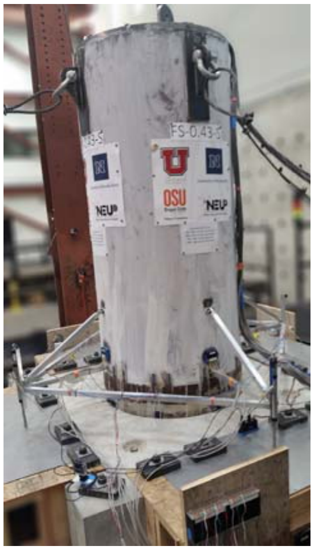


Figure 3.1 Experimental setup prior to shake table testing.

4. GROUND MOTION SELECTION

Three earthquake records were chosen for the experimental tests: San Fernando Pacoima Dam, CA (1971), Erzican, Turkey (1992), and Chi-Chi, Taiwan (1999). These ground motion 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 are shown in Fig. 4.1.

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. 4.2 for the two horizontal components of the original ground motion; 50% of the original San Fernando ground excitation in three orthogonal directions (X, Y and Z) was used for verification of the finite element model. Applying 50% of this ground motion led to the maximum capacity of the shaking table, controlled by the high impact forces during DSC rocking.

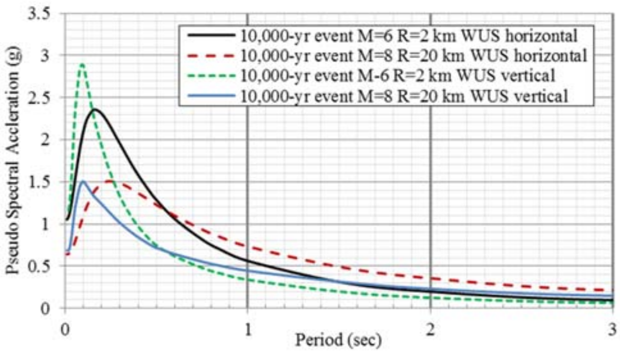


Figure 4.1 Response spectra of 10,000-year event matched to western US rock spectra in both horizontal and vertical directions.

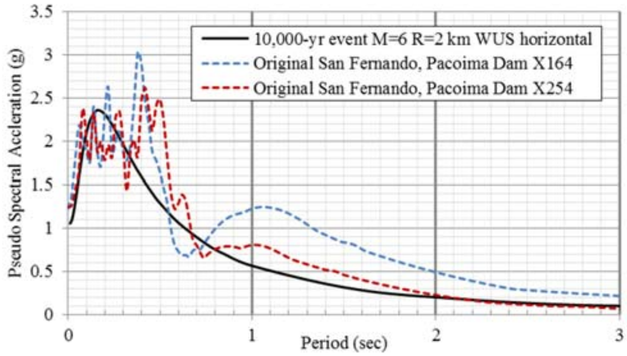


Figure 4.2 Comparison between horizontal response spectrum of the developed near field 10,000-year event and the response spectra of the original San Fernando Pacoima Dam ground motion.

5. DEVELOPED FINITE ELEMENT MODEL

Finite element models were verified using Shirai et al. [2] experimental results, as well as the experimental shaking table results for Cask (II). The finite element models were developed using LS-DYNA version R7.0.0 [6]. Several modeling parameters were used in order to obtain verification. Both models showed satisfactory correlation with experimental results.

5.1 Modeling Parameters

Assessing the rocking-sliding behavior for free standing DSCs under ground motion excitation is complex. LS-DYNA is a powerful tool to model such behavior. All parts of the models were defined as solid elements. Mesh size for the concrete pad was 100 mm × 100 mm, however, the mesh size for the cask components varies between 30 and 160 mm due to radial meshing used for the cylindrical cask. According to the experimental results, none of the components experienced any inelastic behavior, yielding or fracture. For that reason, elastic material properties were used. The contact used in order to define friction was AUTOMATIC_SINGLE_SURFACE between the cask base and concrete pad top surface [6]. Such type of contact allows users to add as much defining parameters as needed in a powerful way. The defined static and dynamic coefficients of friction were 0.7 for the Shirai et al. model and 0.5 for the Cask (II) model.

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. 5.1. 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 the test. The details of the specimen used to model Cask (II) were illustrated previously in Fig. 2.3. The applied verified shake table motion was 50% of original San Fernando Pacoima Dam ground motion.

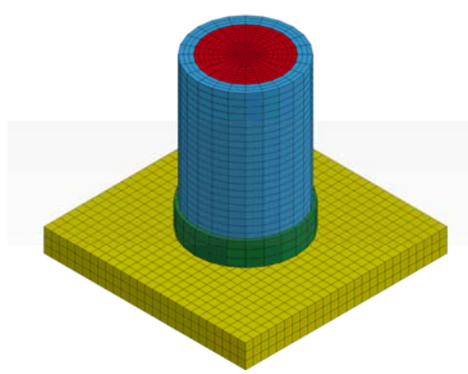


Figure 5.1 Three dimensional view of the verification model of Shirai et al. specimen using LS-DYNA.

5.2 Model Verification Results

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. [3] using ABAQUS [9]. Fig. 5.2 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. 5.3. This relation shows satisfactory correlation between the finite element verification and the Shirai et al. experimental results.

