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SLIDING AND ROCKING OF FREE STANDING DRY STORAGE CASKS UNDER EARTHQUAKE EXCITATION

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Abstract

Nuclear power components must maintain a stringent safety margin during normal operation, accident scenarios, and seismic events. 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, SNF is transferred to Dry Storage Casks (DSCs), which can be designed as free-standing structures resting on a reinforced concrete foundation. DSCs have been considered as a temporary storage solution, and are usually licensed for 20 years, although they can be relicensed for operating periods up to 60 years. In order to extend relicensing periods, the increased seismic hazard on DSCs needs to be re-examined. Thus, the main goal of this study is to evaluate the long-term seismic performance of DSCs.

To evaluate DSC 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 (UNR). During the earthquake excitation, the response of a free-standing cask was manifested as rocking, sliding, precession, nutation, or combination between any of these responses. In addition to the input motion, the response mainly depended on cask slenderness and the friction coefficient between the cask and the foundation pad. Friction is a critical parameter, but it can change significantly with time and is difficult to estimate. Slenderness of the cask affected its dynamic response, and it was calculated as the cask outer radius-to-centroidal height ratio (r/h_{cg}). Five scaled specimens were chosen to cover a range of commercially available DSCs with five different r/h_{cg} ratios of 0.39, 0.43. 0.55, 0.56, and 0.62. Eight experiments were conducted using these aspect ratios; five of them were free-standing specimens, while three experiments were anchored. Three freestanding specimens with aspect ratios of 0.39, 0.43, and 0.55 are the focus of this paper. The DSC specimens were free-standing structures on the shake table, instrumented to capture the response. Several ground motions were chosen as evaluation earthquakes. The seismic hazard for the evaluation earthquakes was developed for 1,000-, 10,000-, and 30,000-year return periods. Experimental results were not consistent during motion repetition in some cases, however, matching results were obtained in other cases. Factors affecting experimental result consistency are investigated and discussed.

LS-DYNA was used to develop a Finite Element Model (FEM) for the cask pad system, and model sensitivity was investigated in this study. The resulting FEM of the DSC showed acceptable correlation with experimental results. Several factors affecting the FEM response were considered, including: small changes in the coefficient of friction, specimen alignment relative to the center of the concrete pad, specimen centroid, damping, mesh size and type of contact. This sensitivity study was presented to provide more confidence in the developed model.

Keywords: Dry Storage Cask, Shake Table Experiment, Free-standing Structures, Non-linear Analysis.

1. Introduction

DSCs are designed to provide adequate passive heat removal, radiation shielding during normal operation, accidental scenarios and off-normal normal events [1]. Earthquakes are considered one of the major events for DSC performance, especially for relicensing periods. Most DSCs are canisterized casks that include inner and outer cylindrical shells. The outer shell is called the overpack, which is a shield used to protect the SNF from damage and prevent radiation release. The inner cylindrical container is called the Multi-Purpose Canister (MPC), and contains a honeycomb fuel basket to store SNF assemblies.

In order to obtain a seismically resilient DSC 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, however the 0.43 cask was not used for comparisons in this paper. The first specimen was MPC only and the others were canisterized casks that consist of the outer overpack and MPC. Canisterized casks were selected to study the effect of pounding between the outer and inner parts. According to similitude law, the scaled DSCs need additional mass to properly reproduce the dynamic response of the original DSCs. Free-standing DSCs were instrumented to capture the response during shake table experiments. Comparisons between DSC responses of repeated shake table experiments were performed. Experimental results were not always consistent, which led to an investigation of the factors affecting inconsistency. FEMs were developed to assess the rocking-sliding experimental response of the tested specimens. Acceptable correlations between FEM results and the experimental results were obtained. Sensitivity studies of the developed FEMs were conducted to provide confidence in the results.

Previous studies have investigated the earthquake response of rocking temple columns [2] [3], however, boundary conditions and aspect ratios are significantly different from those of DSCs. Assessing the rocking-sliding behavior for free standing DSCs is complex [4], because it is very sensitive to small changes in the size of the tested specimens and their slenderness [5]. One of the early studies of free standing response of rigid bodies was conducted by Housner in 1963 [6], a work followed by several investigations on rigid blocks [4, 5, 7]. Although not discussed in detail in this paper, a primary focus of this study was the six degree-of-freedom response of DSCs, whereas most previous studies have focused on a one or two degree-of-freedom responses [4, 5, 7].

2. Experimental Work

Two factors were considered in the fabrication of the scaled specimens used during the shake table experiments: i) selecting DSC specimen configurations to cover a wide range of commercial available DSCs, and ii) application of similitude laws to make certain that the behavior of the scaled specimens is equivalent to that of full-scale casks. The specimens were fabricated from Grade 36 steel plates. Lead assemblies and sand were used as additional mass to meet similitude law requirements [8, 9]. 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 in case of cask tip over.

Selection of the specimen dimensions was performed to cover a range of commercial DSCs as presented in NUREG/CR-6865 [10]. 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. The dimensions, weight and scale of the chosen DSC specimens are summarized in Table 1.

Table 1 – Dimensions, weight, and scale of chosen DSCs

Cask Type	**r/h_{cg}**	**Weight** (metric 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

A reinforced concrete pad was fixed to the 6DOF shake table to represent the footing supporting the DSC. 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. 1. Accelerometers were placed at the top, bottom, and middle of the overpack and MPC. A space frame, in conjunction with vertical LVDTs, was used to capture vertical displacements at the base of the specimens. In addition, eight rosette strain gauges were attached to the outer surface of the overpack to monitor stresses at the base of the outer shell overpack. The test setup of the MPC specimen is illustrated in Fig. 2.

