U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Methodologies Acceptable to the Staff for Performing Seismic Stability Analyses of a Stack-up Configuration within a 10 CFR Part 50 Facility

Presented by

Gordon S. Bjorkman, Jr.
Senior Technical Advisor, Structural Mechanics
Spent Fuel Storage and Transportation Division

November 1, 2011

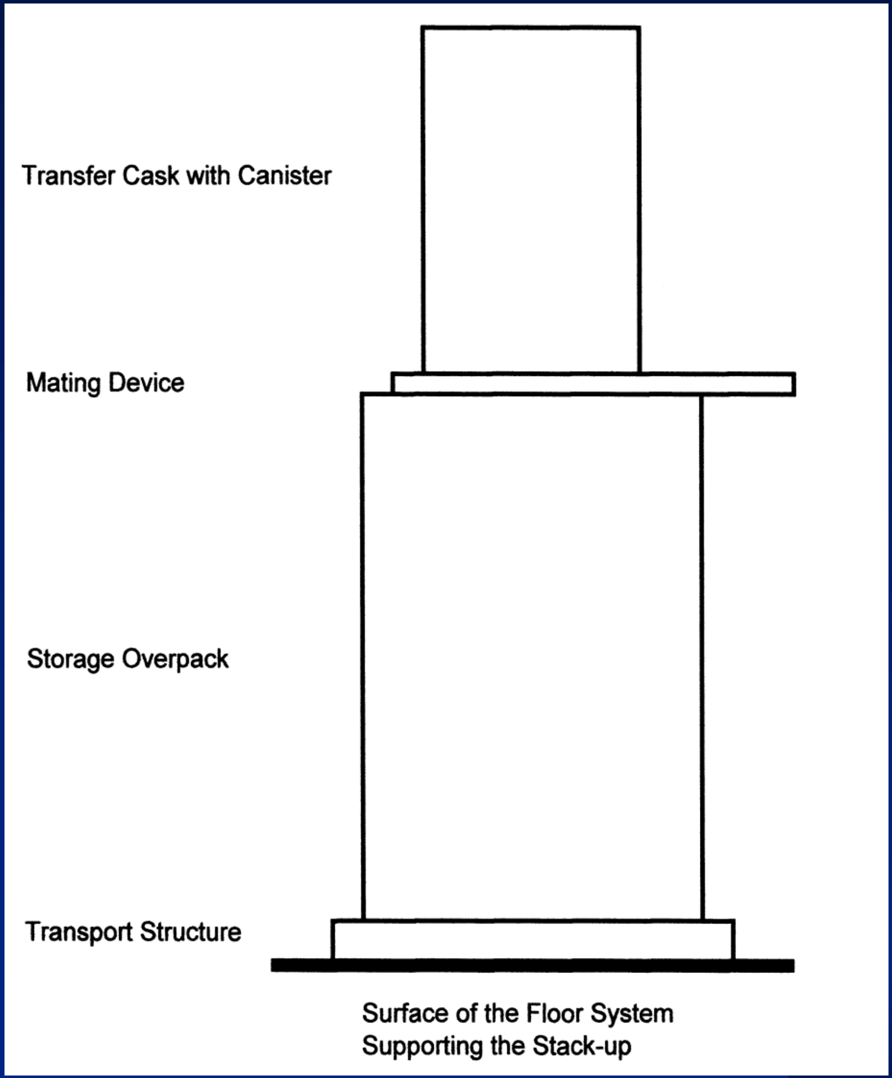
Outline

- Unique Aspects of Stack-up
- Some Definitions
- Rocking Behavior of a Rigid Body
- ASCE Standard 43-05 Appendix A Methodology and its Acceptability
- Key Elements of a draft NRC Guidance Document

