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ANALYTICAL STUDY OF HI-STORM 100 CASK SYSTEM FOR SLIDING AND TIP-OVER POTENTIAL DURING HIGH-LEVEL SEISMIC EVENT

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Mohsin Khan

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1.0 INTRODUCTION

The purpose of this study is to perform sliding and tip-over nonlinear time history analysis of HI-STORM 100 casks. The cask system is planned to sit vertically unanchored on a concrete slab in a 2 by 4 array as described in References 1, 2 and 3. The concrete slab rests on ground soil. This study will use three ground motion time histories for 2000-year return period of the region as provided in Reference 4. The nonlinear dynamic analyses will simulate the cask behavior due to specified input motions applied at the cask base. It will demonstrate the sensitivity of HI-STORM 100 cask response (sliding and rocking) movements due to various input data selected. The results of this study will be compared with the results presented in Reference 1.

2.0 INPUT DATA

The following structural design and analyses information is based on Reference 1, 2 and 3.

Overpack Weight = 267,664 lbs.
Radial Concrete Weight = 163,673 lbs.
Maximum Cask Weight = 360,000 lbs.
MPC Weight (including fuel) = 88,857 lbs.

Length of the Cask = 231.25 inches
Diameter of the Bottom Plate = 132.50 inches
Inside Diameter of the Cask Shell = 72.50 inches
Outside Diameter of the Cask Shells = 132.50 inches

MPC Height = 190.5 inches
MPC Diameter = 68.375 inches
MPC Bottom Plate Thickness = 2.5 inches
MPC Top Plate Thickness = 9.5 inches

Total Vertical Stiffness Between the Pad and Cask = 4.541×10^8 lbs./inch
Total Horizontal Stiffness Between the Pad and Cask = 4.541×10^{11} lbs./inch

Lowest Coefficient of Friction = 0.2
Highest Coefficient of Friction = 0.8

Two horizontal time histories and one vertical time histories are provided in Reference 4. The amplitudes of these time histories are in terms of gravity (i.e., g) and are at a constant time interval of 0.005 seconds. The time history duration is 30 seconds.

3.0 METHODOLOGY FOR FINITE ELEMENT ANALYSIS

Figure 1 shows a rigid mass than can slide and uplift. Various forces and local stiffnesses needed to solve this problem are also shown. The block moves when inertial forces acting on this mass exceed the frictional force μW. Local contact stiffnesses in the horizontal and vertical direction (K_H and K_V) are needed in mathematical simulation just before any sliding occurs at any instant of time. There are several structural analyses codes, which can solve this nonlinear analysis problem. SAP2000 and ANSYS structural analysis codes described in References 5 and 6 are used to perform nonlinear time history analyses. The methodologies and the formulation of the finite elements and nonlinear solution methods are described in these references. Three mathematical models considered in this study, are described in section 4.0.

4.0 CASK MODEL STUDIES

Three mathematical cask models with varying degree of complexity are considered in this study as follows:

- The purpose of the first model is to obtain horizontal sliding displacements for the HI-STORM100 cask without any vertical excitation. For this case, two industry standard structural analysis codes, ANSYS and SAP2000, are used to compare the maximum sliding displacements values and the nodal displacement time history traces for benchmarking purposes.
- The second model includes the effect of vertical excitation without any rocking effects due to cask height.
- The third model represents a three-dimensional cask with vertical and horizontal rigid beam finite elements. The mass density of the vertical beam elements are adjusted to obtain approximately the weight of a fully loaded HI-STORM100 cask.

For the last two models, several parametric analyses are performed to show the effect of change of contact stiffnesses and coefficient of friction values on the HI-STORM100 cask motion. The effect of use of various structural damping values (ALFA, BETA, or Modal) is also studied in the third model.

4.1 Rigid Mass Sliding Model

A HI-STORM 100 cask weighing 360 kips is modeled by a single rigid beam element that can slide horizontally. Figure 2 shows the SAP2000 model. The height of beam element is chosen small enough to avoid any rocking effects. The bottom of this element is connected to a nonlinear element that accommodates sliding effects. At the base of the nonlinear springs, horizontal time histories corresponding to 2000-year return period were applied. For checking the adequacy of these input time histories, corresponding response spectra were generated and were compared with those spectra in Reference 4.