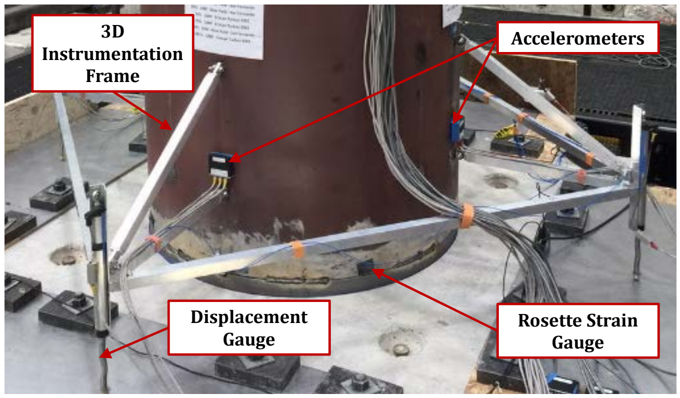


Fig. 1 – Typical bottom instrumentation for specimens

Fig. 2 – Final test setup of MPC specimen on shake table

3. Ground Motion Selection and Scaling

Three earthquake records from the PEER database [11] were chosen for the experiments: San Fernando Pacoima Dam, CA (1971), Erzican, Turkey (1992), and Chi-Chi, Taiwan (1999). Using the methods outlined in NUREG 6728 [12], standard spectral shapes were developed for the evaluation basis earthquake including appropriate rock conditions. The seismic hazard for the evaluation earthquakes was developed for 1,000-, 10,000-, and 30,000-year return periods. 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). Sixteen different ground acceleration time histories were developed at varying amplitudes for shake table testing, while the motions of interest for this paper are limited to the 1,000-yr and

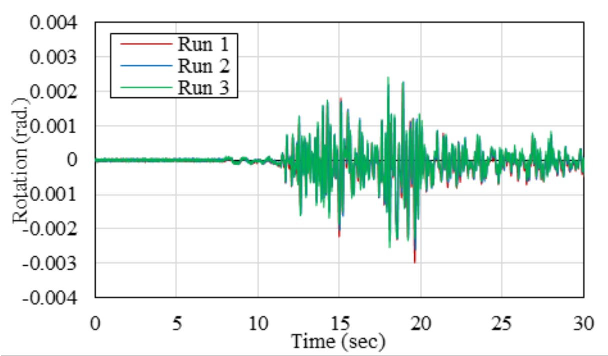
10,000-yr spectrally matched Chi-Chi, Taiwan (1999) and 10,000-yr spectrally matched Erzican, Turkey (1992), as shown in Table 2.

Table 2 – PGAs for matched motions considered in this study

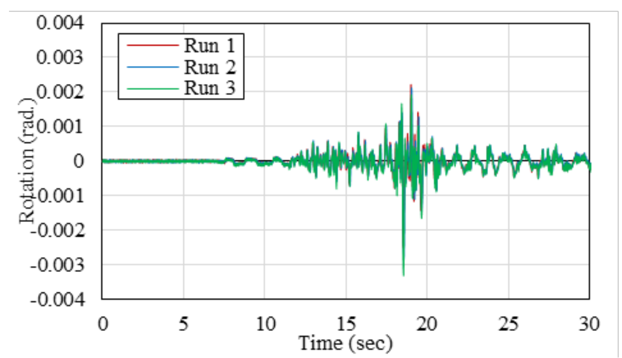
Earthquake	Year	Station	Spectrum Return Period	Scale	Matched PGAs (g)			Set #	Cask Type
					X	Y	Z		
Chi-Chi	1999	CHY 101	1,000-yr	100%	0.269	0.268	0.286	I	Cask (I)
Chi-Chi	1999	CHY 101	10,000-yr	75%	0.638	0.640	0.681	II	MPC
Erzican	1992	Erzican	10,000-yr	75%	0.761	0.930	0.673	NA	MPC

4. Consistency of Experimental Results

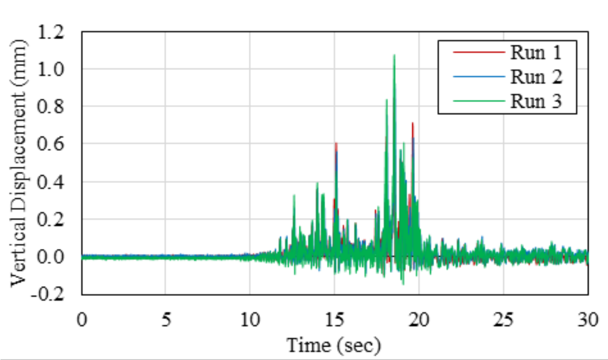
Due to a lack of consistency between repeated experimental results, a comparison between two sets of repeated motions were conducted. Set (I), Cask I with r/h_{cg} of 0.55 was subjected to Chi-Chi, Taiwan (1999) matched to far field 1,000-year event response spectrum. Set (II), MPC with r/h_{cg} of 0.39 was subjected to 75% of Chi-Chi, Taiwan (1999) matched to far field 10,000-year event response spectrum. Both sets were repeated three times on the shake table under the same input motions presented in Table 2. Experimental results for Set (I) and Set (II) are shown in Fig. 3 and Fig. 4, respectively. These experimental results include the response angle of rotation for the specimen's vertical axis in both X and Y directions, the vertical displacement of the cask center in addition to the horizontal displacement in the X direction. The results of Set (I) are relatively consistent, except for the approximately 0.5 mm variations in the displacements in X-direction, while the results of Set (II) are more inconsistent. The relative roughness between different points on the concrete pad supporting the specimen as well as the shake table capability of applying the exact same ground motions over a specific frequency range are likely influencing these results.