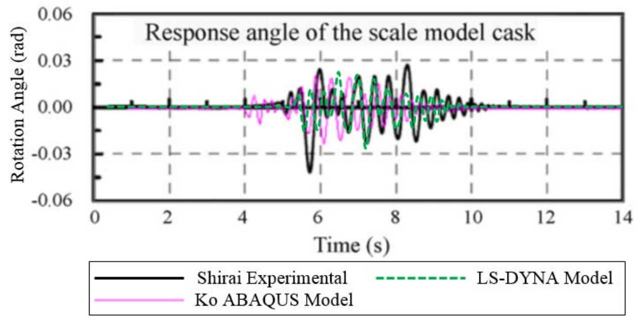


Figure 5.2 Response angle of rotation for the cask vertical axis for verified model compared to Shirai et al. experimental results and Ko et al. verification using ABAQUS.

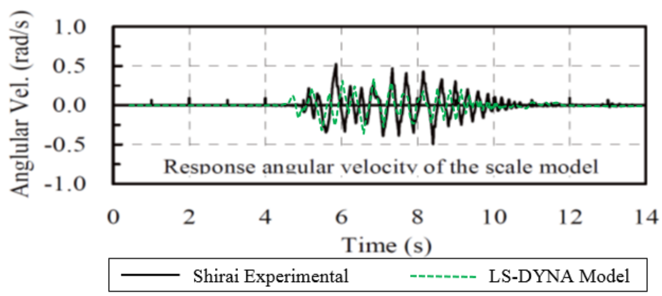
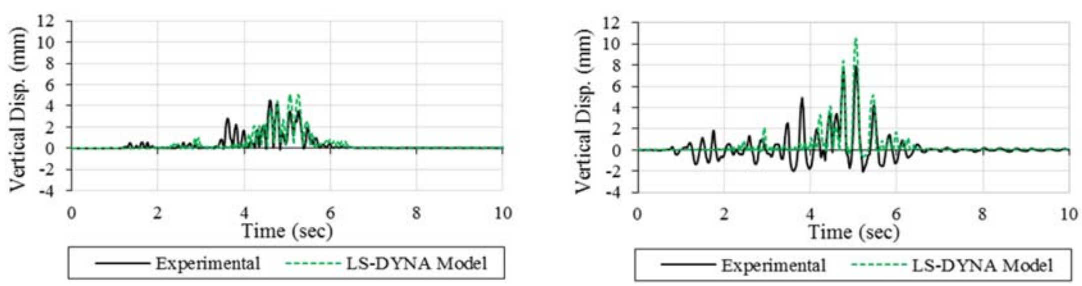


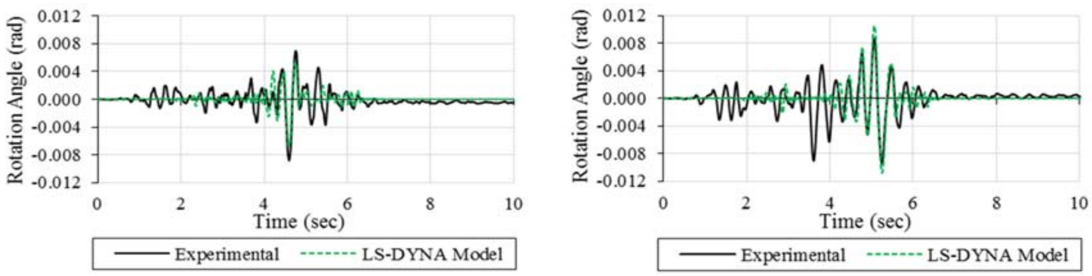
Figure 5.3 Response angular velocity for verified model compared to Shirai et al. experimental results.

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. 5.4 (a) and (b), respectively. However, there is a negative vertical displacement in Cask (II) north edge which was not obtained from the model. This negative value of vertical displacement represents 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. 5.5 (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)

Figure 5.4 Cask (II) vertical displacement response experimental results compared to LS-DYNA model results: for both (a) cask center and (b) north edge.



(a) (b)

Figure 5.5 Cask (II) vertical axis rotation angle response experimental results compared to LS-DYNA model results for both (a) X-direction and (b) Y-direction.

6. CONCLUSIONS

This study investigates the seismic performance of free standing DSCs. Experimental tests were performed on a 6 DOF shaking table. Experimental testing of DSC on a shaking table provides good understanding for the expected seismic performance. The choice of DSC specimens to cover a large portion of the current inventory depends mainly on its slenderness ($r/h_{c.g.}$). Scaling and similitude of free rocking structures is a main concern especially under vertical excitation. Using lead units for mass compensation in bulk free rocking structures like DSCs is a convenient method. Safety cables provide a dependable safety system to prevent the specimens from tipping over and damaging adjacent equipment. Design of scaled DSC specimens shall include stresses due to handling as well as impact during shaking.

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 for Cask (II) specimen using the San Fernando Pacoima Dam ground motion in three orthogonal directions showed satisfactory correlation compared to the experimental results. In addition, the developed model for the Shirai et al. specimen using the JMA Kobe ground motion in the X and Z direction presents a good correlation with the experimental results. The ability of the finite element method for modelling sliding and rocking behavior was demonstrated. Such developed models can be used to conduct further parametric studies.

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