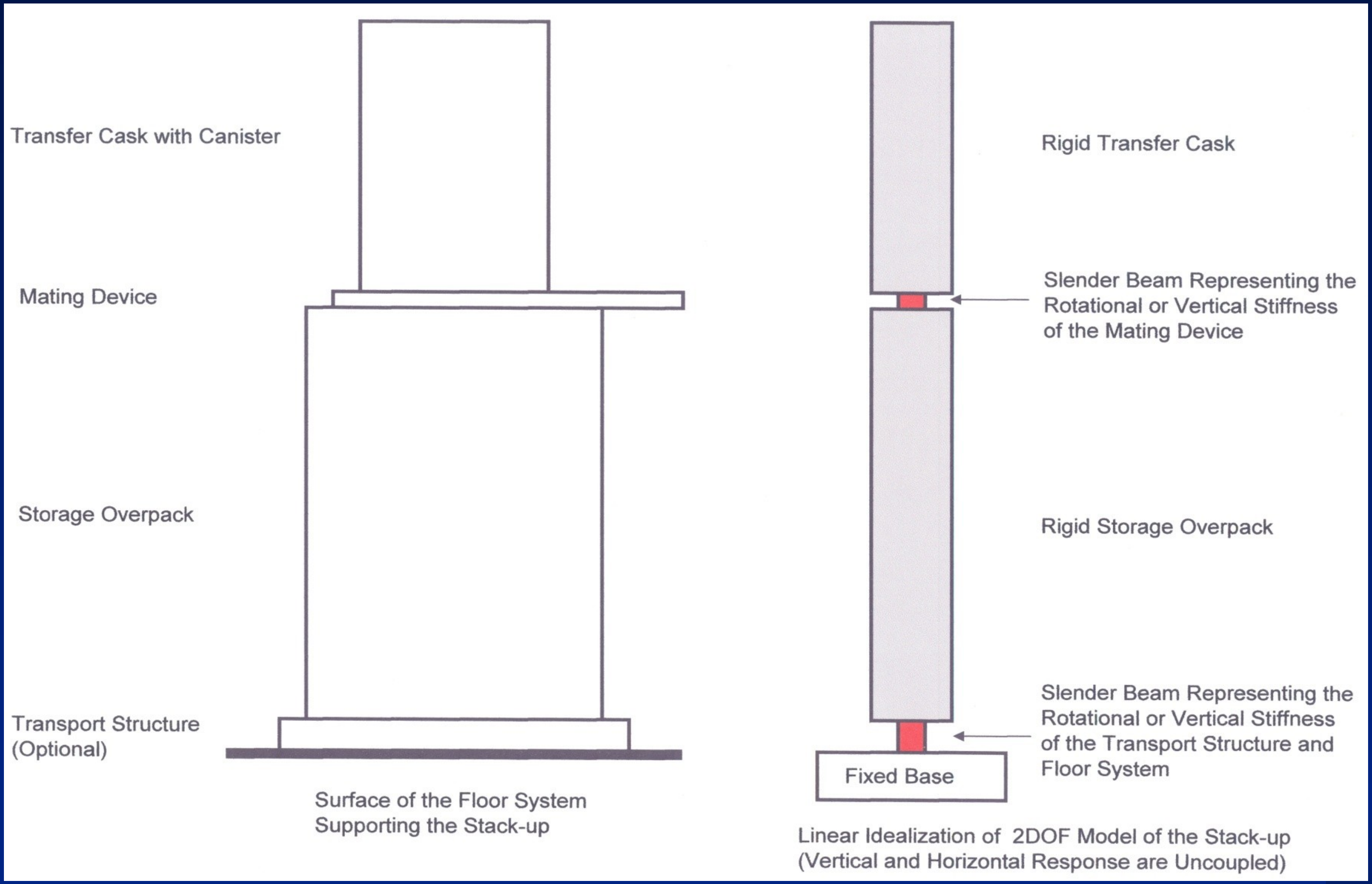
Stack-up Configuration

- <u>Unique Aspects of Stack-up</u>

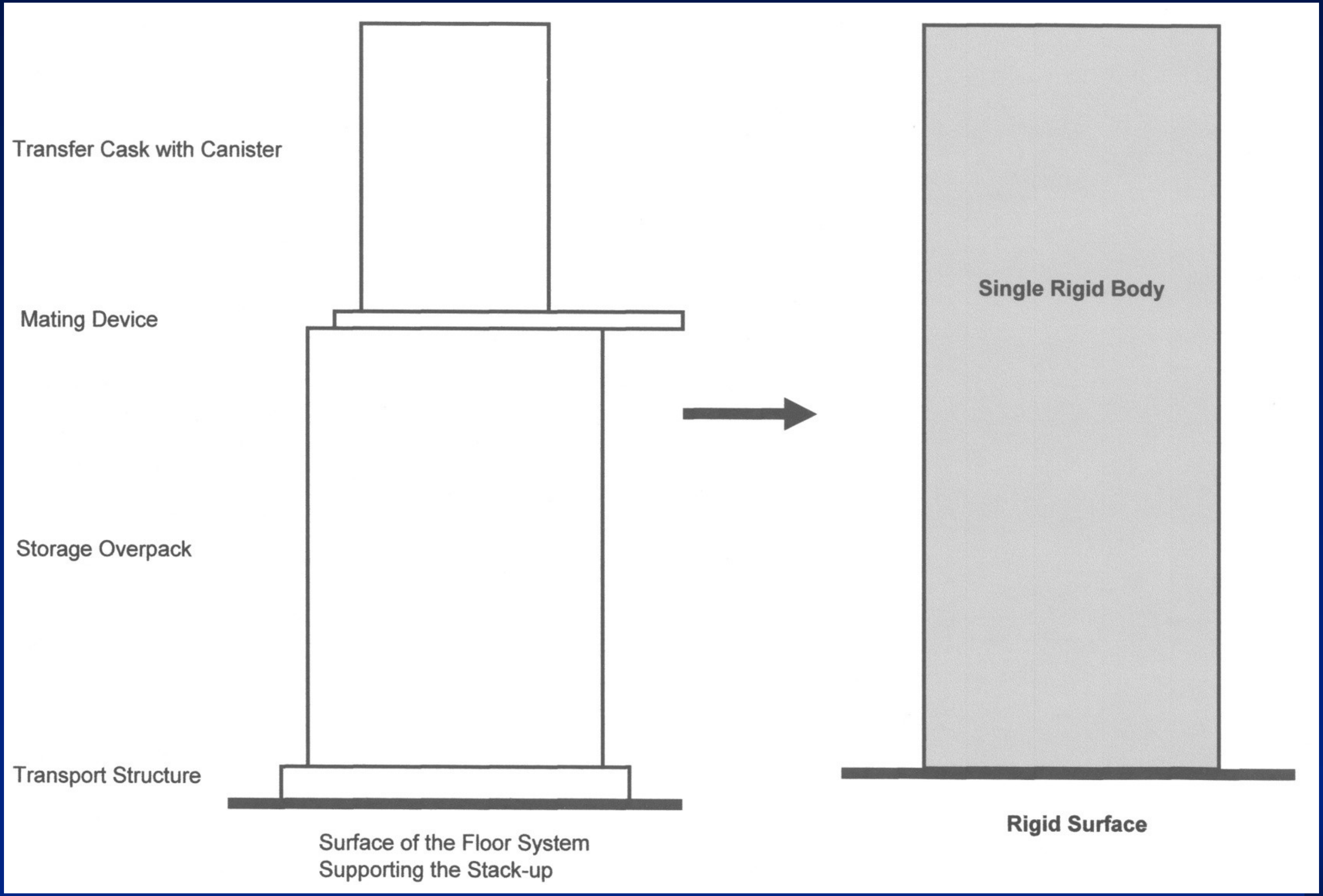
- Multiple rigid bodies
- Significant Mass
- High Slenderness Ratio (high center of gravity)
- Most Prone to Rocking