The results of nonlinear sliding displacements are shown in Figures 3 and 4. Figure 5 provides the sliding displacements results obtained from ANSYS Computer Code (Reference 6). Table 1 provides the absolute maximum relative displacement values obtained by the two computer codes. This table shows good agreements between sliding displacement values obtained by SAP2000 and ANSYS computer codes.

Table 1

Absolute Maximum Relative Displacements in Horizontal Directions for Sliding Cask

		Stiffness for Non-Linear Elements		Relative Cask Displacements		
Computer Code	Coefficient of Friction μ	Vertical Stiffness K_V (lbs./in.)	Horizontal Stiffness K_H (lbs./in.)	Horizontal Displacement D_x (in.)	Horizontal Displacement D_y (in.)	Vertical Dispalcement D_z (in.)
SAP2000	0.2	0	1×10^5	9.371	5.599	NA
ANSYS	0.2	0	1×10^5	9.371	5.599	NA

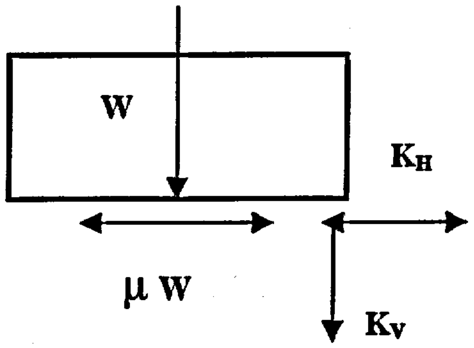

Figure 1
Cask Model for Sliding and Uplift

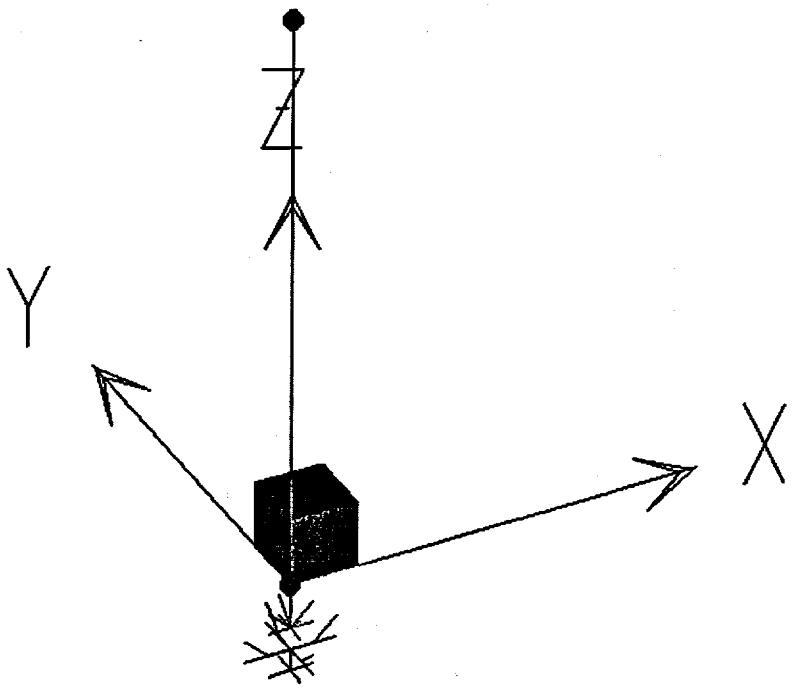

Figure 2
Cask Math Model for Sliding and Uplift

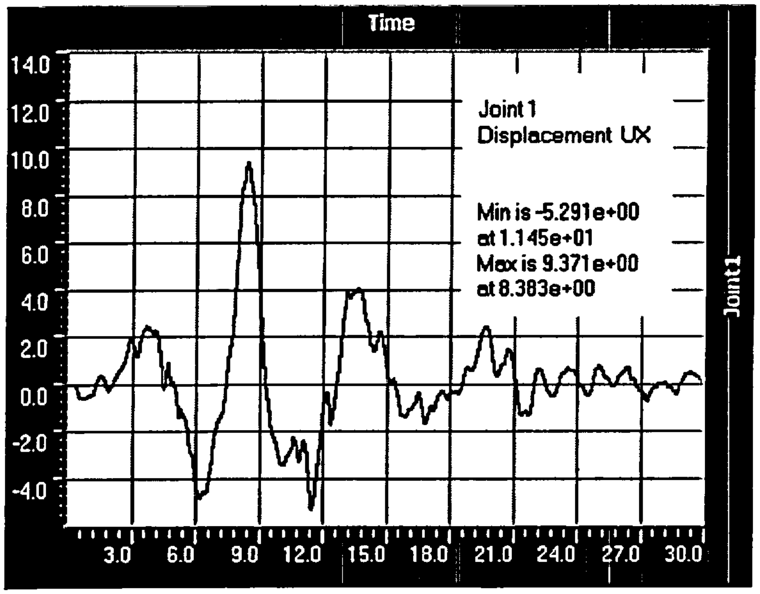

Figure 3
Sliding Cask – Relative Displacement Time History for Horizontal X-Direction

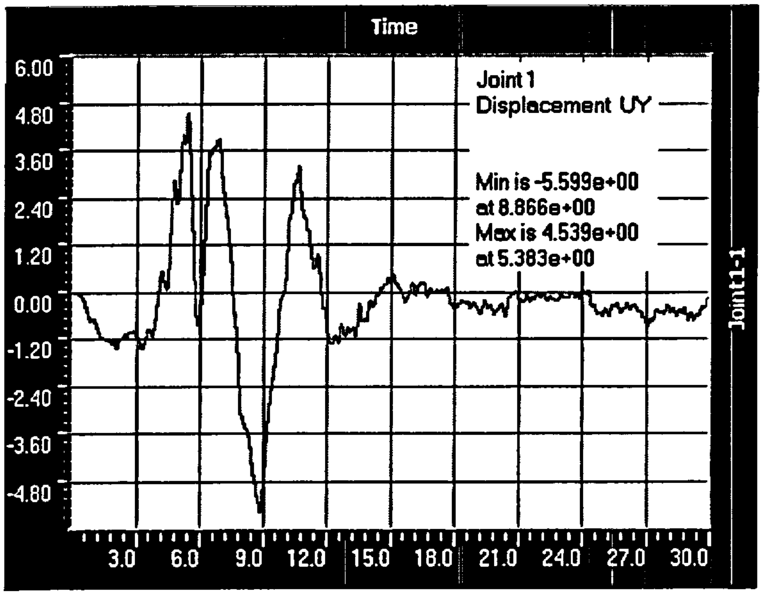

Figure 4
Sliding Cask – Relative Displacement Time History for Horizontal Y-Direction

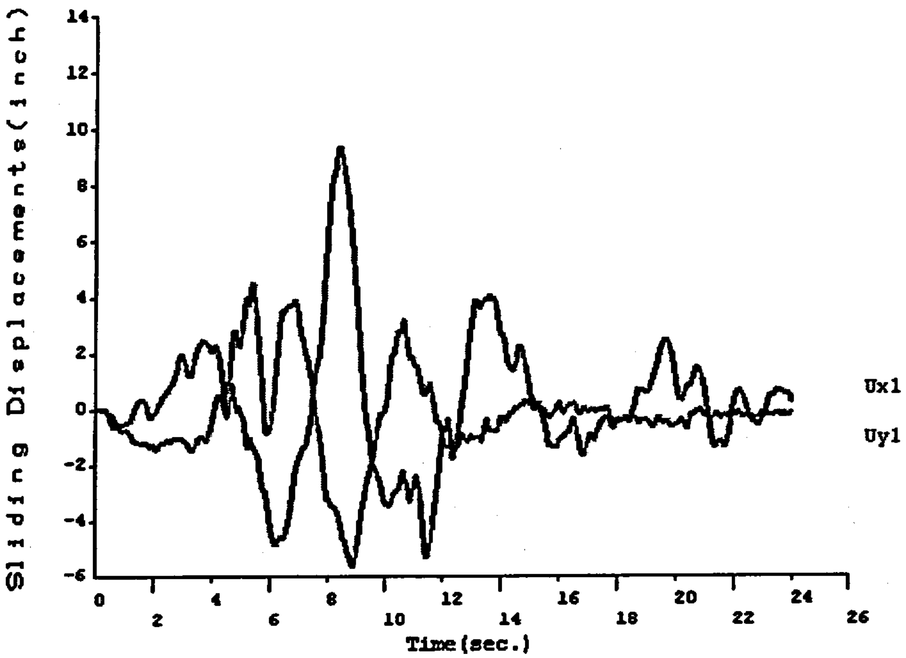

Figure 5
Sliding Cask – Relative Displacement Time History for Horizontal X and Y Directions (ANSYS)