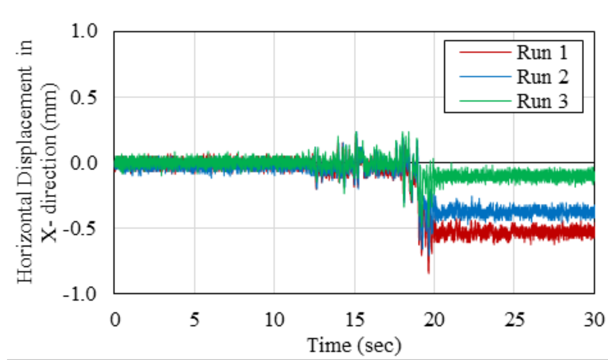
(a) Response angle of rotation for Cask I vertical axis in X-direction



(b) Response angle of rotation for Cask I vertical axis in Y-direction

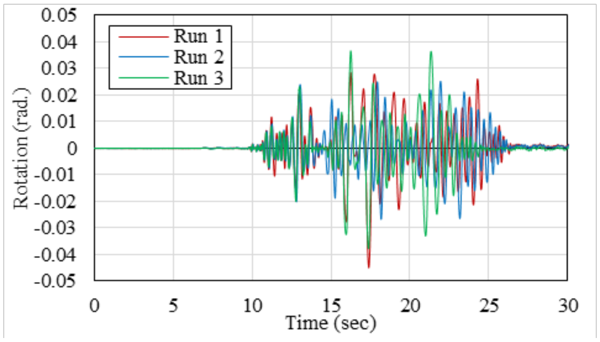


(c) Vertical displacement response for Cask I center

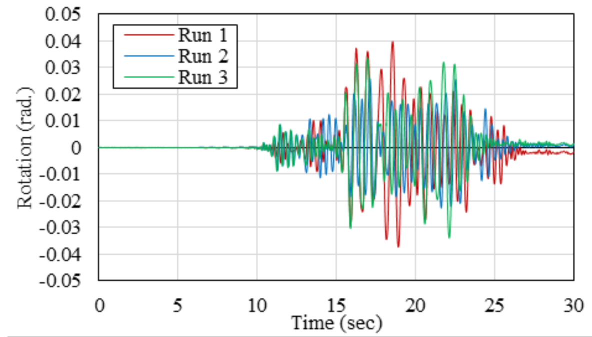


(d) Horizontal displacement response for Cask I in X-direction

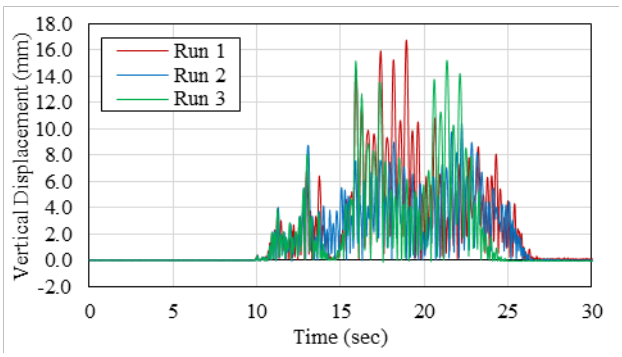
Fig. 3 – Experimental results for Set (I) repeated motions



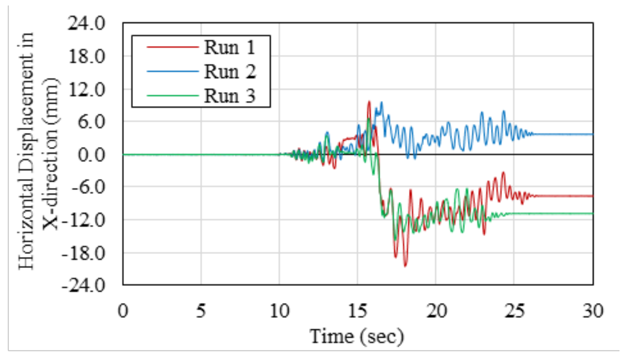
(a) Response angle of rotation for MPC vertical axis in X-direction



(b) Response angle of rotation for MPC vertical axis in Y-direction



(c) Vertical displacement response for MPC center



(d) Horizontal displacement response for MPC in X-direction

Fig. 4 – Experimental results for Set (II) repeated motions

4.1 Effect of surface roughness

Friction is a critical parameter that can change significantly at different timesteps of the ground motion and is difficult to estimate. The response of a free-standing structure to ground accelerations is dependent on the friction coefficient between the structure and the supporting system. Concrete is a non-homogeneous material, which leads to varied friction values at different points of any concrete surface. Such differences can be neglected in the case of an isotropic homogeneous surface however, this effect is considerable in a complex free-rocking system. The effect of minor changes in friction will be discussed using FEMs in the following section.

Several factors affect the surface layout of the concrete pad starting from roughness at each point to the global waviness of the surface. The elevation of various points of the top surface of the concrete pad were measured, as shown in Fig. 5. A grid of 150 mm was created and the elevation of each point was obtained relative to the lower left corner of the grid. The maximum difference between two points was 5.5 mm. Small imperfections in the concrete pad caused these slight differences in elevation, which can change the response of a cylindrical free-rocking structure. At a certain instant of the rocking motion the cylindrical specimen is supported on one point of contact with the concrete pad. Any change of friction or irregularities at this point of contact can affect the response. This difference in elevation between different points clarifies the waviness that existed in the tested concrete pad, which is considered as one of the reasons for the difference in results between the different runs. The variations in elevation within the concrete pad will be smaller than the variations of the in-situ pad due to their sizes. This uncertainty is a factor that cannot be reduced using current reinforced concrete pad construction methods. In addition, Set (I) has lower response results relative to Set (II), which may be the cause of magnification in the inconsistency of the results within the runs in Set (II) over the runs in Set (I).