Linear Idealization as a 2 Degree of Freedom (2DOF) Model



Advantageous to Treat the Stack-up as a Single Rigid Body



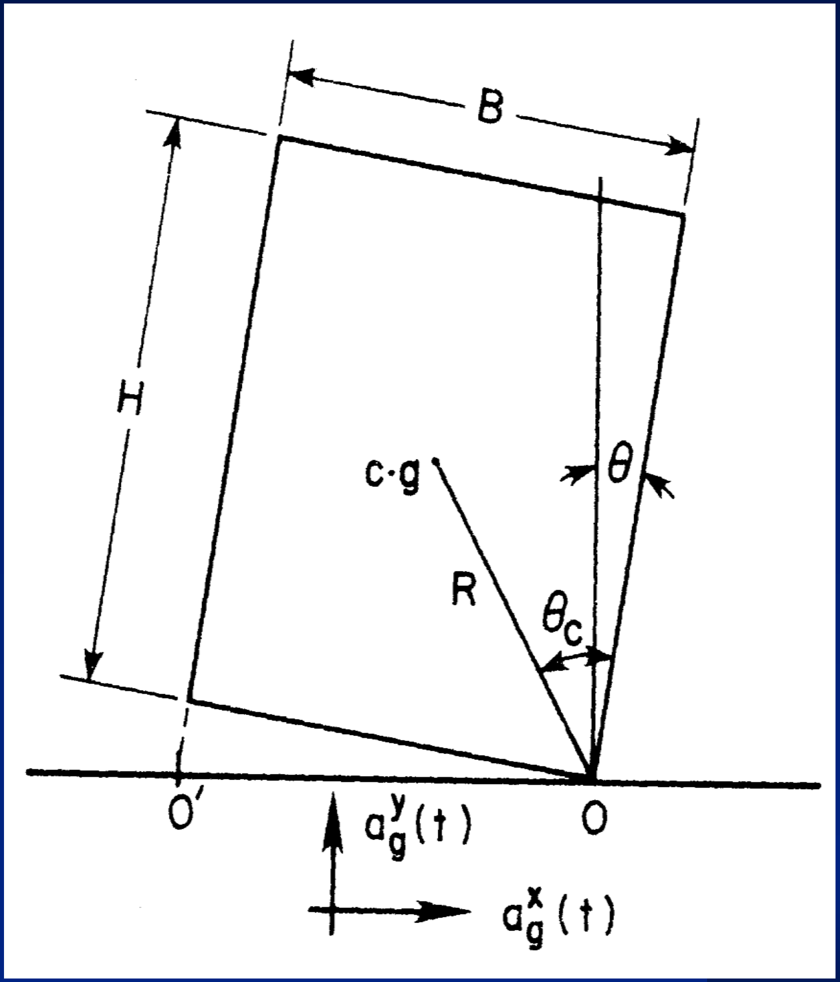
The Rocking of Rigid Bodies

- What do we do as Engineers?
- What do we know about Earthquakes?
- Codes, Standards and Regulations will change. The Physics of the Problem does not change.

- Good Guidance begins with an understanding of the Physics of the problem.

The Rocking of a Rigid Body Some Definitions

- Slenderness Ratio = H/B
- Size = R
- Rocking Angle =
- Critical Angle =



The Rocking of a Rigid Body

- "the response of a rigid block is very sensitive to small changes in its size and slenderness ratio and to the details of the ground motion. Systematic trends are not apparent:" (Yim, Chorpa and Penzien, 1980)

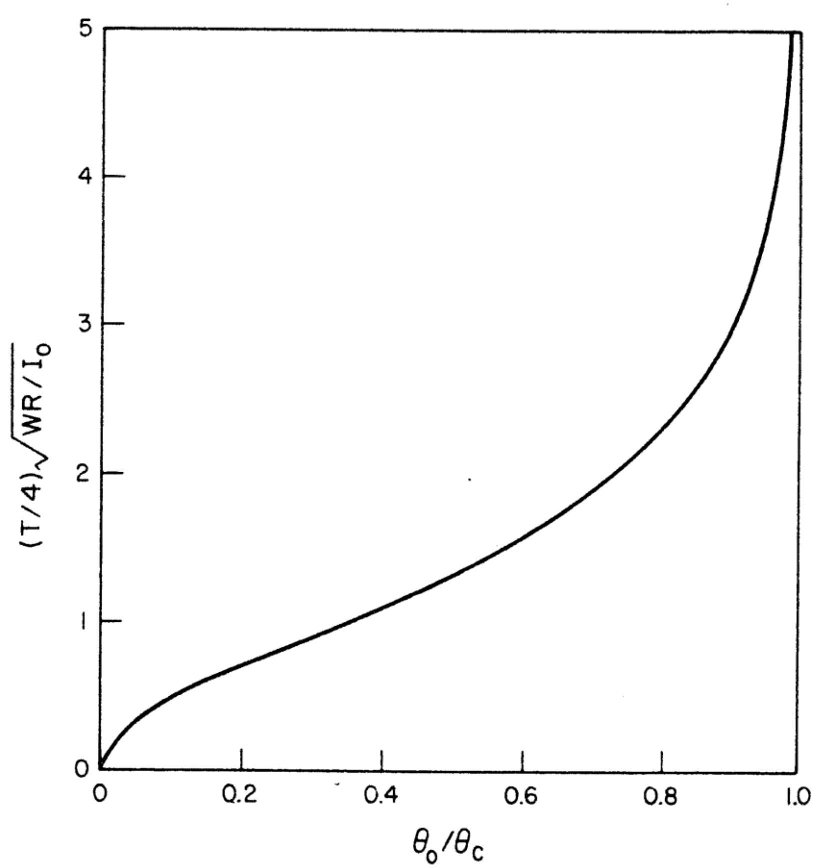
- "In an attempt to understand the nonlinear and poorly conditioned phenomena of the response of rigid structures to ground motion, these structures are idealized as rigid blocks. Despite this idealization, the problem of simulating the response of rigid blocks is still a very difficult problem in solid mechanics." (Lucero and Ross, 2003)

The Rocking of A Rigid Body

- What are some of the behavioral characteristics that make rigid body rocking such a difficult problem?
- Answer: It is highly nonlinear in almost every aspect of its behavior and sensitive to initial conditions.

