STAFF EXHIBIT P

NRC Project on Seismic Behavior of Spent Fuel Storage Cask Systems

Seismic Analysis Report on HI-STORM 100 Casks at Private Fuel Storage Facility, Rev. 1

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1. EXECUTIVE SUMMARY

The Spent Fuel Project Office (SFPO) in the Office of the Nuclear Material Safety and Safeguards (NMSS) at the Nuclear Regulatory Commission (NRC) is involved in investigating technical issues concerning the dry storage and transportation of spent nuclear fuel. Sandia National Laboratories (SNL) was contracted by the Engineering Research Applications Branch, Office of Nuclear Regulatory Research (RES) at the NRC for establishing criteria and review guidelines for the seismic behavior of dry cask storage systems (DCSS). The results of this research are expected to aid the NMSS staff in performing the safety review of licensing applications of DCSS.

A typical Independent Spent Fuel Storage Installation (ISFSI) licensed under 10 CFR Part 72 consists of arrays of freestanding storage casks resting on a concrete pad. In the safety review process of these cask systems, it is important to know their dynamic response in terms of sliding, tipping, collision of neighboring casks, and the integrity of cask internals under seismic loads.

This report documents the development of the finite element models and the analysis results to examine the seismic behavior of cylindrical HI-STORM 100 casks to be installed on concrete pads at the proposed Private Fuel Storage (PFS) Facility in the state of Utah. The research team consisting of analysts and engineers at SNL, ANATECH, and Earth Mechanics developed three-dimensional coupled finite element models and performed seismic analyses. The ABAQUS / Explicit code was used to develop the coupled models that consist of cylindrical cask, a flexible concrete pad, a soil-cement layer under and adjacent to the pad, and an underlying soil foundation. The research project focuses on examining the dynamic and nonlinear behavior of the model including the soil-structure-interaction effects during a seismic event.

Three sets of seismic time histories were considered in the coupled model analyses. Two of them are specific to the PFS site using seismic input time-histories based on a 2,000-year and a 10,000-year return period. The third one is based on the 1971 San Fernando Earthquake, Pacoima Dam record. Each set has one vertical and two horizontal components of statistically independent seismic accelerations. For the seismic event with a 2,000-year return period, the peak ground accelerations (PGAs) are 0.728 g (horizontal, east - west), 0.707 g (horizontal, north - south), and 0.721 g (vertical), which envelop the 2,000-year design basis response spectra of 0.711 g (horizontal) and 0.695 g (vertical) stated in the Safety Evaluation Report for the PFS Facility. The corresponding peak ground accelerations for the seismic event with a 10,000-year return period are: 1.25 g, 1.23 g, and 1.33 g, which envelop the PFS earthquake hazard spectra. The duration of both events is 30 seconds. For the 1971 San Fernando Earthquake, Pacoima Dam record with duration of 41.8 seconds, the peak ground accelerations for the two horizontal components are 0.641 g and that for the vertical component is 0.433 g. A deconvolution procedure was used to adjust the amplitudes and frequency contents of the surface defined accelerations before applying them simultaneously at the base of soil foundation in the coupled model.

There are two other important parameters involved in the seismic analyses of the PFS casks. The first parameter is the coefficient of friction at each of the three interfaces in the model: cask/pad, pad/soil-cement layer, and soil-cement layer/soil foundation. A lower bound coefficient of friction of 0.20 (for investigating cask sliding) and an upper bound coefficient of friction of 0.80 (for examining the possibility of cask tipping-over) were used at the cask/pad interface. Coefficients of friction of 1.00 and 0.31 were also assumed at the other two interfaces. The second parameter is the selection of soil profile data for the soil foundation model. The best estimate, the lower bound and the upper bound soil profile data were used separately in the seismic analyses of PFS casks.

The separation distance between neighboring casks is 47.50 inches and half of this distance equal to 23.75 inches has been regarded as the cask collision criterion. The analysis results indicate that the maximum horizontal cask sliding displacements are 15.94 inches (for the 10,000-year return period), 3.98 inches (for the 2,000-year return period), and 3.00 inches (for the 1971 San Fernando Earthquake, Pacoima Dam record). Therefore, no cask collision will occur in all cases under investigation. In addition, the analysis results show that the maximum cask rotation with respect to the vertical axis in either horizontal direction is less than 1.5 degrees, which is significantly less than the cask rotation for tipping over (approximately 29 degrees). Therefore, the PFS casks are not anticipated to tip over during an earthquake return period of either 2,000 years or 10,000 years.

2. PROJECT TASK DESCRIPTION

2.1 Project Objectives

There is a research project at Sandia National Laboratories (SNL), funded by the Engineering Research Applications Branch, Office of Nuclear Regulatory Research (RES) at the Nuclear Regulatory Commission (NRC), to pursue the following objectives:

1. To investigate the dynamic responses of a freestanding dry cask storage system subjected to a prescribed seismic excitation through:
   a) Developing a coupled finite element model of module/cask, pad, soil-cement layer under and adjacent to pad, and soil/rock foundation,
   b) Applying sets of properly prescribed seismic time histories to the model, and
   c) Applying appropriately selected material properties to the submodels and physical parameters at their interfaces.
2. To provide support to the NRC in revising the Regulatory Guidelines for the dry cask storage systems.