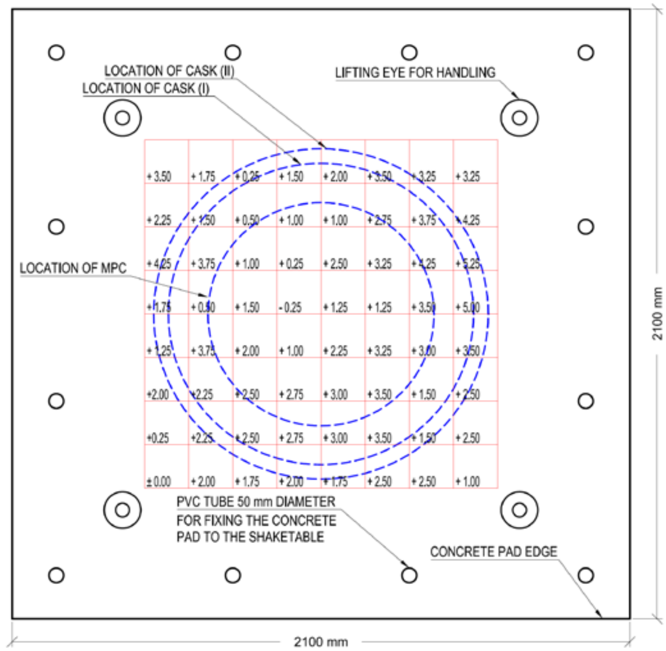
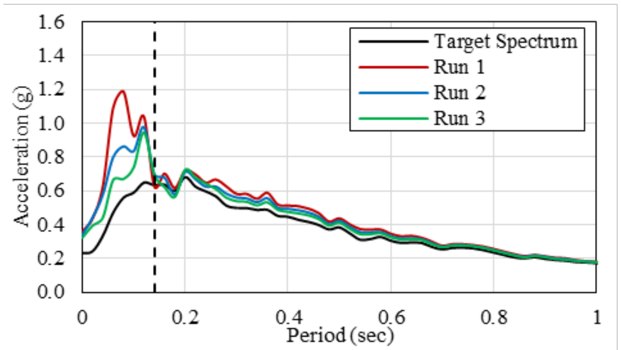


Fig. 5 – Elevation of grid points for top surface of tested concrete pad

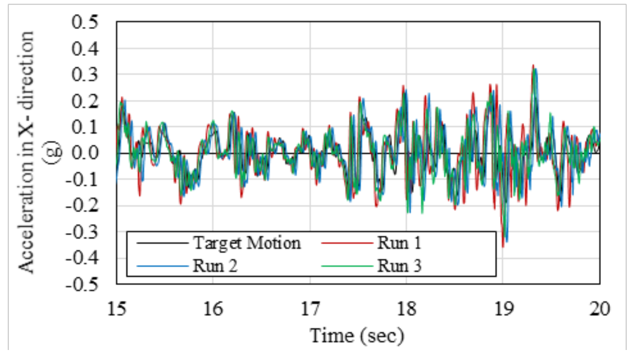
4.2 Shake table response

The six degree-of-freedom shake table at the UNR consists of four vertical and four horizontal actuators that are connected to a rigid table surface. While applying ground acceleration histories, the actuators try to match the referenced input motion. However, several factors affect the actual shake table performance such as: damping of table components, reaction of tested specimen to excitation, and impact between specimen and the concrete pad during testing. The impacts during testing of a free rocking structure are one of the main concerns in testing DSC specimens. Small vertical displacements can cause large impact forces, leading to differences between the referenced input motion and the actual shake table performance. To evaluate these discrepancies, response spectra and acceleration time histories are plotted in Fig. 6 and Fig. 7 for Set (I) and Set (II), respectively. The spectra clarify the difference between the input target motion and the resulting shake table output, while the acceleration histories show similar trends with small variations in amplitude. The main differences between the spectra curves with Set (I) and Set (II) are in the high frequency (i.e., short period) region, and have a small effect on the input vibration characteristics affecting the cask response. The casks will not be significantly affected by these differences, because although the cask vibrational periods vary during the time history, they will be longer than the rest period indicated with a vertical dotted line in the spectra plots of Figs. 6 and 7. Acceleration time histories have been clipped in Figs. 6 and 7 to illustrate the variation within repeated motions.