4.2 Sliding and Uplift Model Without Consideration of Rotational Effects

A HI-STORM 100 cask weighing 360 kips is modeled by a small single rigid beam element that can slide and uplift. Figure 2 shows the beam model. The height of this element is chosen small enough to avoid any rocking effects. The bottom of this element is connected to a nonlinear element that can slide and provides compression only nonlinear effect. The rotational effects are ignored. Three time histories corresponding to 2000-year return period were applied at the base of the nonlinear spring.

Starting contact stiffnesses in the horizontal and vertical directions are used as input in performing analyses. These stiffnesses are effective before any sliding or during compression condition. In general, high contact stiffness values are used during numerical simulation of these types of analyses. The real problem with using high stiffnesses is that it artificially treats the solution to be a linear for a significant duration of the input motions. The artificially high stiffnesses also absorb significant amount of energy before sliding actually occurs. The "instantaneous" structural frequencies (before sliding) could also alter the initial sliding velocities, which would affect the final structural response during high level ground input motions. Table 2 summarizes the results of this study. A significant variation in cask displacements are found by selecting different combination of three input parameters; coefficient of friction μ, and local contact stiffnesses in the horizontal and vertical direction (K_H and K_V).

Table 2 shows that as the vertical contact stiffness between the cask and the ISFSI pad increases, the sliding displacements reduce significantly. This effect shows that the cask is approaching a simulated anchored condition to the ISFSI pad and there is no dynamic amplification in the vertical direction. Similarly, as the horizontal contact stiffness increases, the horizontal sliding displacement also reduces. However, the change in vertical stiffness has a greater impact in changing the cask displacements than the horizontal contact stiffness. When vertical displacement is large, small variation in mass also influences the horizontal response siginificantly.

The results presented in Table 2 show that the sliding and uplift displacements are not unique and tend to reduce significantly with the increase in contact stiffness values. Reference 3 also gives a range of displacement solutions, which are not unique. The solution given in Reference 3 would change significantly with lower contact stiffnesses and with lower damping values. The convergent sliding displacements should be obtained by selecting a range of contact stiffnesses. A contact stiffness value of 10^8 lbs/in is considered too high for an unanchored cask that can slide and rock. Ideally, these stiffnesses should be small values for an unanchored cask.

Table 2

Absolute Maximum Relative Displacements for Sliding Cask Associated with Sliding and Uplift Model Without Consideration of Rocking Effects Due to Cask Height

		Stiffness for Non-Linear Elements		Relative Cask Displacements		
Study Run Number	Coefficient of Friction μ	Vertical Stiffness K_V (lbs./in.)	Horizontal Stiffness K_H (lbs./in.)	Horizontal Displacement D_x (in.)	Horizontal Displacement D_y (in.)	Vertical Dispalcement D_z (in.)
1	0.2	1×10^6	1×10^5	9.16	12.25	2.10
2	0.8	1×10^6	1×10^5	42.74	31.35	1.75
3	0.2	10×10^6	1×10^5	19.25	7.69	1.93
4	0.8	10×10^6	1×10^5	12.70	14.03	1.94
5	0.2	100×10^6	1×10^5	6.38	3.86	0.006
6	0.8	100×10^6	1×10^5	4.74	3.05	0.006
7	0.2	100×10^6	1×10^6	1.91	1.29	0.006
8	0.8	100×10^6	1×10^6	3.80	1.38	0.006
9	0.2	454×10^6 (**)	1×10^5	6.39	3.86	0.001
10	0.8	454×10^6 (**)	1×10^5	4.83	3.06	0.001
11	0.8	454×10^6 (**)	454×10^6	0.057	0.071	0.001

** Stiffness values correspond to those values given in Reference 1.

4.3 Three-Dimensional Sliding and Uplift/Tip-Over Model

A HI-STORM 100 cask weighing approximately 360 kips is modeled by 72 beam elements. Figure 3 shows a three-dimensional (3D) beam model. The cask can slide, uplift and rock or tip-over under the specified seismic input motions. The base diameter of this model is 132 inches and the cask height is 231 inches. The model is graphically generated using the GUI feature of SAP2000. The bottom 8 nodes are connected to nonlinear elements. Three time histories corresponding to 2000-year return period were applied at the base of the nonlinear springs.

