Experimental Seismic Response of Scaled Storage Containments under Identical Loading Conditions - 16318

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ABSTRACT

Dry Storage Casks (DSCs) store spent nuclear fuel (SNF), usually at sites contiguous to nuclear power plants known as Independent Spent Fuel Storage Installation (ISFSI). DSCs have been considered as a temporary storage solution, and are usually licensed for 20 years, which can be extended up to an operating periods of 60 years. Recently, however, DSCs have been considered as a potential mid-term solution for hundreds of years. This consideration requires reevaluation of DSC performance under a larger seismic hazard. That leads to larger horizontal and vertical accelerations.
This study is a part of a research project evaluating the seismic response of free-standing DSCs under long return period seismic events. This article assess whether the response of free-standing structures under seismic excitation is repeatable. For this purpose, experimental tests were conducted using a six degree-of-freedom (6DOF) shake table. During the experimental tests, several ground motions were repeated multiple times to obtain the dynamic response under identical loading conditions. Scaled casks of four aspect ratios (radius to centroidal height ratio, r/h_{cg}) were studied: 0.39, 0.43, 0.55 and 0.62. The specimens studied are considered to be 1:2.5 and 1:3.5 scaled model of generic prototype casks. The experimental results show that a small change in initial conditions leads to change in the boundary condition of moving bodies and in combination with acceleration being applied at different frequencies contained within the applied ground motions may lead to a large variation in the response.

INTRODUCTION

Dry Storage Casks (DSCs) store spent nuclear fuel at sites contiguous to nuclear power plants (NPPs), known as Interim Spent Fuel Storage Installations (ISFSIs). DSCs have been considered as a temporary storage solution, and usually are licensed for 20 years, although they can be relicensed for operating periods up to 60 years. Recent code changes allows maximum operating periods up to 80 years. The suspension of the licensing process of the geologic repository at Yucca Mountain has triggered a re-evaluation of DSCs as a potential mid-term solution, in which the operating period may be extended for up to 300 years. Although there is no current requirement to change the compliance period for storage facilities, this study considers the possibility of extended storage. Consideration of DSC longer compliance period results in larger accelerations, and larger vertical-to-horizontal spectral acceleration ratios, which could have a destabilizing effect on cask response. In addition, aging mechanisms deteriorate the mechanical properties of the DSCs components reducing their capacity to withstand external events, such as impacts caused by sliding or tipping over during earthquakes; these mechanisms are not part of the scope of this paper.

The problem of free-standing body's response subjected to horizontal support motion was first characterized by Housner [1]. After Housner, several studies have been carried out on rigid blocks [2]–[7]. Most of these studies simplify the problem by focusing only on pure rocking planar rigid bodies (two dimensional blocks, 2D). It has been shown that even for the simplified 2D rocking problem, the dynamic response of these blocks is highly complex, resulting in a non-linear and sensitive phenomenon. Yim et al. [4] suggested that responses of an object (even for rocking only motion) may deviate with minute changes in the system parameters or excitation details. This finding was confirmed experimentally by Aslam et al. [2]. They show that depending on certain system and excitation parameters, the experiments were not repeatable. This lack of repeatability was also mentioned in similar studies [8]–[10].

Very few studies consider both sliding and rocking mechanisms [5], [6] and [13]. It can be seen that when rocking and sliding occurs, the response becomes very complex even for 2D rigid block type structures. Jeong et al. [11] carried out a numerical investigation on the effect of sliding, in addition to rocking, on the response of free standing planar bodies, concluding that sliding induces chaotic response in a rocking system. Recent experimental tests on free-standing blocks [12], [13] also indicate that the dynamic response under random ground motions are not repeatable.

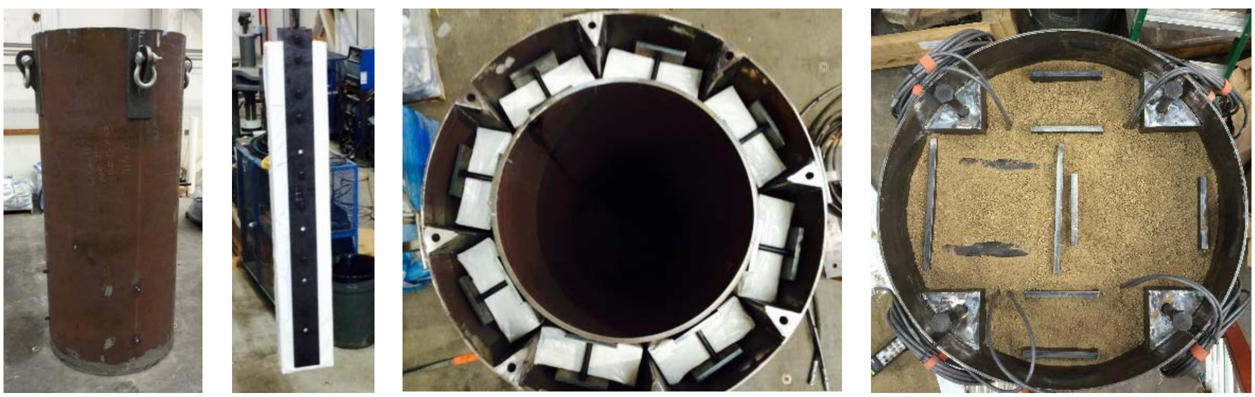
While most of these previous study focuses on rigid "block" type structure, this study addresses cylindrical free-standing bodies that are more likely to exhibit a chaotic response, especially when the system rocks, slides and tumbles along its edge. This study presents the experimental results of scaled free-standing DSC prototypes tested in a 6-degree-of-freedom (DOF) shake table, which are used to investigate the repeatability of their response under identical random ground motions.