Behavioral Characteristics of Rigid Body Rocking

- Non-dimensional Period of Vibration, T, vs. Rocking Amplitude,
- Frequency = 1/T

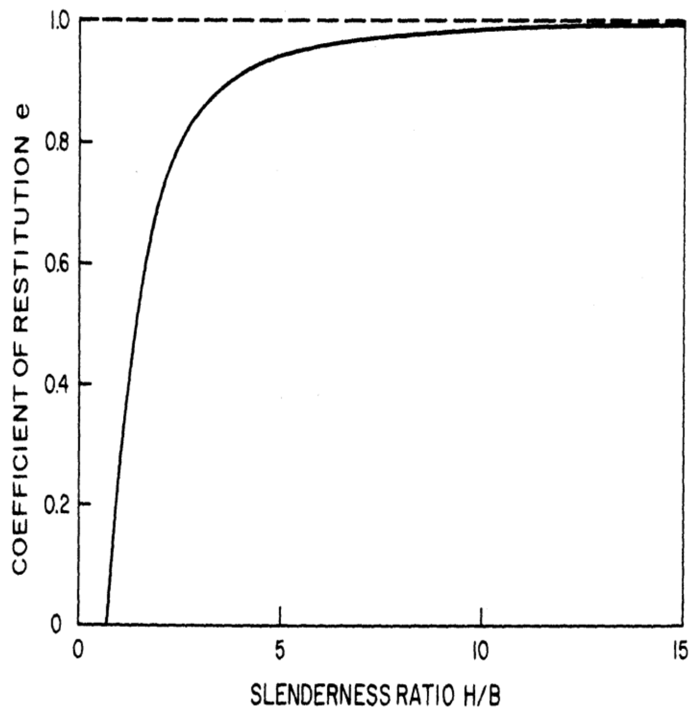


Free vibration period T of block rocking with amplitude θ_0 (Reference 6)

Behavioral Characteristics of Rigid Body Rocking

- Variation of the Coefficient of Restitution, based on the conservation of angular momentum, with slenderness ratio.

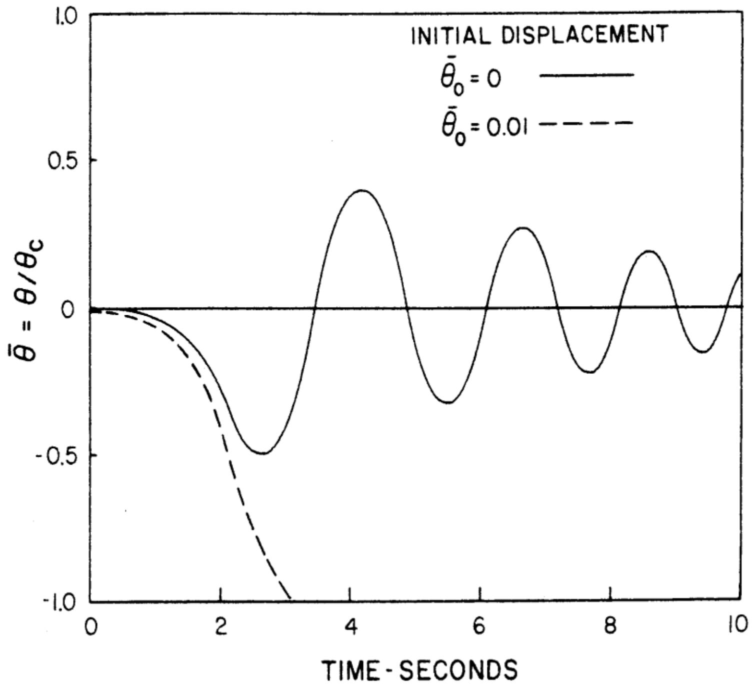
- For a typical Stack-up, H/B = 3 to 3.3
- For a typical storage cask, H/B = 1.5 to 1.8



Variation of coefficient of restitution, based on conservation of angular momentum, with slenderness ratio

Behavioral Characteristics of Rigid Body Rocking

- Rocking Sensitivity to Initial Conditions.



Response of a block ($R = 10$ ft, $H/B = 4$) to a rectangular pulse of acceleration = 0·26 g and duration = 2·1 s