Table 3 summarizes the results of this study. A significant variation in cask displacements found by selecting different combination of three input parameters; coefficient of friction μ, and local contact stiffnesses in the horizontal and vertical direction (K_H and K_V). The cask displacements are comparable to those obtained in Table 2. In this case, solutions are also obtained at 0.01%, 1% and 5% structural damping. In reality, the structural damping (ALFA, BETA or Modal) must be small or insignificant value. Cask sliding and uplift displacements should be independent of structural damping for cask elements, since cask is considered as a rigid body. Only friction should be primary energy dissipation mechanism. From the results presented in Table 3, it is shown that the use of higher damping will significantly lower the nonlinear structural response of the cask system.

Table 3

Absolute Maximum Relative Displacements for Sliding Cask Associated with 3-D Sliding and Tip-Over Model

		Stiffness for Non-Linear Elements		Relative Cask Displacements		
Study Run Number	Coefficient of Friction μ (% Damping)	Vertical Stiffness K_V (lbs./in.)	Horizontal Stiffness K_H (lbs./in.)	Horizontal Displacement D_x (in.)	Horizontal Displacement D_y (in.)	Vertical Dispalcement D_z (in.)
1	0.8 (0.01%)	1×10^6	1×10^5	372.76	229.65	27.24
2	0.2 (1%)	1×10^6	1×10^5	48.69	48.86	2.56
3	0.8 (1%)	1×10^6	1×10^5	306.00	120.45	18.01
4	0.8 (1%)	10×10^6	1×10^5	60.21	46.85	8.59
5	0.2 (5%)	1×10^6	1×10^5	4.38	9.08	2.28
6	0.8 (5%)	1×10^6	1×10^5	21.48	56.85	5.87
7	0.2 (5%)	10×10^6	1×10^5	6.00	4.71	0.15
8	0.8 (5%)	10×10^6	1×10^5	15.11	10.42	0.94
9	0.8 (5%)	100×10^6	1×10^5	27.63	58.27	2.56

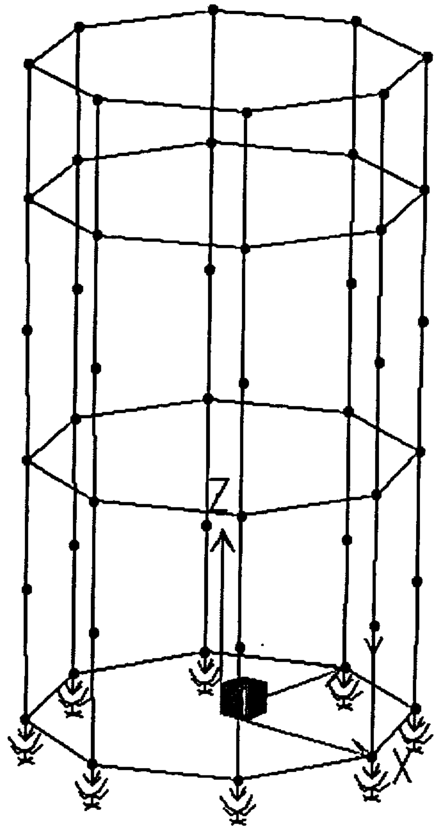

Figure 6
Cask 3-D Math Model for Sliding, Uplift and Rocking

5.0 CASK OVERTURNING/TIPPING

In this section, a calculation is performed to determine the minimum requirement for vertical uplift of the cask body and the kinetic energy (or velocity) required to tip a cask under high level horizontal and vertical earthquake motions. As shown in Figure 7, the cask will tip over when the center of gravity (CG) of the cask body with height (H) and radius (R) moves over one edge.