DESCRIPTION OF EVALUATED SYSTEM

DSC Characteristics

To study the two main response modes (i.e., sliding and rocking) of freestanding casks, two DSC scaled prototypes with different aspect ratio (radius-to-centroidal height, r/h_{cg}) of 0.55 (Cask I) and 0.43 (Cask II) were used in this project. The slender cask with r/h_{cg} = 0.43 is expected to exhibit rotational displacements, whereas the squat cask with r/h_{cg} = 0.55 is more likely to show sliding displacements. Note that these selected caks aspect ratios correspond to the lower bound and average aspect ratios of Nuclear Regulatory Commission (NRC) approved casks [14]. However, the detailed dimensions of the overpack and multi-purpose canister (MPC) do not correspond to commercially available casks. The experimental DSC prototypes are 1:2.5 scaled models of generic DSCs (Fig. 1a) due to physical constrains of the 6- DOF shake table. Thus, the similarity law [15] was used to select the input parameters that define the dynamic response of the scaled casks (TABLE I). Lead units (Fig. 1b) were used to fill the overpack cavity and the canister (Figs. 1c and 1d) to compensate for the additional mass necessary to satisfy the similitude law. To prevent pounding of the lead units and the cylindrical shell, the leftover space of MPC and overpack cavity was filled with sand. TABLE II presents MPC and overpack dimensions for the squat and slender casks. Fig. 2 shows sectional elevation of Cask II overpack.

Two additional specimens of aspect ratio 0.39 and 0.62 were also tested (TABLE II). The first specimen was considered to be scaled at 1:3.5 and included only the MPC Cask I (Cask I-M). The second specimen was the empty overpack of Cask I, without additional (Cask I-O). Cask I-O was not considered to be confirming to any particular scale, however it was tested under ground motions with time step scaled to that of 1:3.5. These two specimen represents practical lower and upper bounds for free-standing cask's aspect ratio. Also, larger input accelerations can be applied during testing because of their relative light weight.



(a) (b) (c) (d)

Fig. 1. (a) Cask II's Overpack, (b) Assembly of Lead Units in One Panel, (c) Overpack Cavity Filled with Lead, and (d) MPC Filled with Lead and Sand

TABLE I. Similarity Law for Scaled Specimens

Parameter	Notation	Dimension	Similarity Ratio		
			General Form[a]	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	$M_s/M_p = \alpha(1/N^3)$	0.16	0.0816
Mass Moment of Inertia	I	ML^2	$I_s/I_p = M_sL_s^2/M_pL_p^2 = \alpha(1/N^5)$	0.0256	0.0067
Equivalent Cross	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

[a] Suffix (p) refers to generic prototype, and suffix (s) refers to scaled model specimens
α = correction factor = N

Ground Motions

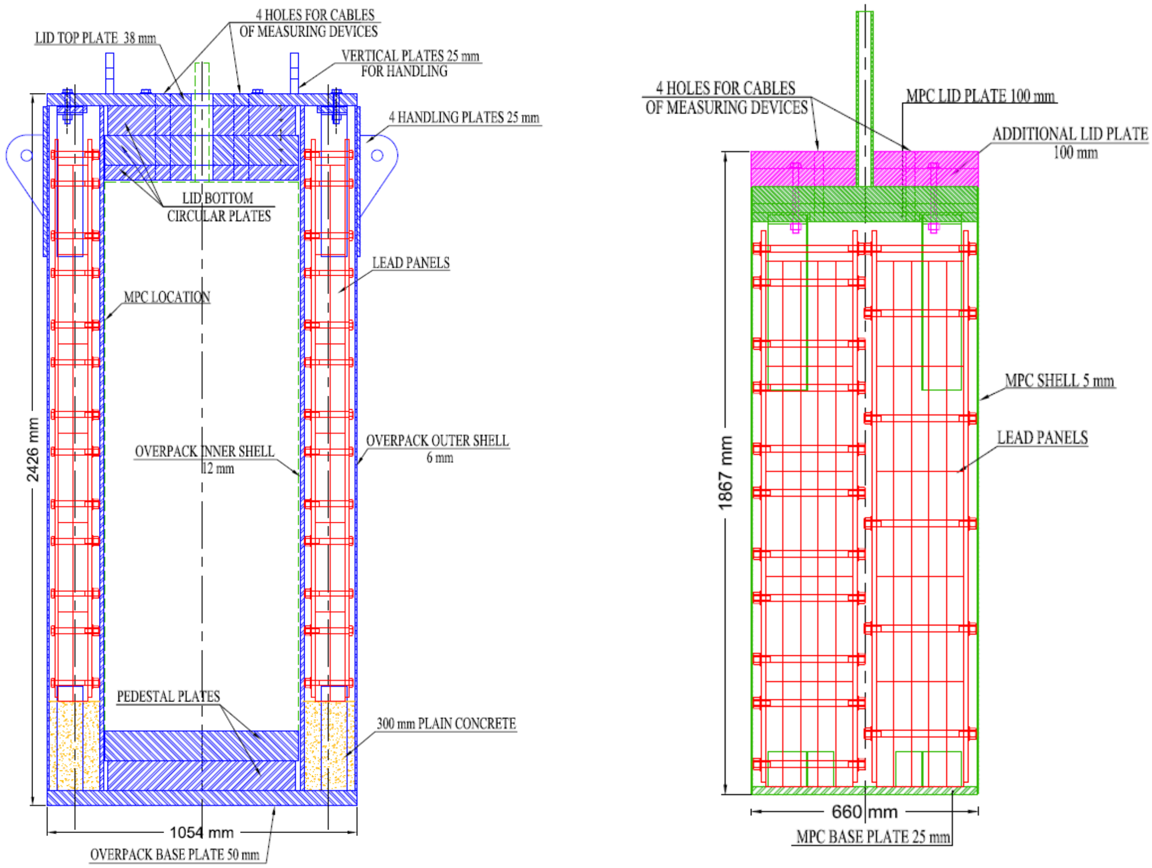
For a 20-year compliance period, ISFSIs are usually designed for a Design Bases Earthquake (DBE) associated to a return period, $T = 2{,}000$ years [16], corresponding to a probability of exceedance $\upsilon = 1/T = 1/\ 5 \times 10^{-4}$/year. To obtain the probability of exceeding the DBE in 20 years (probability of occurrence), a Poisson distribution can be used [17]:

$$P(x > 0) = 1 - P(x = 0) = 1 - e^{-\upsilon t} \qquad \text{(Eq. 1)}$$

In (Eq. 1), t is time in years, and υt is the expected number of occurrences in a given interval. Then, the probability of exceeding the DBE $[P(x > 0)]$ in 20 years is 1%. To obtain the same probability of occurrence of 1% in 300 years, (Eq. 1) indicates that a return period $T \geq 29{,}850$ years needs to be considered in the calculations ($\upsilon \leq 3.3 \times 10^{-5}$/year)[18]. For this reason, the ground motion records used in the study were spectrally matched to earthquake events of 10,000 and 30,000 year return periods[19], [20]. This paper only presents the results for 10,000 year events. TABLE III presents the ground motions used as input for the test and PGA for each at respective return period. Fig. 3 presents the target response spectra of the three return periods for Western US rock. The original San Fernando Pacoima Dam ground motion records were also included in the testing without any spectral matching process. Figs. 4 and 5 show the time histories for spectrally matched motions (10,000 year return period) and original San Fernando earthquake, respectively.