Behavioral Characteristics of Rigid Body Rocking

- Very Sensitive to the Details of the Ground Motion

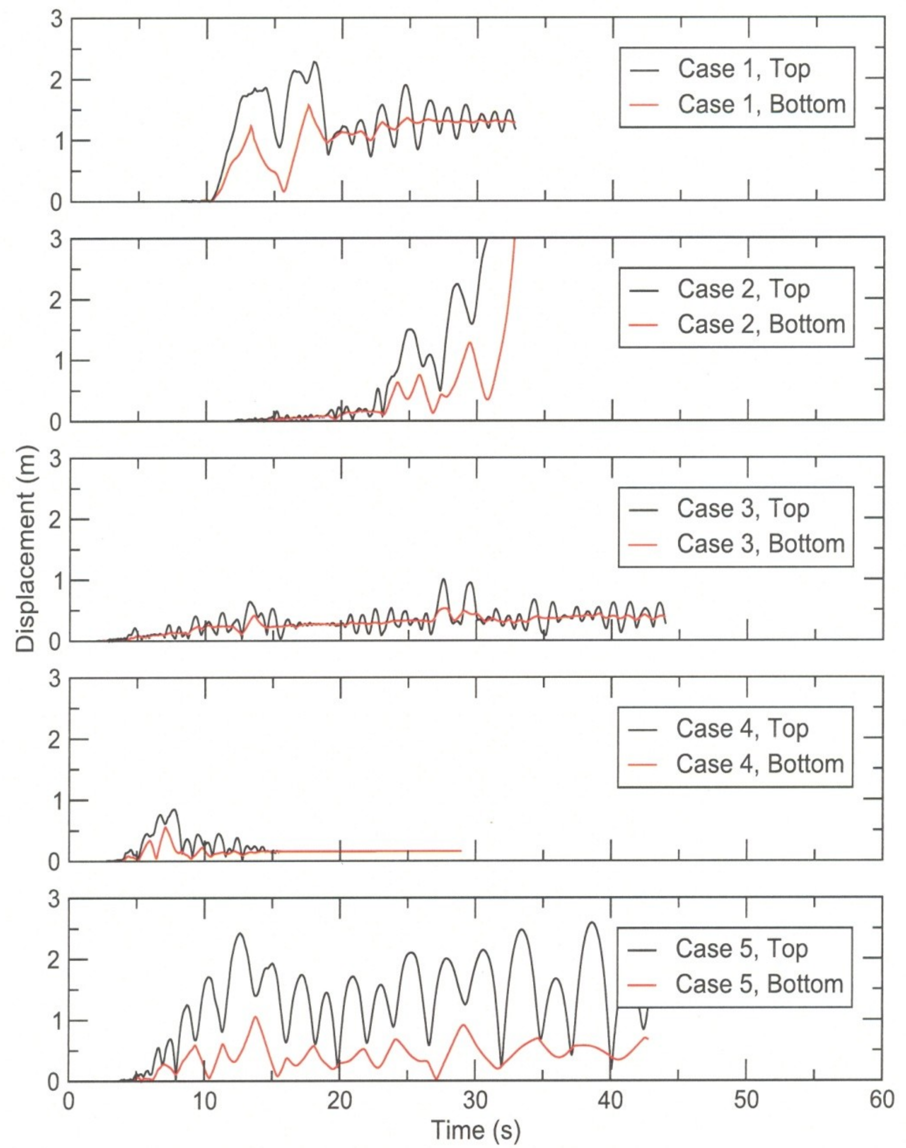


Figure 5.12: Time Histories of Cask Displacement Relative to Pad for Cylindrical Cask, Stiff Soil Profile, Cask/Pad μ=0.8, All 5 Earthquakes, NUREG/CR-0098 Spectral Shape, PGA=1.0 g

Observations by Researchers

- The rocking response of a rigid block is very sensitive to small changes in its size and slenderness ratio and to details of the ground motion.
- The stability of a block subjected to a particular ground motion does not necessarily increase with increasing size or decreasing slenderness ratio.
- Overturning of a block by a ground motion of particular intensity does not imply that the block will necessarily overturn under the action of more intense ground motion.
- Vertical ground motion significantly affects the rocking response of a rigid block, although in no apparently systematic way.
- In contrast, systematic trends are observed when the rocking response of rigid blocks is studied from a probabilistic point of view.

Draft Guidance

- Early Summer 2011: A draft guidance document was sent to SFST, NRO and NRR staff for review and comment.

- An important element of the draft guidance was the use of the ASCE Standard 43-05 Appendix A methodology.

- Of the comments received, two would require a significant effort to resolve.

Comments Related to the Use of ASCE Standard 43-05 Appendix A

- ASCE Standard 43-05 Appendix A only considers the rocking mode. It does not consider the sliding-rocking mode. Does the sliding-rocking mode produce greater rocking than rocking alone?

- What is the NRC staff's basis for accepting the ASCE Standard 43-05 Appendix A methodology? (NUREG/CR-6926 specifically states that "the application of such methods should be reviewed on a case-by-case basis.")

- NUREG/CR-6926, "Evaluation of the Seismic Design Criteria in ASCE/SEI Standard 43-05 for Application to Nuclear Power Plants," Brookhaven National Laboratory, March 2007.

Resolution

- The most expeditious way to resolve these two questions would be to use the results presented in NUREG/CR-6865.

- NUREG/CR-6865, "Parametric Evaluation of Seismic Behavior of Freestanding Spent Fuel Dry Cask Storage Systems," Sandia National Laboratories, February 2005

Scope of the Parametric Analyses

Table 4.1: Scope of Parametric Analyses

Input Parameter	Description	Details
Coupled finite element models	2 Cask designs	Vertical cylindrical cask and horizontal rectangular module
	3 Foundation types	Soft soil, stiff soil, and rock
	3 Coefficients of friction at cask/pad interface	0.20, 0.55, and 0.80
Seismic ground motions	3 Spectral shapes	NUREG/CR-0098 Regulatory Guide 1.60 NUREG/CR-6728
	5 Selected earthquake records	NUREG/CR-0098 and Regulatory Guide 1.60: 1) 1978 Iran Tabas 2) 1999 Taiwan Chi-Chi 3) 1992 Landers 4) 1994 Northridge 5) 1979 Imperial Valley
		NUREG/CR-6728: A) 1985 Nahanni B) 1988 Saguenay C) 1979 Imperial Valley D) 1989 Loma Prieta E) 1994 Northridge
	4 PGA (Peak Ground Acceleration) levels	0.25, 0.60, 1.00, and 1.25 g