For HI-STORM 100 Cask:

Height of the Cask (H) = 231.25 inches
Diameter of the Bottom Plate (2R) = 132.50 inches
Maximum Cask Weight = 360,000 lbs.
Cask Velocity = V_M
Horizontal Cask Velocity in X direction = V_X
Horizontal Cask Velocity in Y direction = V_Y
Vertical Cask Velocity in Z direction = V_V
Gravity = 386.4 in./sec.^{2}

$\alpha = \tan^{-1}(H/2R) = \tan^{-1}(231.25/132.50) = 60.2°$

$\beta = 90° - 60.2° = 29.8°$

The value of tipover angle β is conservatively calculated due to selection of cask CG equals to half the cask height.

Maximum Cask Uplift Height = 2 R (sin 29.8°) = 65.85 inches

Change in the C.G Height at Tipping $= \{R^2 + (0.5\,H)^2\}^{1/2} - 0.5\,H = 133.26 - 115.63$
$= 17.63$ in.

Potential Energy (PE) Required for Cask Overturning:

PE = Cask Weight * Change in the C.G height at tipping
PE = (360,000 lbs.) (17.63 in.) = 6,346,800 lbs.-inch

Kinetic Energy (KE) Required for Cask Overturning:

KE = (1/2) * Cask Mass * (Cask Velocity)^2
$KE = (1/2)\,[360{,}000/386.4]\,(V_M)^2$

Considering all three direction of earthquake motions by using SRSS rule for directional response combination, the (Cask Velocity)^2 is:

$(V_M)^2 = (V_X)^2 + (V_Y)^2 + (V_V)^2$

Table 3 summarizes the spectral accelerations and velocities at 5% damping from 0.4 to 2.0 Hz frequency range for a 2000-year return period seismic event. This is an important frequency range and it is judged that the instantaneous rocking and sliding frequencies lie in this range for an unanchored cask. From Table 4, the average horizontal velocity in this frequency range for both the fault-normal and fault-parallel direction is approximately equal and the average vertical velocity is approximately half of the average horizontal velocities.

Therefore,

$V_X \cong V_Y$ and $V_V \cong 0.5 * V_X$

Substituting these values,

$$(V_M)^2 = (V_X)^2 + (V_X)^2 + (0.5*V_X)^2 \quad = 2.25 * (V_X)^2$$

For Possible Cask Overturning/Tipping:

$KE > PE$

$$(1/2)\ [360{,}000/386.4]\ (V_M)^2 > 6{,}346{,}800 \text{ lbs.-inch;}$$

$$(1/2)\ [360{,}000/386.4] * 2.25 * (V_X)^2 \quad > 6{,}346{,}800 \text{ lbs.-inch;} \Rightarrow V_X > 77.82 \text{ in/sec.}$$

For some cases summarized in Table 3, the cask velocities obtained from the velocity traces during an earthquake are much higher than the calculated value of V_X. For example, Figure 8 shows a velocity trace for Study Run Number 1 in Table 3. In this case the maximum cask velocity is 271 in/sec.. Therefore, it is possible for HI STORM 100 cask to overturn (i.e., tip over) during a high-level seismic event.

Table 4

Spectral Accelerations and Velocities at 5% Damping From 2000-Year Return Period Seismic Input Time Histories

		Fault-Normal		Fault-Parallel		Vertical	
Period (sec)	Frequency (Hz)	Accelerations (g)	Velocity inch/sec.	Accelerations (g)	Velocity inch/sec.	Accelerations (g)	Velocity inch/sec.
2.500	0.4	0.2020	31.05	0.14228	21.87	0.09851	15.15
2.000	0.5	0.2500	30.75	0.20892	25.70	0.12739	15.67
1.667	0.6	0.3084	31.61	0.28255	28.96	0.14389	14.75
1.429	0.7	0.3604	31.66	0.3794	33.33	0.18618	16.36
1.250	0.8	0.4175	32.09	0.44719	34.38	0.20408	15.69
1.111	0.9	0.4485	30.65	0.50923	34.80	0.23842	16.29
1.000	1.0	0.5851	35.98	0.56703	34.87	0.26506	16.30
0.909	1.1	0.5838	32.64	0.63656	35.59	0.28059	15.69
0.833	1.2	0.6480	33.21	0.71335	36.56	0.33617	17.23
0.769	1.3	0.7524	35.59	0.77482	36.65	0.30952	14.64
0.714	1.4	0.7858	34.52	0.85834	37.70	0.38997	17.13
0.667	1.5	0.7393	30.31	0.94301	38.66	0.39032	16.00
0.625	1.6	0.8890	34.17	0.92933	35.72	0.42693	16.41
0.556	1.8	0.8856	30.26	1.12603	38.47	0.47324	16.17
0.500	2.0	1.0783	33.15	1.17603	36.16	0.56712	17.44
Average Velocity			32.51		33.96		16.06