TABLE II. Dimensions of 1:2.5 Scaled Casks

DSC Specimen	Component	Diameter (mm.)	Height (h, mm.)	Weight (ton)	Scale (1:N)
Cask I (r/h_{cg} = 0.55)	MPC	660	1765	4.8	1:2.5
	Overpack	670 (inside) 1156 (outside)	1786 (cavity) 2223 (total)	11.96	
Cask II (r/h_{cg} = 0.43)	MPC	660	1867	5.05	1:2.5
	Overpack	670 (inside) 1054 (outside)	1880 (cavity) 2426 (total)	9.72	
Cask I-M (r/h_{cg} =0.39)	MPC	660	1765	4.8	1:3.5
Cask I-O (r/h_{cg} = 0.62)	Empty overpack only	1156 (outside)	2223 (total)	3.39	1:3.5

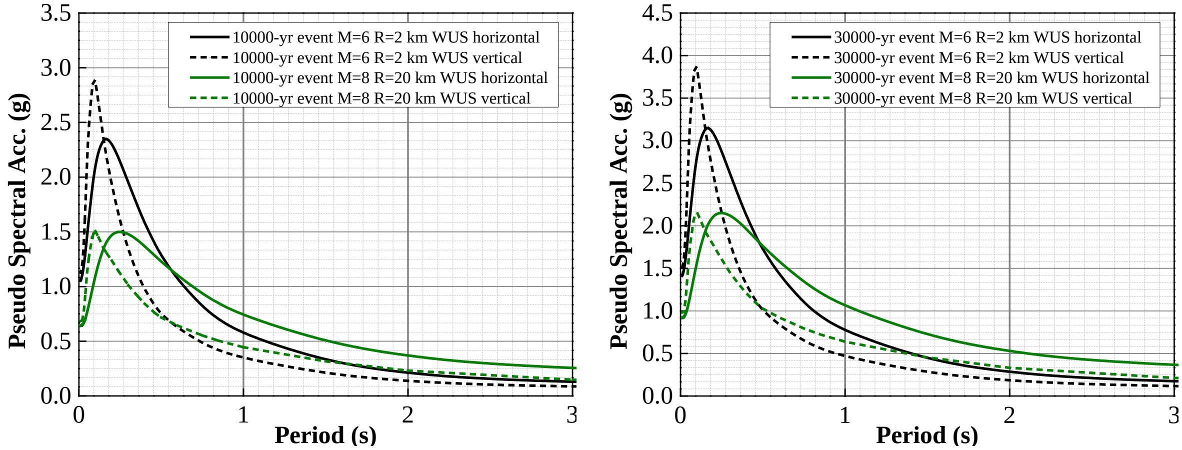


(a) (b)

Fig. 2. Sectional Elevation (a) Overpack of Cask II, (b) MPC

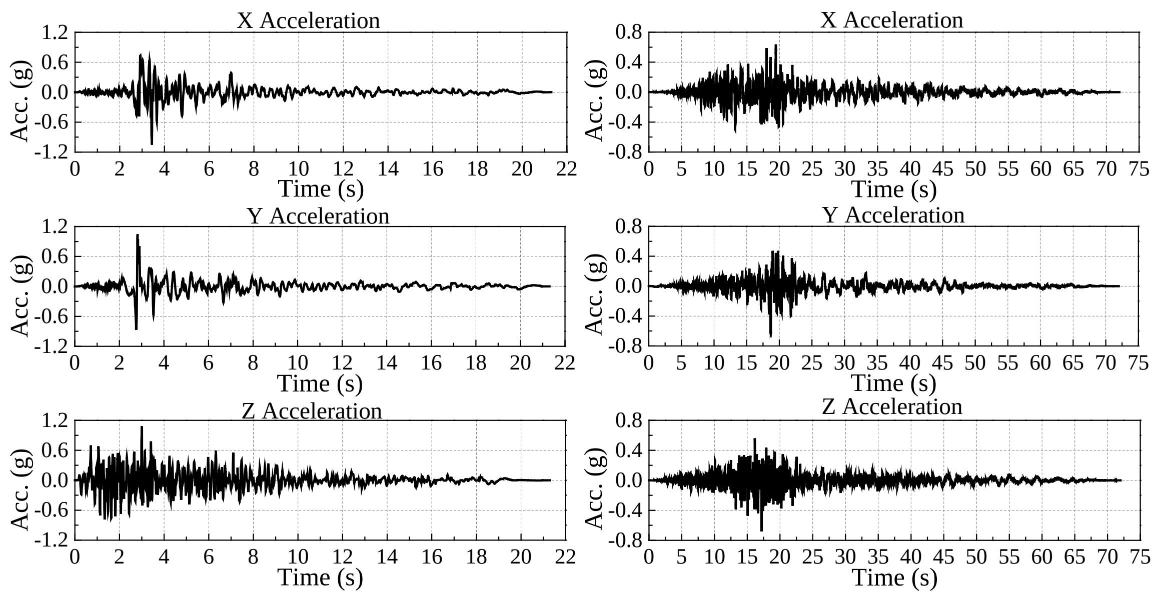
TABLE III. Peak Ground Accelerations (PGAs) of Target Spectra