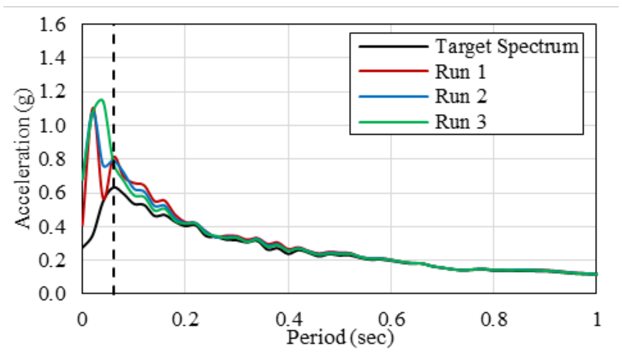
To illustrate the difference between Set (I) consistent results and Set (II) inconsistent results, the vertical and horizontal periods of the specimens were calculated at rest. Before starting any shake table experiments, the specimen is subjected to low amplitude white noise ground motions. From the white noise, the dominant periods for the specimens at rest were obtained using Fast Fourier Transformation (FFT). The horizontal and vertical periods for Set (I) were 0.14 sec and 0.06 sec, respectively. However, the horizontal period was 0.165 sec and vertical period was 0.042 sec for Set (II); as indicated by the vertical dashed lines in Figs. 6 (a, c) and 7 (a, c). These vibrational periods are not the specimen periods during testing, because once rocking initiates, the natural period changes as the rocking and rotation angle change. Obtained natural periods at rest represent the static periods of the structure, which affects initiation of motion. Figures 6 (b, d) and 7 (b, d) show that acceleration time histories for the two sets are very similar. Figures 6 (a, c) and 7 (a, c) show the high frequency content of the ground motion differs slightly between repeated runs. Figure 6 (a, b) shows similar frequency content between the rest period of the specimen and the excitation frequencies, while Fig. 7 (a) shows a slight difference in excitation frequencies when compared to rest frequencies. An observation made was that more consistent results occurred when the frequency content of the repeated motions coincides with the specimen frequency at rest. On the other hand, Set (I) has lower response results relative to Set (II), which may be the reason that the results of Set (I) are more consistent than those of Set (II).



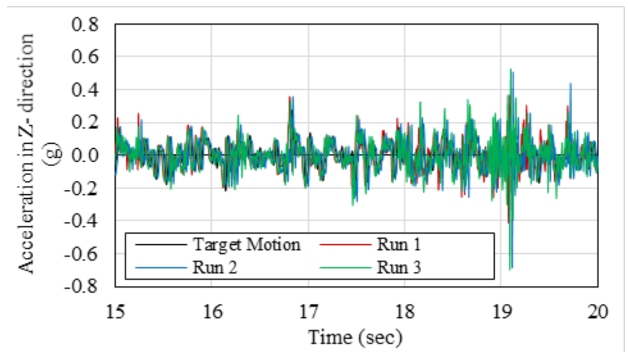
(a) Response spectrum X-direction



(b) Acceleration history in X-direction

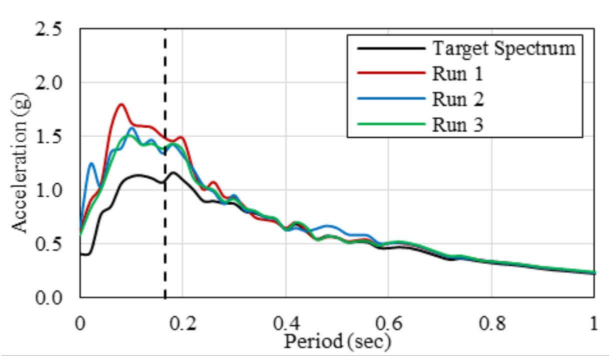


(c) Response spectrum Z-direction

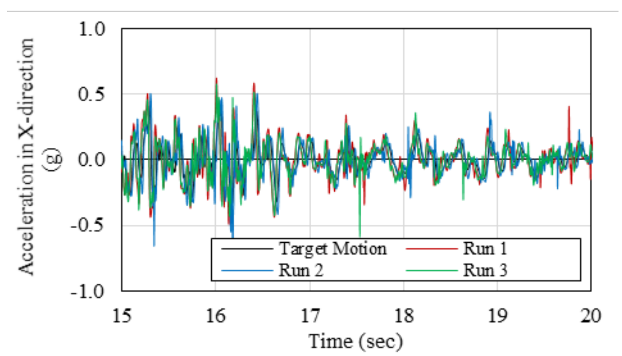


(d) Acceleration history in Z-direction

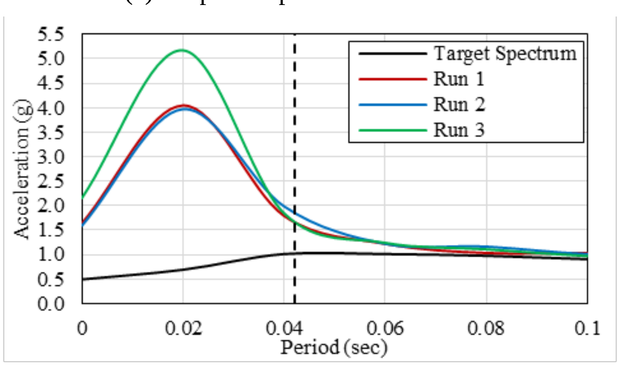
Fig. 6 – Response spectra and accelerations histories in the X and Z-directions for repeated motions of Set (I)



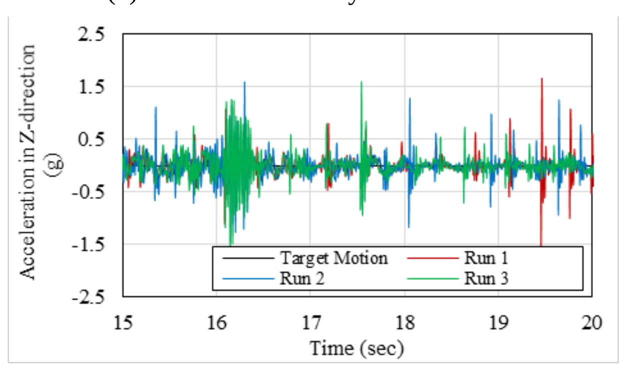
(a) Response spectrum X-direction



(b) Acceleration history in X-direction



(c) Response spectrum Z-direction



(d) Acceleration history in Z-direction

Fig. 7 – Response spectra and accelerations histories in the X and Z-directions for repeated motions of Set (II)

5. Finite Element Modeling

FEMs were verified using shake table experimental results. LS-DYNA version R7.0.0 [13] was utilized to develop this verification. Several modeling parameters were used to obtain satisfactory correlation with experimental results. Many trials were conducted to reach acceptable results due to problem complexity. One of the reasons for complexity is that minor changes in the boundary conditions, applied motion, properties or shape of the structure affect the specimen responses due to the nonlinear nature of the problem [5][14][15]. Also, the coefficient of friction, which is difficult to model and determine, is one of the most influential factors affecting rocking motion [16].