Distribution of the Coefficient of Friction (CoF) between Steel and Concrete

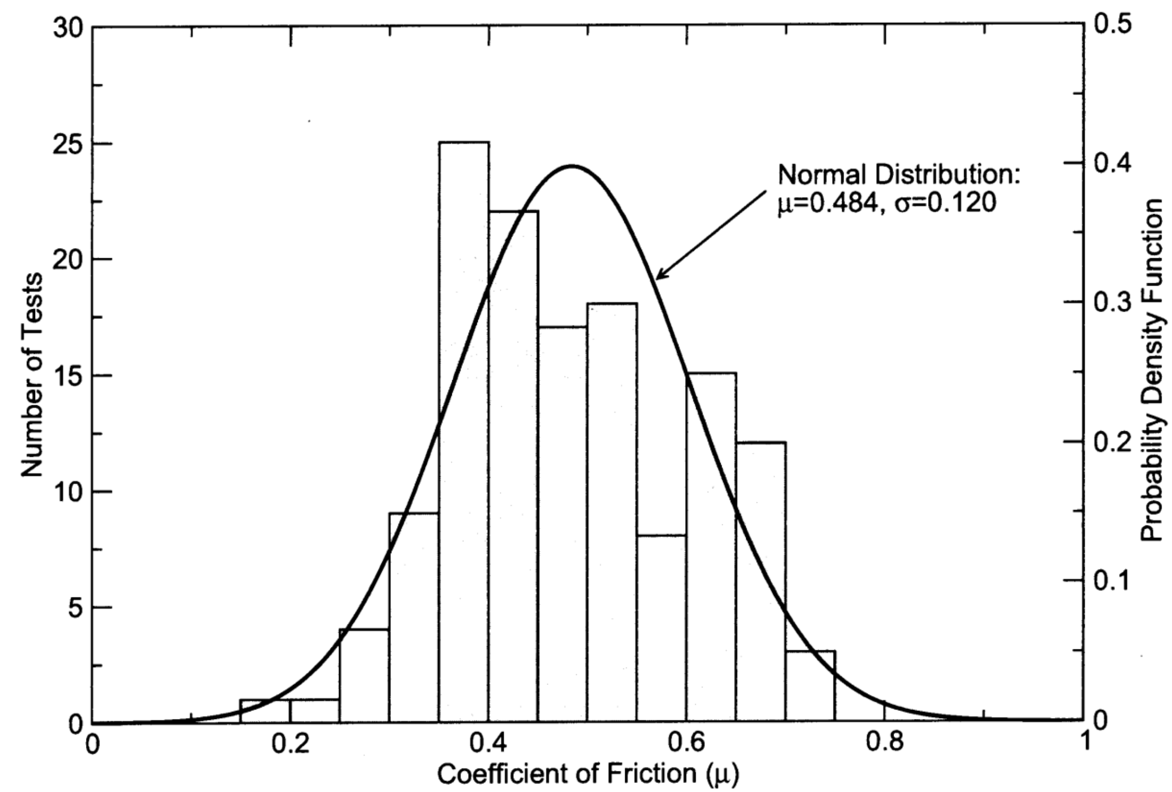
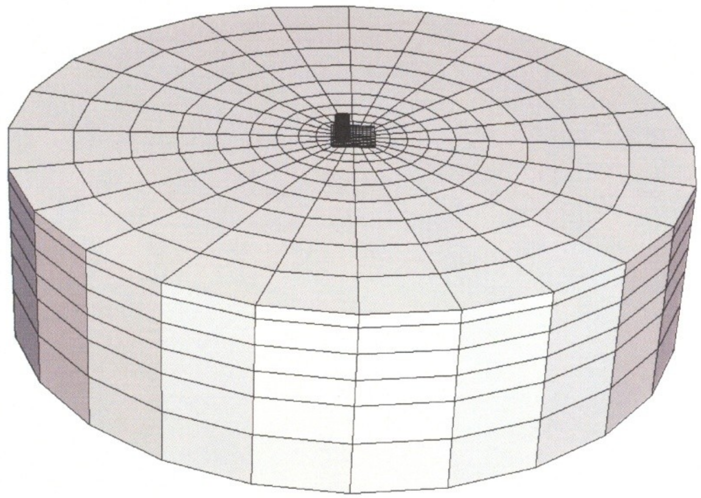
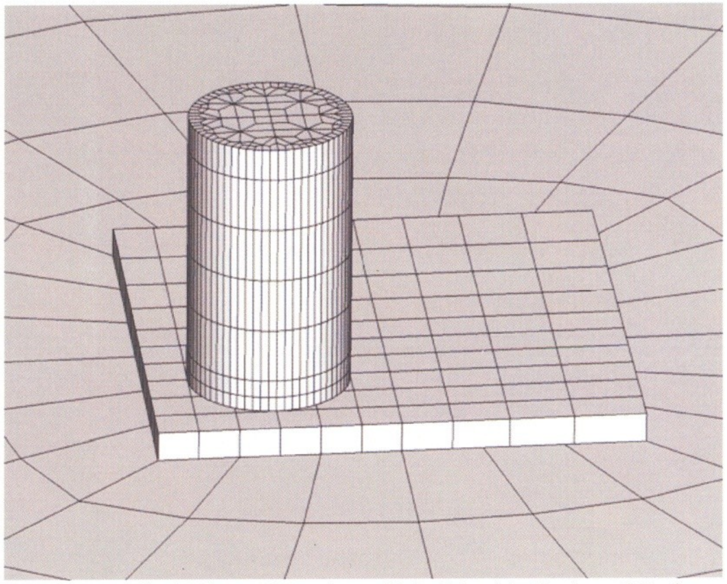


Figure 4.5: Histogram of Steel/Concrete Coefficient of Friction Test Results

Seismic Analysis Model for the HI-STORM 100 Cask



(a) Overall Model



(b) Detailed View of Region of Model with Cask and Pad

Figure 3.6: Finite Element Model of Cylindrical Cask, Pad, and Foundation

Sliding-Rocking Evaluation

Sliding-Rocking Evaluation

Based on NUREG/CR-6865

RG 1.60 Spectra, All Soil Profiles

	$\mu = 0.20$	$\mu = 0.55$	$\mu = 0.80$
PGA	Median Peak Cask Rotation (Degrees)		
0.25	0.01	0.09	0.12
0.40	0.02	0.84	1.23
0.60	0.03	5.64	9.14
1.00	0.07	62.50	114.00