Earthquake Name	Year	Station	Target Spectrum		Peak Ground Acceleration (PGA), g	
					Original	10,000 yr. return period
Erzikan, Turkey	1992	Erzikan	NFGM	Horizontal	EW 0.496, NS 0.515	1.053
				Vertical	0.248	1.127
Chi-Chi, Taiwan	1999	CHY101	FFGM	Horizontal	EW 0.353, NS 0.440	0.640
				Vertical	0.165	0.685
San Fernando	1971	Pacoima Dam	---	Horizontal	EW 1.220, NS 1.240	---
				Vertical	0.687	---



(a) (b)

Fig. 3. Target Response Spectra (Western US Rock): (a) 10,000 Year Event; (b) 30,000 Year Event



Erzikan, Turkey Chi-Chi, Taiwan

Fig. 4. Input ground motions spectrally matched to 10,000 year return period

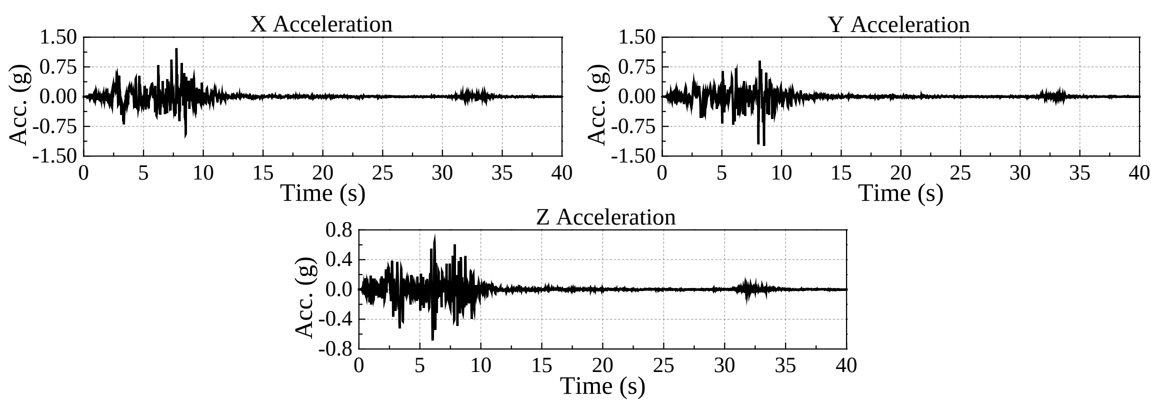


Fig. 5. Time History of Original San Fernando, Pacoima Dam (1971)

EXPERIMENTAL SETUP

Fig. 6 shows the experimental setup of the cask on top of concrete pad (2,134 mm × 2,134 mm × 354 mm). The pad is anchored to the 6-degree-of-freedom shaking table, while the cask is free standing on top of the concrete pad. To prevent damage due to potential tip-over, safety cables were attached to the cask during the tests. Fig. 6 also shows part of the instrumentation, which includes 12 string-pots to measure horizontal displacements at top and bottom surface points of the cask, 4 LVDTs to measure vertical displacement at four edge points at base of cask, 8 accelerometers to measure overpack acceleration response, and 10 accelerometers for MPC response accelerations.

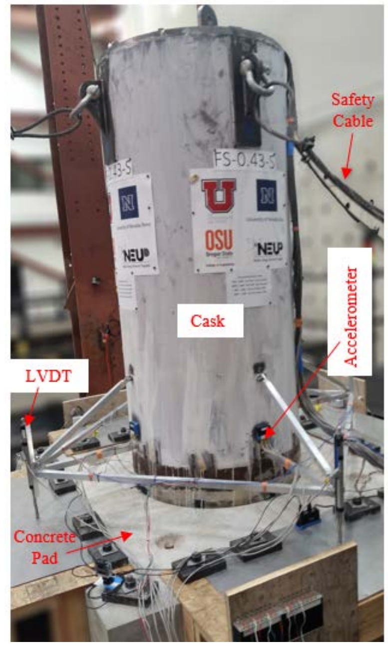


Fig. 6. Experimental test setup of free-standing cask

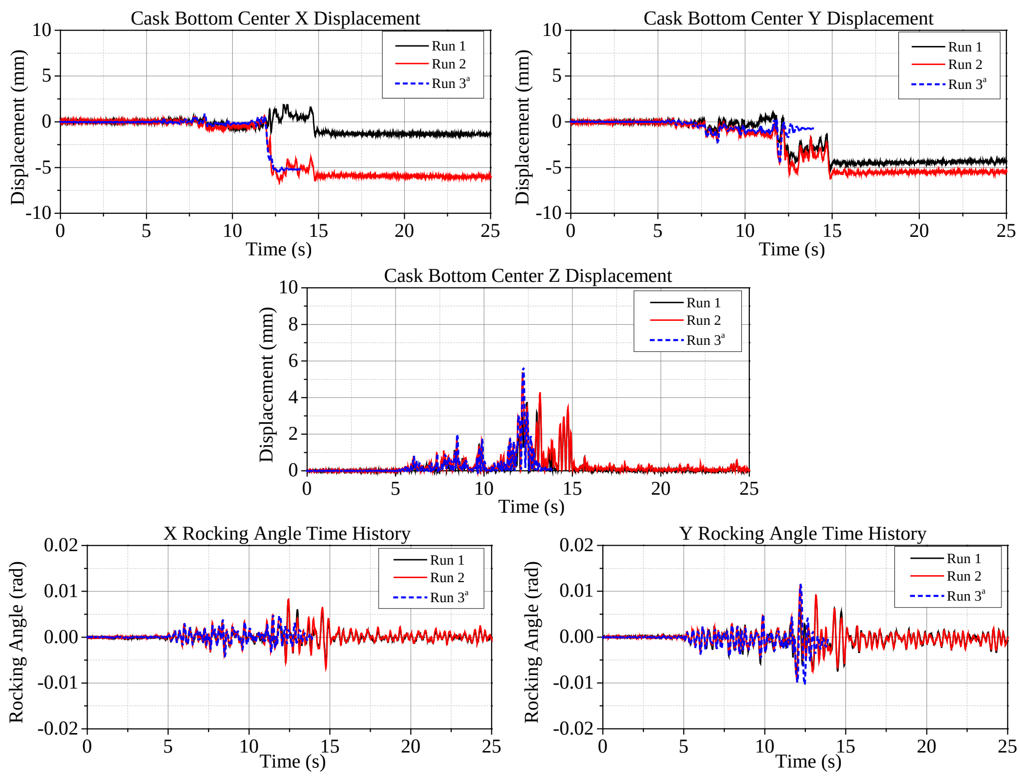
During the experimental tests, the ground motions presented in Figs. 4 and 5 were applied to the scaled cask at monotonically increasing magnitudes until the shake table was automatically stopped when the impact accelerations exceeded the allowable load capa The ground motions applied were repeated a minimum of two times.