LS-DYNA is a powerful tool for modeling rocking-sliding behavior of structures. All parts of the models were defined as solid elastic elements. Mesh size for the concrete pad was 100 mm × 100 mm; however, the mesh size for the cask components ranged between 30 and 160 mm due to the radial meshing used for the cylindrical cask. According to the experimental results, none of the components experienced inelastic behavior. For that reason, elastic material properties were used. The contact used to define friction was AUTOMATIC_SINGLE_SURFACE between the cask base and concrete pad top surface [13]. Such type of contact allows users to add as many defining parameters as needed. Several damping values have been defined in the model including: contact damping, global damping as well as a scale factor for vertical damping to consider impact and the coefficient of restitution.

5.1 Model verification

MPC specimen results were used for model verification. The dimensions of the tested specimen were presented in Table 1. The MPC specimen with r/h_{cg} of 0.39, subjected to 75% of Erzican, Turkey (1992) ground motion matched to near field 10,000-year event response spectrum, was used for FEM verification. An extruded view of the developed finite element LS-DYNA model is shown in Fig. 8. For specimen model verification, several numerical results were compared to experimental data collected during shake table testing. A comparison between LS-DYNA and experimental results for the north edge, south edge and center of base vertical displacements is illustrated in Fig. 9 (a), (b) and (c), respectively. Note that there is a negative vertical displacement in MPC north and south edges, which was not captured in the model. This negative value of vertical displacement very likely represents the uneven surface of the concrete pad, where the maximum difference in the level between different points on the concrete surface was only 3 mm within the limit of the MPC base, as illustrated in Fig. 5. Fig. 10 (a) and (b) present the response angle of rotation for MPC about the vertical axis compared to experimental results for the X and Y direction, respectively. The vertical displacement time histories and rocking angle time histories follow the same trends with only differences in the amplitudes. These results show a reasonable correlation between the experimental data and LS-DYNA model results.

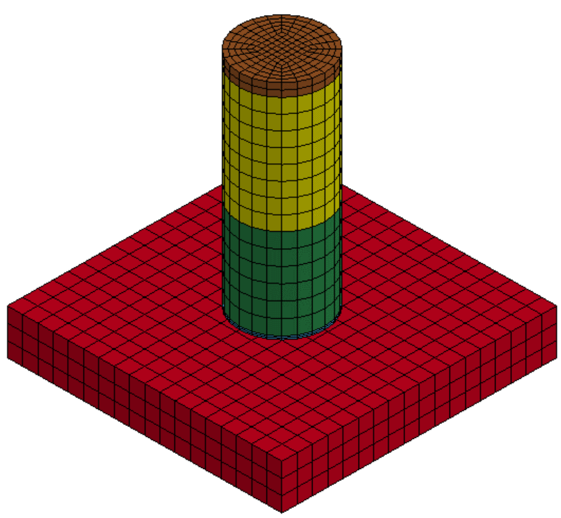
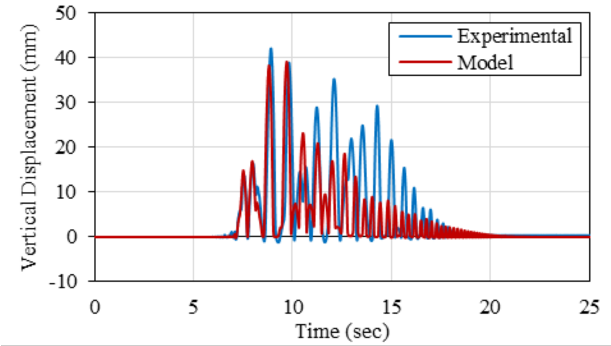
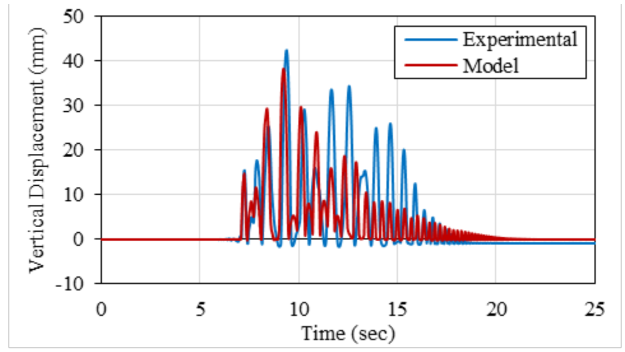


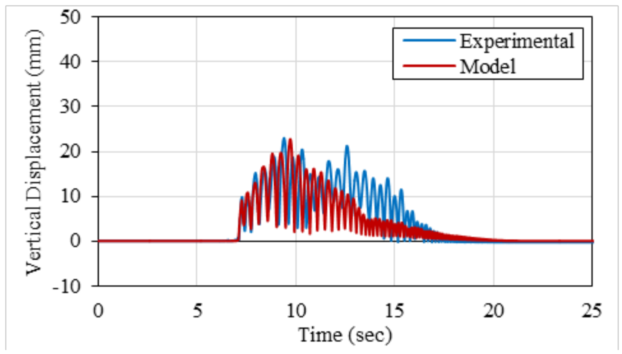
Fig. 8 – Extruded view of the verification model of MPC specimen using LS-DYNA.