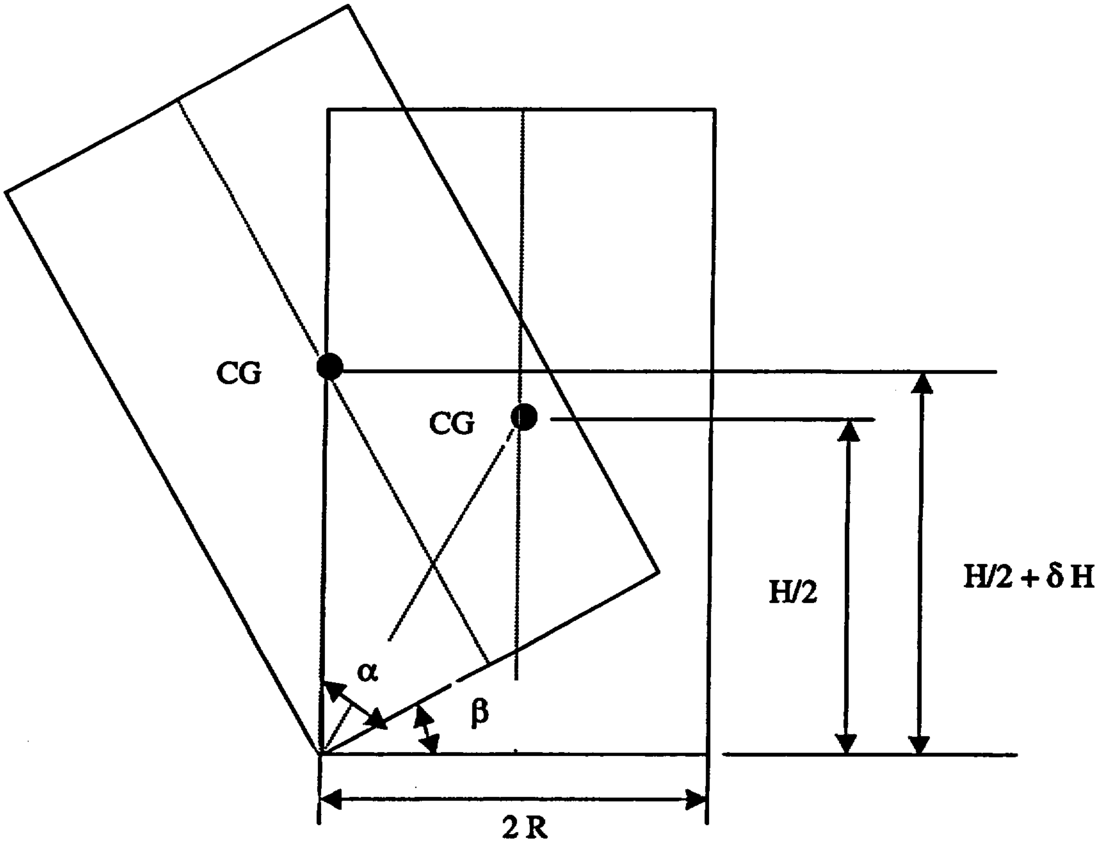

Figure 7
Cask Overturning/Tipping

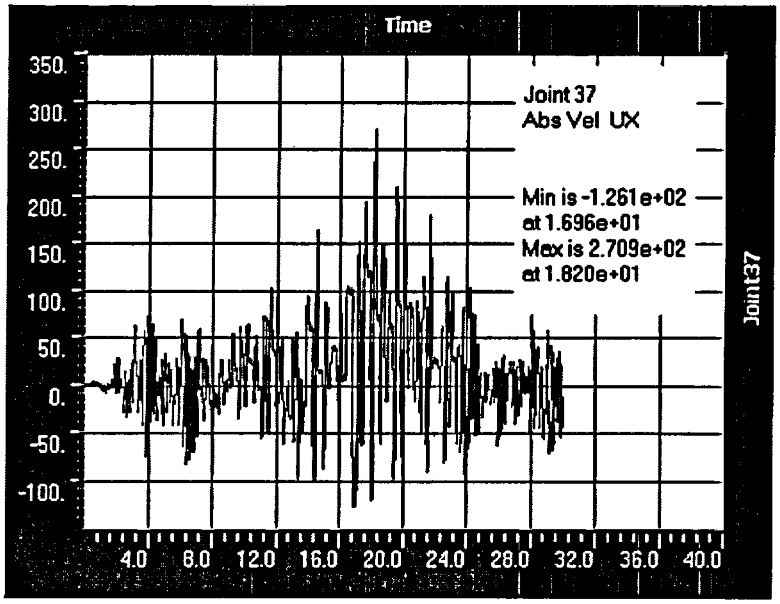

Figure 8
Cask Velocity Trace For Study Run Number 1

6.0 CONCLUSIONS

In this study, evaluation of sliding and tip-over potential of HI-STORM 100 cask under seismic input motion has been performed. The HI-STORM 100 cask movements have been calculated in various ways, from a simple rigid body sliding to a detailed three-dimensional beam model. It has been demonstrated that a wide range of sliding and uplift displacements can be obtained based on the selected input values of the local contact stiffnesses and the coefficient of friction. These local contact stiffnesses are effective before the sliding or uplift begins. In general, high stiffness values are used for solving sliding and tip over type problems. The real issue with this approach is that if these stiffnesses are selected too high, then the program artificially assumes the problem to be linear for a significant duration of the input motion. Using high stiffnesses could absorb some amount of energy before sliding actually occurs. Also, with high stiffnesses the "instantaneous" structural frequencies (before sliding) could also alter the sliding velocities, which would affect the final structural response during high level ground input motion.

Key insights and observations from our study are summarized below.

- The input time histories used for these evaluations were obtained from reference 4 and are based on a 2000-year return period seismic event. Reference 4 time histories did not consider the amplification due to soil structural interaction at the top of ISFSI pad. The soil structural interaction effect would amplify the time history response on top of the ISFSI pad. Therefore, the vertical input motion at the base of the cask would be much higher than those used in this study.

- This study shows that he sliding and rocking displacements are significantly affected by the local stiffness values used as input in the mathematical model simulation. However, the sliding displacements should be independent of the local contact stiffness values used.