EXPERIMENTAL RESULTS

The intensity of ground motions successfully applied to Cask I were too small to produce significant cask displacements, and these results are not presented in this paper. The tests of the remaining three specimens resulted in larger cask displacements and repeated ground motions were successfully applied. Cask II was subjected to three repeats of 75% of 10,000 year Chi-Chi. Cask I-M was subjected to two repeats of 75% of original San Fernando and under 75% of 10,000 year Chi-Chi, four different times. Cask I-O was tested under 100% of Original San Fernando five times. Fig. 7 shows the results Cask II repeated test response comparison. Figs.8 and 9 presents the same for repeat tests for Cask I-M. Lastly, Fig. 10 presents the response comparison for the five repeat test for Cask I-O. TABLE IV presents the peak and residual values for Cask I-O response under 100% 10,000 year Chi-Chi (Fig. 10). TABLE IV also calculates the standard deviation and coefficient of variation for the data obtained from five repeats. It has to be noted that having only five data point is considered to be statistically insufficient.

Figs. 7-10 suggest that the response of free-standing cask lacks is not repeatable. These results are consistent with similar observation of previous studies [2], [4], [11]–[13]. It can be clearly seen that the variation in response is significant, particularly for the lateral displacement of the cask, and in a lesser degree on the rocking response of the cask. Coefficient of variation calculated in TABLE IV also suggests the same. The variation on the response is caused by small changes in initial conditions. This change initial position, which exists during rocking results in difference boundary condition at any given instance of movement. This, in combination with high frequencies contained within the applied ground motions results in different movement in the subsequent times. The variability on the experimental results complicates the dynamic motion prediction using any FE and numerical models.

Specimens Cask I-M and Cask I-O, were also tested under repeated bidirectional and unidirectional excitations. Figs. 11-13 present the response of Cask I-M under unidirectional (X only) and bidirectional (X and Y; X and Z) components, respectively, under 75% of 10,000 year Chi-Chi. Figs. 14-15 present the response of Cask I-D unidirectional (X only) and bidirectional (X and Z) components, respectively, for100% of 10,000 year Chi-Chi. The results show the lack of repeatability on the response, even for unidirectional and bidirectional excitations. Note that significant out-of-plane motion was recorded for cases where only one horizontal component is applied. A similar out-of-plane displacement was observed for realizations with one horizontal and one vertical excitation.



[a] Run 3 was aborted

Fig. 7. Cask II Response under Repeated 75% of 10,000 year Chi-Chi

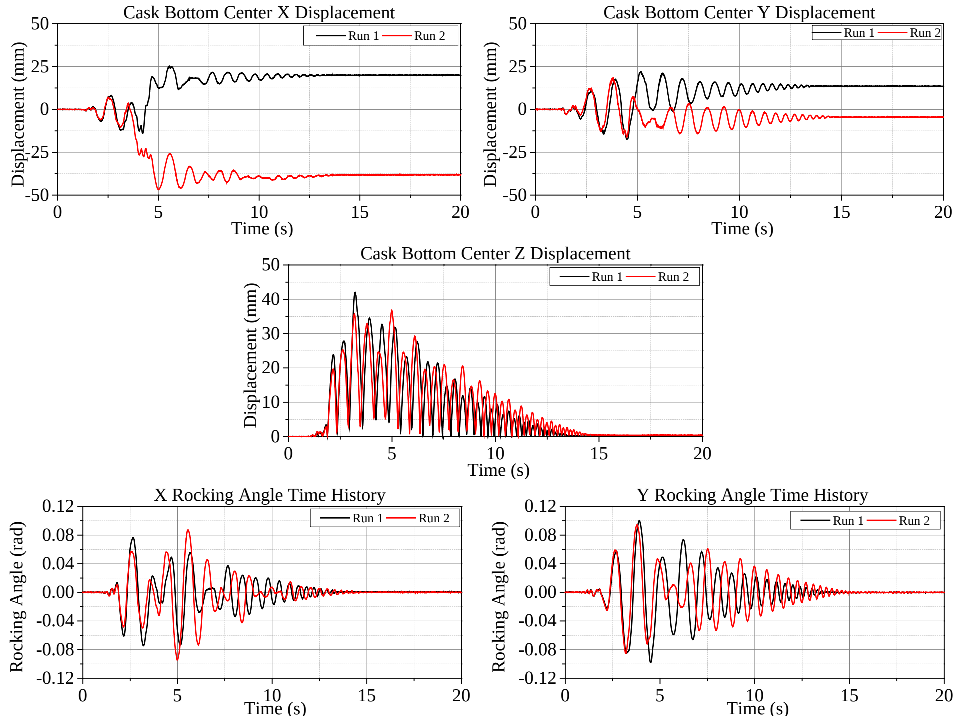
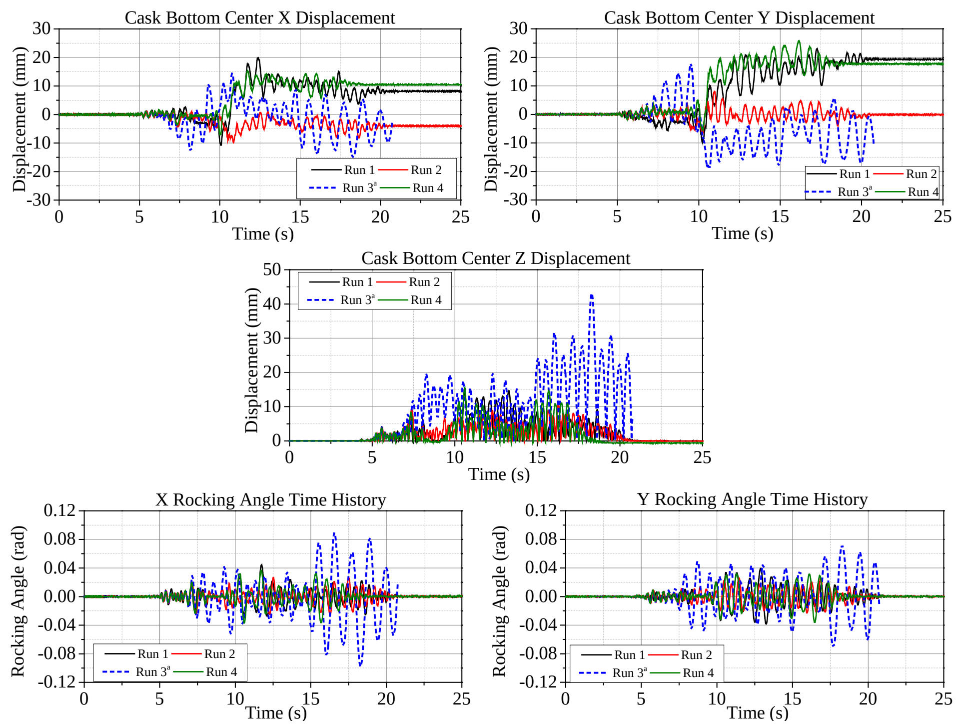