(a) North Edge

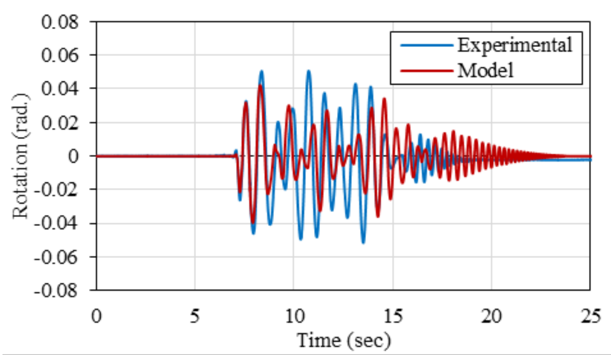


(a) South Edge

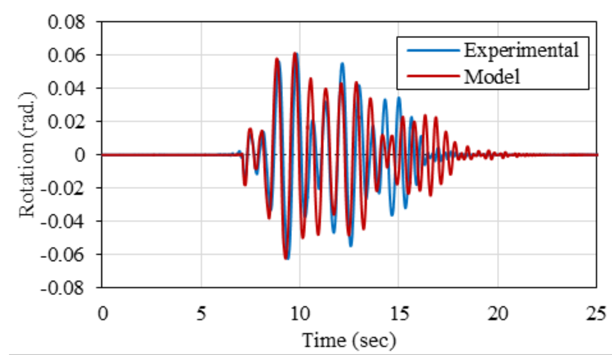


(c) Center

Fig. 9 – MPC vertical displacement response experimental results compared to LS-DYNA model results for 75% of Erzican, Turkey (1992) ground motion matched to near field 10,000-year event response spectrum.



(a) X-direction



(b) Y-direction

Fig. 10 – MPC vertical axis rotation angle response experimental results compared to LS-DYNA model results for 75% of Erzican, Turkey (1992) ground motion matched to near field 10,000-year event response spectrum.

5.2 FEM model sensitivity

Sensitivity studies of the developed FEMs were conducted to provide confidence in the results. Several parameters affect the output response of the finite element model including the friction coefficient, specimen alignment relative to the center of the concrete pad, specimen centroid, damping, mesh size and type of contact. The first two parameters are the scope of this study. Several coefficient of friction values (μ) were used during model verification. The relation between the implemented μ and the ratio between maximum model output to maximum experimental results of the MPC are presented in Fig. 11. The figure includes vertical displacement at different points of the specimen base (north, south, east, west and center) and the maximum rotation in both X and Y directions.

A coefficient of friction from 0.55 to 0.6 nearly matches the experimental results by obtaining a ratio between model/experimental results that is nearly equal to 1.0; the response is different with each coefficient of friction. For illustration of the variation of the model output with different coefficients of friction (0.550, 0.575, 0.580 and 0.600), the response angle of rotation for MPC about the vertical axis for the X and Y direction is presented in Fig. 12 and Fig. 13, respectively. These figures show that a minor change of the coefficient of friction from 0.575 to 0.580 (0.86% variation) can change the response significantly.

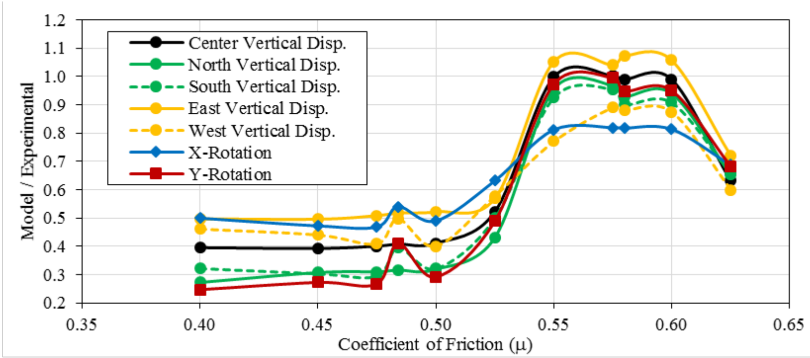


Fig. 11 – Relation between implemented μ and the ratio between maximum model outputs to maximum experimental results of the 0.39 cask.

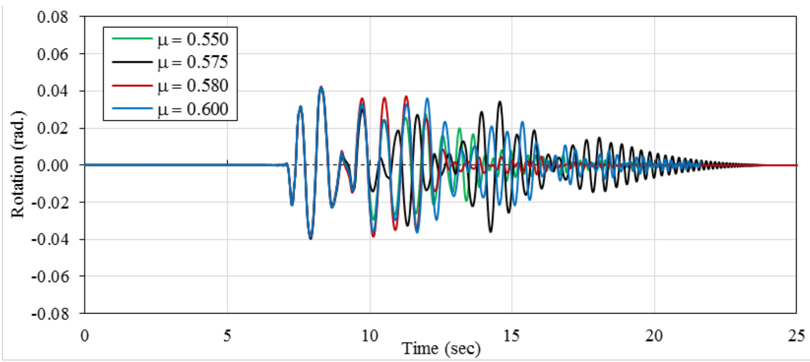


Fig. 12 – MPC LS-DYNA model vertical axis rotation angle response for different values of μ in X-direction.