Peak Cask Rotation

RG 1.60 & CoF = 0.8

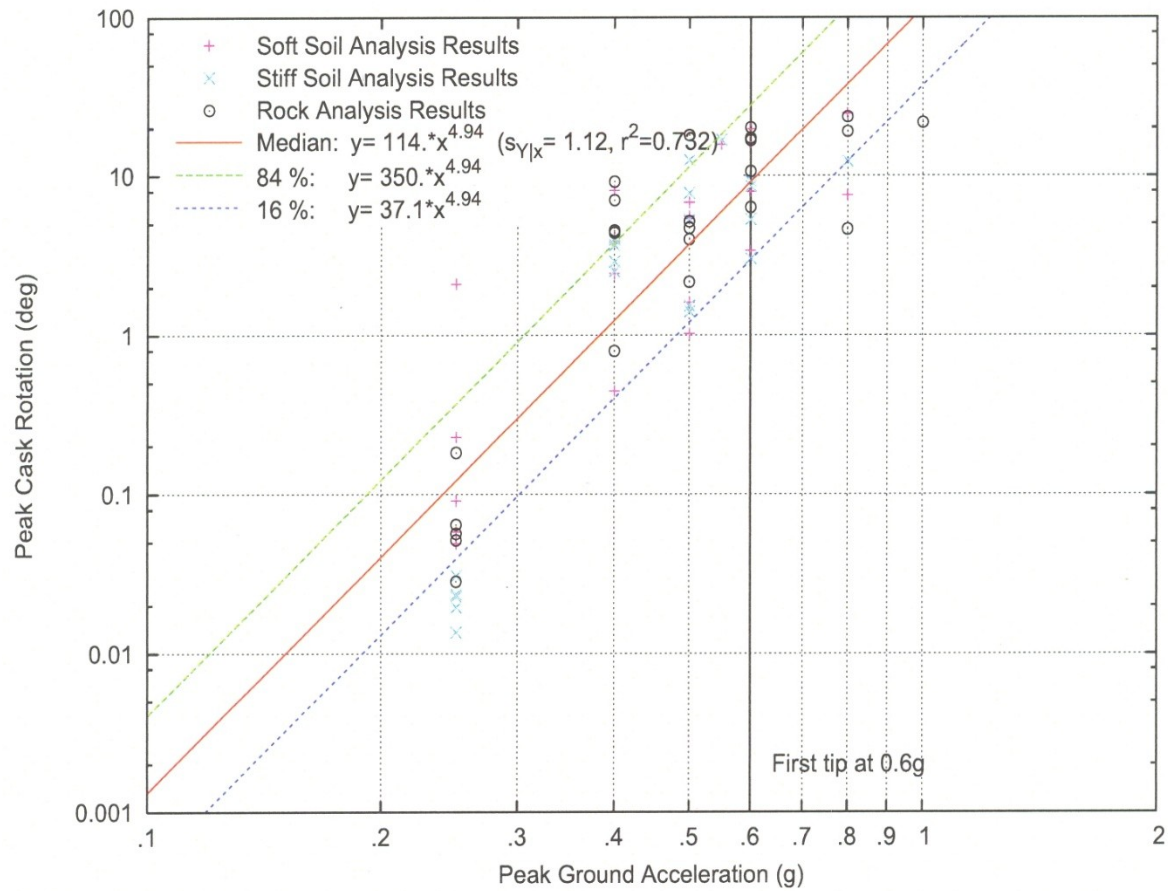


Figure VI.24: Peak Rotation Regression Fit, Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