Fig. 8. Cask I-M Response under Repeated 75% of Original San Fernando



[a] Run 3 was aborted

Fig. 9. Cask I-M Response under Repeated 75% of 10,000 year Chi-Chi

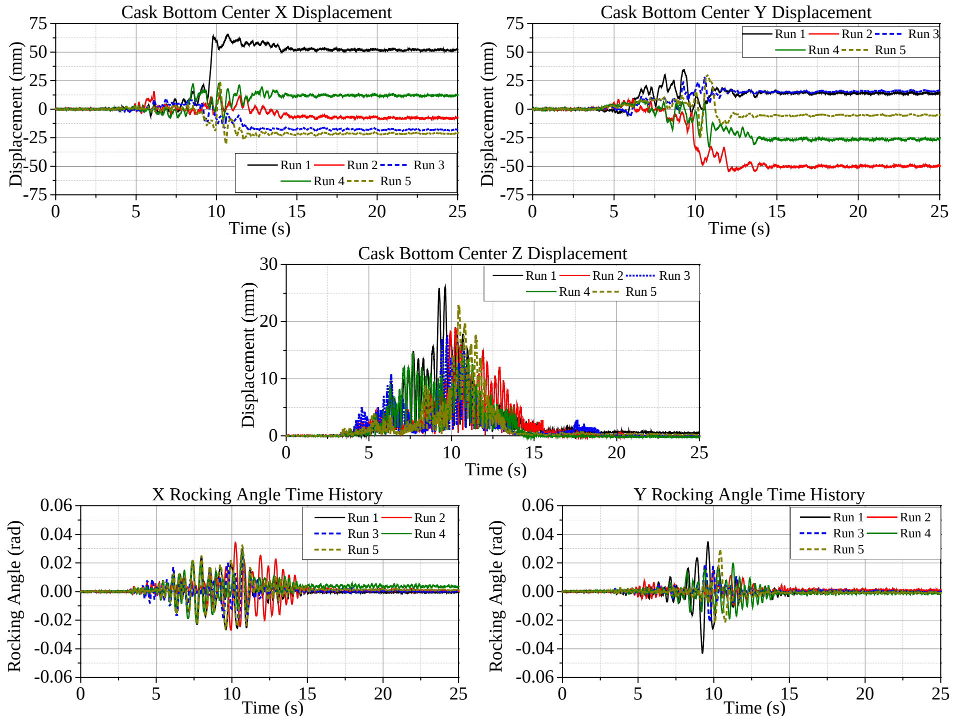


Fig. 10. Cask I-O Response under Repeated 100% of 10,000 year Chi-Chi

TABLE IV. Peak and Residual values of Cask I-O Response (100% of 10,000 year Chi-Chi)

Description		**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Std. Dev[a]**	**cov[b]**
X Displacement (mm)	Peak	65.03	15.31	-18.89	22.48	-30.92	20.14	0.66
	Residual	51.92	-7.70	-17.95	12.14	-21.15	17.42	0.79
Y Displacement (mm)	Peak	34.06	-54.29	28.06	-33.16	30.17	10.53	0.29
	Residual	13.88	-49.85	15.78	-26.45	-5.24	17.18	0.77
Z Displacement (mm)	Peak	26.06	19.01	17.53	17.53	22.99	3.78	0.18
X Rocking Angle (rad)	Abs Max[c]	0.030	0.034	0.027	0.028	0.032	0.003	0.10
Y Rocking Angle (rad)	Abs Max[c]	0.043	0.014	0.021	0.020	0.029	0.011	0.44

[a] Std. Dev: Standard Deviation, calculated using absolute values
[b] cov: Coefficient of Variation, calculated using absolute values
[c] Abs Max: Absolute Maximum