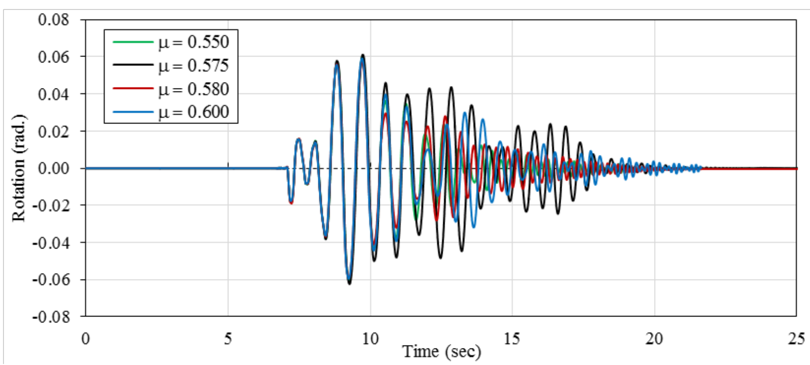


Fig. 13 – MPC LS-DYNA model vertical axis rotation angle response for different values of μ in Y-direction.

The second parameter investigated for model sensitivity was the location of the specimen relative to the center of the concrete pad. During rocking of free-standing bodies, the point of rotation is one of the main parameters that affects the response. The response of a free rocking cylinder can be rocking, sliding, precession, nutation or combination between any of these responses. To study the effect of specimen location, four models were developed from the verified model of the MPC. These models were modified by shifting the specimen from the center of the concrete pad 25 mm in the north, south, east and west direction, which is approximately 3.8% of the specimen diameter. While this seems to be a minor change, a significant change in the response was obtained, as shown in Fig. 14 and Fig. 15 for the vertical axis rotation angle response in the X and Y direction, respectively.

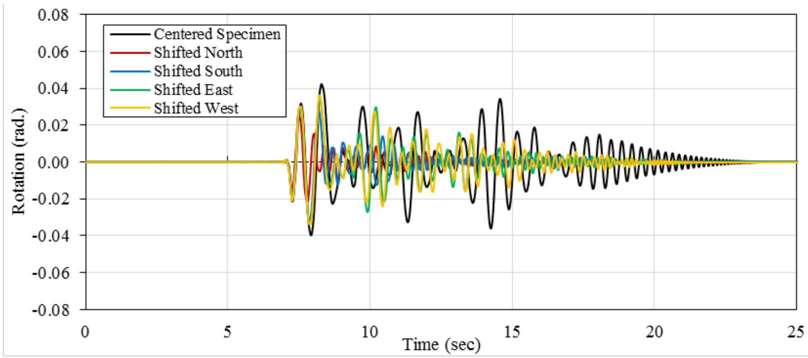


Fig. 14 – MPC LS-DYNA model vertical axis rotation angle response in X-direction for shifted specimens

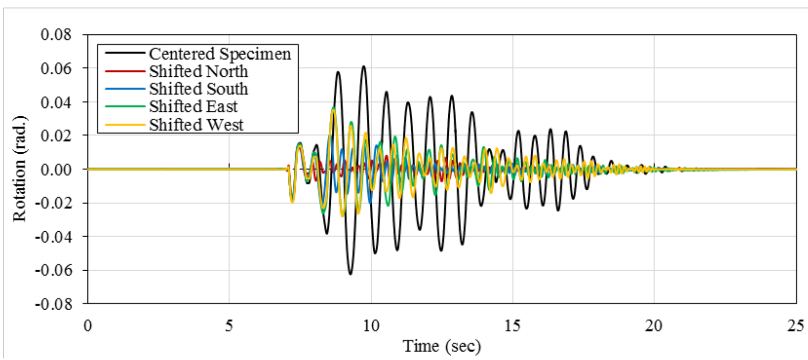


Fig. 15 – MPC LS-DYNA model vertical axis rotation angle response in Y-direction for shifted specimens

6. Discussion and Conclusions

This study is part of a research project investigating the seismic performance of free standing and anchored DSCs. This paper focuses on experiments of free standing DSCs performed on the UNR 6DOF shaking table. Experimental results exhibited different levels of variation when repeating the same input motion. To highlight the problem, a comparison between two sets of repeated motions was conducted. A three-dimensional model of a cask-pad system was developed using LS-DYNA, and experimental results were used to validate the FEM. The LS-DYNA model showed satisfactory correlation compared to the experimental results. Sensitivity or inconsistency of the results from both experimental and analytical results was obtained. The reasons of this inconsistency can be partially illustrated as follows:

I. A slight change in the coefficient of friction leads to a significant change in the response of a free rocking body. This was confirmed analytically by applying a minor change in the developed finite element model, which led to a different response. In addition, the waviness of the surface and non-homogenous nature of the concrete impacted the experimental results.

II. From the response spectra of the shake table output feedback, the generated ground motions cannot be considered as identical excitations, due to several factors affecting the shake table feedback especially the impact of cask specimens with the concrete foundation pad.

III. The location of the tested specimens relative to the center of the concrete pad affects the resulting response, which was explained by shifting the developed model in the north, south, east and west directions. In each case a different response was obtained.

The three previously mentioned parameters show that freestanding DSCs are extremely sensitive to initial conditions in both experimental and numerical studies. While the actual response cannot easily be obtained analytically, the developed LS-DYNA model can be considered acceptable to assess the performance or investigate the effect of certain parameters on the general performance due to the sensitivity and nonlinear nature of the system.

7. Acknowledgements

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