2.2 Introduction

The Spent Fuel Project Office (SFPO) in the Office of the Nuclear Material Safety and Safeguards (NMSS) at the Nuclear Regulatory Commission (NRC) is involved in investigating technical issues concerning the dry storage and transportation of spent nuclear fuel. Sandia National Laboratories (SNL) was contracted by the Engineering Research Applications Branch, Office of Nuclear Regulatory Research (RES) at the NRC for establishing criteria and review guidelines for the seismic behavior of dry cask storage systems (DCSS). The results of this research are expected to aid the NMSS staff in performing the safety review of licensing applications of DCSS.

One type of Independent Spent Fuel Storage Installations (ISFSI) licensed under 10 CFR Part 72 [1] consists of array(s) of freestanding storage casks resting on a concrete pad constructed on a natural sub-grade or engineered fill soil. The cask stability is an important issue for evaluating the seismic safety of a DCSS.

Seismic evaluation is one of the key areas in the cask safety review. The research project will provide insight on the seismic behavior of a freestanding DCSS. The findings from this project will generate a common basis for the NRC to develop the seismic acceptance criteria and safety review guidance for licensing applications.

2.3 Background

The Private Fuel Storage, L.L.C. (PFS) submitted an application to the NRC for a license to install cylindrical HI-STORM 100 casks on the Reservation of the Skull Valley Band of Goshute Indians, a federally-recognized Indian Tribe [2]. This report documents the analysis results of research conducted in response to a specific request from the NRC to

examine the seismic behavior of these casks to be installed at the PFS Facility. The NMSS staff provided the project team with the basic information on cask design, pad dimensions, soil-cement layers under and adjacent to the pad, site specific soil profile, and time histories of seismic accelerations. Two sets of seismic excitations specific to the PFS site were considered in the seismic analyses of the PFS casks using the seismic input time-histories, based on a 2,000-year and a 10,000-year return period. A sensitivity analysis was also performed using the 1971 San Fernando Earthquake, Pacoima Dam record [3]. In each case of seismic excitations, a deconvolution procedure was used to adjust the amplitudes and frequency contents of the surface defined accelerations before applying them simultaneously at the base of soil foundation in the coupled model.

The coupled model has three interfaces at cask/pad, pad/soil-cement layer, and soil-cement layer/soil foundation. Different combinations of coefficients of friction were used at these interfaces. According to the analysis results on rectangular and cylindrical casks obtained by Luk, et al [4 and 5], the cask usually experiences higher sliding displacements with a lower coefficient of friction at the cask/pad interface and higher angular rotations with respect to the vertical axis for a higher coefficient of friction. A lower bound coefficient of friction of 0.20 (for investigating cask sliding) and an upper bound coefficient of friction of 0.80 (for examining the possibility of cask tipping-over) were used at the cask/pad interface. Coefficients of friction of 1.00 and 0.31 were also assumed at the other two interfaces. Three sets of soil profile data (the best estimate, the lower bound and the upper bound) were used separately in the seismic analyses of PFS casks.

3. FINITE ELEMENT ANALYSIS MODELING APPROACH

This section documents the development effort of the coupled model to investigate the dynamic response of freestanding Holtec HI-STORM 100 casks subjected to prescribed seismic excitations. The analysis effort involved the development of a coupled 3D finite element model consisting of a cylindrical cask, a flexible concrete pad, a soil-cement layer under and adjacent to the pad, and an underlying soil foundation. The analysis results from the model address the dynamic coupling among these structural subsystems, in particular, the soil-structure-interaction effects.

The analysts and engineers at SNL, ANATECH, and Earth Mechanics worked jointly in developing the coupled model. The model development effort involved two separate investigations. The first one focused on defining the material properties and investigating the size of soil foundation submodel, which was calibrated by exercising the 1D SHAKE [6] and 2D DYNA-FLOW [7] simulations. The second one was to address the dynamic and nonlinear response of the cylindrical cask in terms of its wobbling and sliding by examining closely the nonlinear contact behavior at the cask/pad, pad/soil-cement layer, and soil-cement layer/soil foundation interfaces in the coupled model.

There are many factors influencing the dynamic response of casks in an earthquake event. This project focused on performing sensitivity studies on the cask response with three key factors. They are: 1) prescribed seismic loading, 2) coefficients of friction at the interfaces in the coupled model, and 3) soil profile data.

A total of three sets of seismic loading were used as input excitations to the coupled model. A prescribed time history of seismic accelerations with a duration of 30 seconds, which is based on the design basis response spectra of the PFS site for a 2,000-year return period, was used to generate the design basis response of the cask [2]. A similar site-specific time history of seismic accelerations for a 10,000-year return period was used to provide a limiting case assessment of cask response. A sensitivity study was also performed using the 1971 San Fernando Earthquake, Pacoima Dam record [3], which is an actual earthquake record. Each set of seismic loading has one vertical and two horizontal components of statistically independent accelerations. Each one of the three seismic acceleration components was treated with a deconvolution procedure to produce a modified time history of deconvoluted accelerations with properly adjusted frequencies and magnitudes. All three components of deconvoluted accelerations were applied simultaneously at the base of soil foundation in the coupled model. The concept of deconvolution is a mathematically rigorous solution process that applies the wave propagation equation of the free-field surface along with the boundary conditions. It has been proven that the solution would be unique and rigorously correct for a linear representation of the soil mass (that is, linear shear modulus and viscous damping model). Idriss and Seed [8] and Schnabel, et al. [9] provided detailed discussions on the deconvolution procedure.