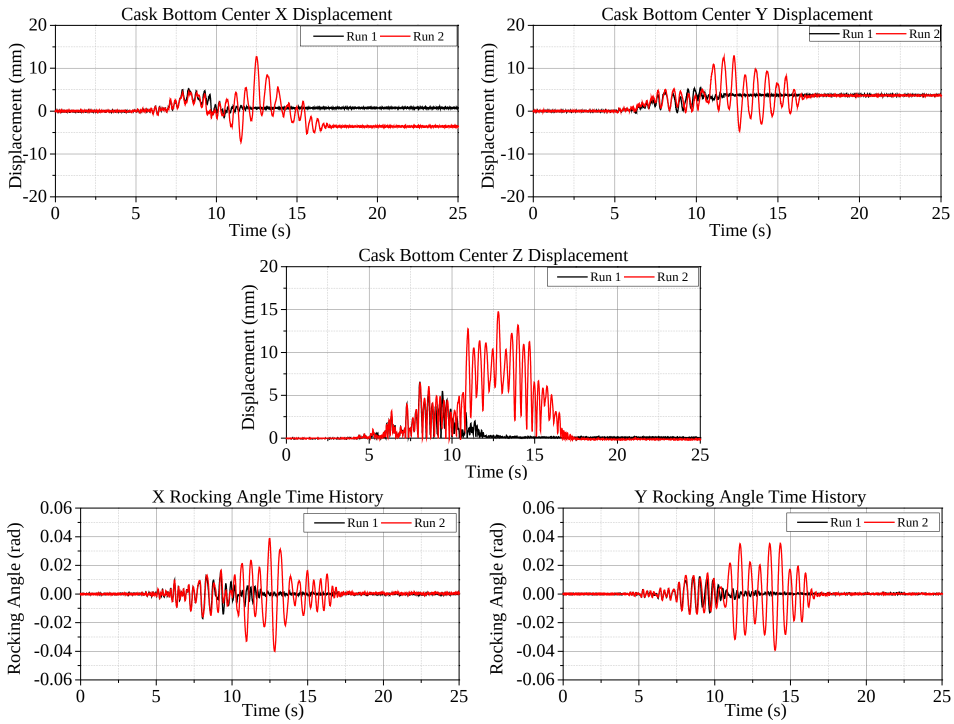


Fig. 11. Cask I-M Response under Repeated 75% of 10,000 year Chi-Chi (Horizontal X only)

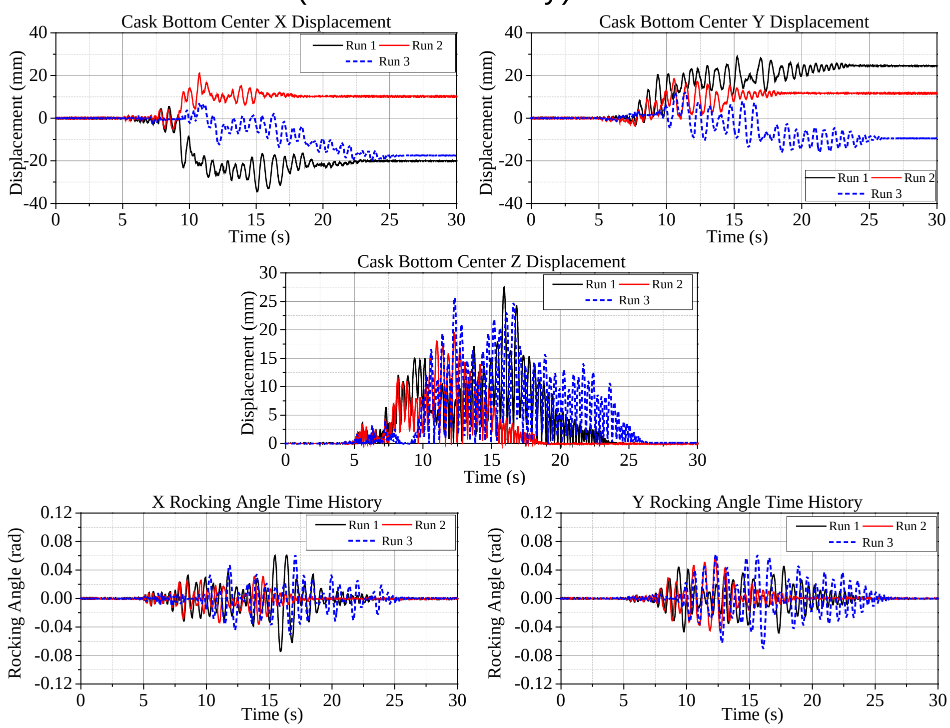


Fig. 12. Cask I-M Response under Repeated 75% of 10,000 year Chi-Chi (Horizontal X and Y only)

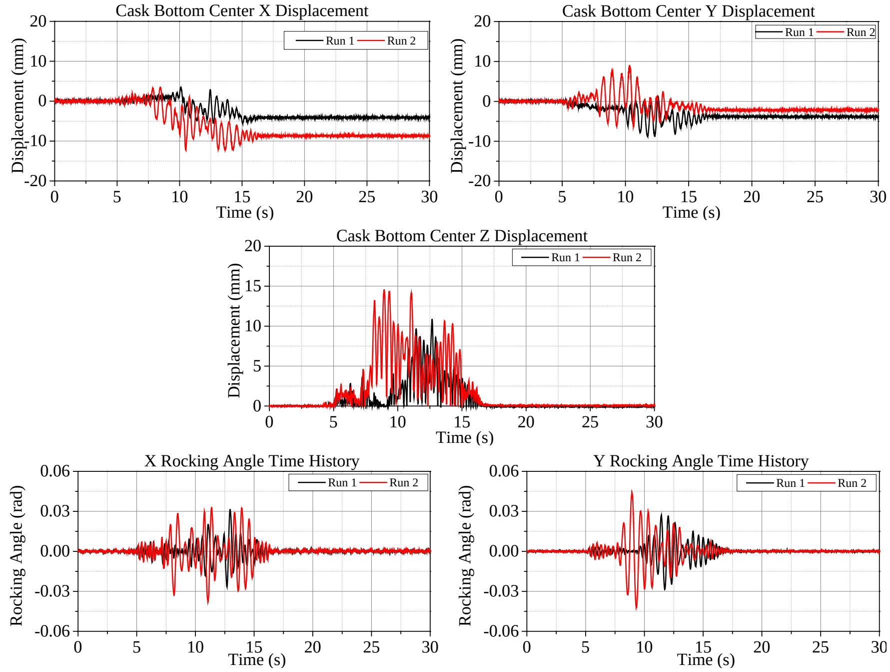


Fig. 13. Cask I-M Response under Repeated 75% of 10,000 year Chi-Chi (Horizontal X and Vertical Z only)