Peak Cask Rotation

NUREG-6865 vs ASCE Standard 43-05 App. A

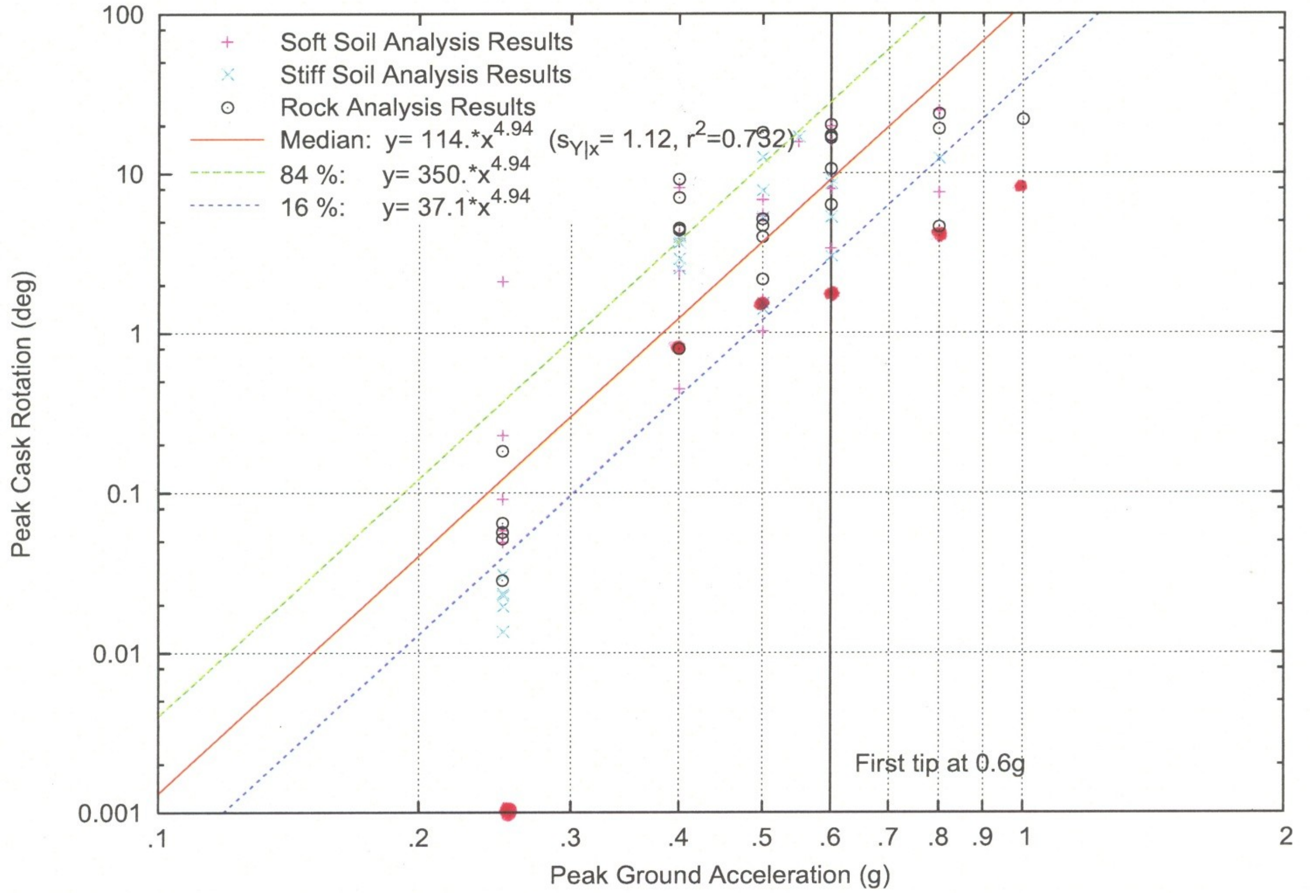


Figure VI.24: Peak Rotation Regression Fit, Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

Peak Cask Rotation

Comparison of ASCE 43-05 Appendix A Results with NUREG/CR-6865 Time History Results

$\mu = 0.80$, RG 1.60, All Soil Profiles
Critical Angle = 29.2 degrees

	Median Peak Cask Rotation (Degrees)	
PGA	NUREG/CR-6865 Median	ASCE 43-05 App. A, 10% Damping
0.25	0.1	0
0.40	1.2	0.8
0.50	3.7	1.4
0.60	9.1	2.1
0.80	37.9	4.4
1.00	114.0	7.9

Key Elements of the Proposed Draft NRC Guidance Document for the Evaluation of the Seismic Stability of a Stack-up Configuration

Rocking Evaluation Methods

Pre-Decisional Information

- For low levels of floor motion intensity, the stack-up configuration may be evaluated using linear elastic dynamic analysis methods (e.g., response spectrum analysis). If such an analysis shows that insipient tipping will take place, then nonlinear time history analysis methods shall be used.

Pre-Decisional Information

Connection of the Transfer Cask to the Storage Overpack via the Mating Device

- The transfer cask shall be attached to the mating device and the mating device shall be attached to the storage overpack by positive mechanical connections. The connections and mating device shall be designed to resist DL, LL and SSE without exceeding the Level D Stress Limits of the ASME B&PV Code Section III, Division 1, Subsection NF.

- DL = Dead Load; LL = Live Load; SSE = Safe Shutdown Earthquake

Pre-Decisional Information

Rotational Stiffness of the Mating Device

- To determine the rotational stiffness of the mating device a detailed finite element model incorporating the effects of prying action may be required. Given the possible asymmetry of the mating device about the horizontal rotational axes, the stiffness about a horizontal axis in one direction may be different about the same axis in the other direction. Because of the sensitivity of rocking to small changes in initial conditions, analyses shall be performed using both stiffnesses. However, if the rocking frequency of the transfer cask using the lower of the two frequencies is greater than the frequency at the ZPA of the floor spectra, the entire stack-up may be considered to respond as a single rigid body.

Pre-Decisional Information

ASCE Standard 43-05 Appendix A Rocking Methodology

- At this time the staff has no basis for accepting the rocking methodology of ASCE Standard 43-05 Appendix A.

Use of Multiple Time Histories

Pre-Decisional Information

- When performing nonlinear time history analyses of the stack-up configuration, multiple sets of floor motion time histories should be used to represent the floor motion. Each set of floor motion time histories shall be selected from real recorded ground motions. The staff suggests that the five ground motion time histories used to envelope the RG 1.60 ground spectrum in NUREG/CR-6865 be used. The amplitude of these ground motions may be scaled but the phasing of the Fourier components must be maintained.
- The mean plus one standard deviation of the calculated responses shall be an estimate of the maximum rocking angle. This estimate multiplied by a safety factor of 2.0 shall not exceed the critical angle for tip-over.

Pre-Decisional Information

Canister Movement within the Transfer Cask

- When the nominal radial gap between the canister and transfer cask is small (<1/2”) the canister and transfer cask may be considered to respond together as a rigid body.

Damping

Pre-Decisional Information

- Two distinctly different types of damping exist in the rocking of a solid (non-rigid) body.
- The first type of damping is rigid body impact damping, which results solely from considering the conservation of momentum of a rocking rigid body, and is not related to material, or hysteretic damping.
- The second type of damping is material damping, which results from energy dissipation within the material itself. The damping values given in RG 1.61 shall be used for material damping.
- Only material damping shall be used in the time history rocking analysis, since impact damping is already accounted for in the rocking of a rigid body.

Supporting Structure

Pre-Decisional Information

- The supporting structure (floor system or combined transport structure and floor system) shall be designed to support the concentrated load of the stack-up configuration in a slightly tipped condition. The flexibility of the supporting structure shall be modeled in the dynamic analysis.

Crane Supported Stack-up

Pre-Decisional Information

- When the transfer cask is supported and held by the main crane, the stack-up configuration shall be considered stable.

- Questions