- This study shows that using initial high local contact vertical stiffness in Reference 1, 2, 3 significantly minimizes the vertical displacements. This approach also helps in significantly reducing the horizontal sliding displacements.

- For an unconstrained cask that acts as a rigid body, only frictional forces should provide energy dissipation mechanism during sliding and rocking.

- This study shows that the sliding and rocking displacements are significantly affected by using higher damping values during numerical simulation. Reference 1 used a high beta damping value. Use of high structural damping (ALFA, BETA, or Modal) must be avoided since the cask acts as a rigid body. A very small damping value should be used for numerical stability purposes.

- From the numerical study, it is shown that the sliding results presented in References 1, 2, and 3 are unconservative and are not unique. Due to wide variation in cask response obtained based on input data used, it is recommended that the sliding displacements presented in References 1, 2 and 3 be based on mathematical models that have been benchmarked with actual or prototype models based on shake table test data.

- Since the vertical response alters the cask dynamic reactions significantly, the computed cask reactions during cask uplift/drop and impact due to vertical amplifications would be much higher than those used in the pad design. See Reference 1.
- It is possible that for high-level ground input motion, the HI STORM 100 cask could overturn (i.e., tip over).

7.0 REFERENCES

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2. Excerpt from Holtec Report No. HI-2012653, *PFSF Site-Specific HI-STORM Drop/TipOver Analyses*, Rev 1, prepared by Holtec International, May 2001.
3. Excerpt from Holtec Report No. HI-2012640, *Multi Cask Response at PFS ISFSI From 2000-YR Seismic Event*, Rev. 2, prepared by Holtec International.
4. *Development of Design Ground Motions for the Private Fuel Storage Facility*, Revision 1, prepared by Geomatrix Consultants, Inc., March 2001.
5. SAP2000 User's Manual, Version 7.4, Computers and Structures, Inc.
6. ANSYS Version 5.7 Computer Code, ANSYS Inc.