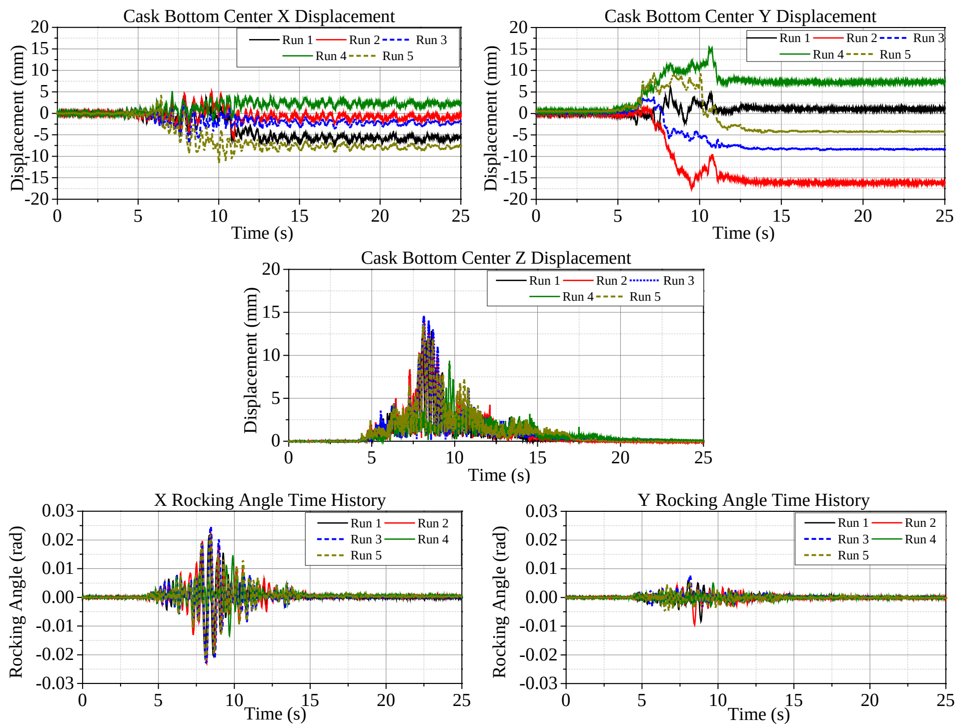


Fig. 14. Cask I-O Response under Repeated 100% of 10,000 year Chi-Chi (Horizontal X only)

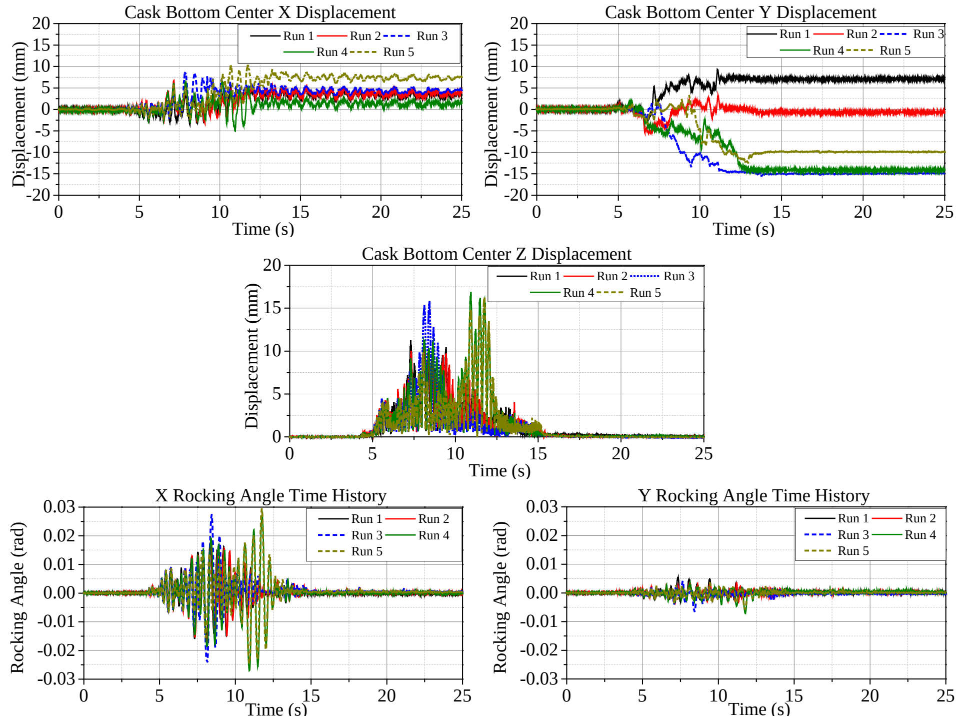


Fig. 15. Cask I-O Response under Repeated 100% of 10,000 year Chi-Chi (Horizontal X and Vertical Z only)

CONCLUSIONS

Scaled free-standing casks were subjected to multi-directional earthquake motions to study the response of dry storage casks (DSCs) under long term seismic events. The specimens used in this study have aspect ratios of 0.62, 0.55, 0.43 and 0.39. Repeat tests were performed to investigate the potential variation on the dynamic cask response. The main findings are summarized below:

i. Repeated tests under identical ground motions leads to large variation on the dynamic response of free-standing DSCs. A small change in initial conditions of the time history leading to change in specimen boundary conditions, causes large variations in the response.
ii. The variation in response not only exists when accelerations are applied in three orthogonal directions, but also under bidirectional and unidirectional excitations.
iii. While most of the previous studies focus on block type structures (2D or 3D), this study investigated response of 3D cylindrical free-standing DSCs. The fact that DSCs have a circular base, increases the likelihood of motions along the cask edge, resulting in tumbling or nutation motion. Any minute differences at an instance of DSCs' response (initial condition at that instance) while on its edge can lead to different results in the following instances.
iv. Response variation was not only limited to lateral displacements, but rocking responses also had considerable differences. This is particularly true for free-standing bodies with lower aspect ratios (slender bodies).

The fact that the seismic response can be drastically different due to small changes in initial condition, is an important finding because it indicates the existence of a chaotic response. Anchoring the cask to the concrete foundation could be a solution to avoid such unpredictable response. Such systems can also help in reducing the possibility of extreme events like cask overturning or excessive movement, but they require the additional anchor design, a thicker foundation base, and there is a possibility of sliding of the entire foundation pad. The scope of this project includes the evaluation of both free-standing and anchored casks. A comparison of free-standing and anchored cask performance will be performed in the last stage of this project.

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