The coupled model has three interfaces at cask/pad, pad/soil-cement layer, and soil-cement layer/soil foundation. Different combinations with upper and lower bound coefficients of friction were used at these interfaces in search of governing cases for

maximum horizontal sliding displacement or angular rotation of the cask. A lower bound coefficient of friction of 0.20 (for investigating cask sliding) and an upper bound coefficient of friction of 0.80 (for examining the possibility of cask tipping-over) were used at the steel-to-concrete cask/pad interface. Bounding coefficients of friction of 1.00 and 0.31 were also assumed at the other two interfaces.

There are three sets of soil profile data (the best estimate, the lower bound and the upper bound) for the PFS site. Each set of soil profile data was used separately in the seismic analyses of PFS casks. Different soil profile data were used for the seismic events with 2,000-year and 10,000-year return periods and the 1971 San Fernando Earthquake, Pacoima Dam record. For the seismic event with the 10,000-year return period, the shear modulus and damping of each layer of the soil foundation are adjusted for shear strains while for the seismic events with the 2,000-year return period the low strain shear modulus and damping were used.

3.1 Description of Analysis Model

The three-dimensional coupled finite element models of a cylindrical HI-STORM 100 cask, a flexible concrete pad, a soil-cement layer under and adjacent to the pad, and an underlying soil foundation were developed using the ABAQUS / Explicit code, Version 5-8.19 [10]. The layout of the entire model is shown in Figure 1. The directional views of the model in three orthogonal axes are illustrated in Figures 2, 3, and 4, respectively. The coupled model consists of a HI-STORM 100 overpack cask with MPC-68 option freestanding on a full-sized concrete pad that is designed to hold 8 (2x4) casks, as shown in Figure 5. There is a shallow layer of compact aggregate and soil-cement, acting as a passive constraint, adjacent to the concrete pad. This shallow surface layer and the concrete pad are placed on a continuous soil-cement layer that is on top of the soil foundation. Figure 6 shows a detailed surface layout above the soil foundation.

All of the ABAQUS elements of the coupled model are of the type "C3D8R", which is a three-dimensional continuum/solid of 8-nodes, with reduced (one Gauss point) integration and built-in hourglass control. The cask is modeled as a solid cylindrical body partitioned into four horizontal sections with six radial rows of solid elements in each section and 64 elements around the outside perimeter. The density of solid elements in each horizontal section is calculated and distributed in such a manner that the center of gravity of the cask is located at the correct design position. The cask, the concrete pad, the compacted aggregate, and the soil-cement layers are modeled as elastic bodies.

In the coupled model, contact elements are used at the three interfaces of cask/pad, pad/soil-cement layer, and soil-cement layer/soil foundation. At the top two interfaces involving the pad, the pad surface is designated as the "master' surface and the "slave" option is assigned to its interacting partner. At the third interface, the underside of the soil-cement layer is designated as the "slave" surface and the top of the soil foundation as the "master" surface. Different combinations of upper bound and lower bound interfacial coefficients of friction were selected in the seismic analyses of casks to search for the governing cases of maximum horizontal sliding displacement or angular rotation of casks.

In order to simulate semi-infinite boundary conditions, the outside layer of elements on the four vertical sides of soil foundation submodel are represented by edge columns that allow only horizontal shear deformation. The input motion of the deconvoluted seismic accelerations is applied to all nodes at the base of the soil foundation submodel.

3.2 Model Details

The coupled model consists of four structural components: a single cylindrical HI-STORM 100 cask, a flexible full-sized concrete pad, a soil-cement layer under and adjacent to the pad, and a soil foundation. The modeling details of each submodel are described in the following subsections.

3.2.1 Cask Submodel

The HI-STORM 100 overpack casks with MPC-68 option were used at the PFS Facility.

3.2.1.1 Geometry

Outside Diameter = 132.5"

Height = 231.25"

Height of center of gravity above pad = 118.38"

3.2.1.2 Weight

Weight of an overpack cask with fully loaded MPC-68 = 360,000 lbs.

3.2.2 Concrete Pad Submodel

A continuous concrete pad (30' x 67' x 3') holding 2x4 HI-STORM 100 casks was designed for the PFS Facility. This full-sized pad was used in the coupled model.

3.2.3 Soil-cement Layers and Compact Aggregate

There is a shallow layer of compact aggregate (8") and soil-cement (2'-4"), acting as a passive constraint, adjacent to the concrete pad. The compact aggregate layer, which was only used in a narrow band around the concrete pad, is 10' and 5' wide in U1 and U2 directions, respectively (see Figure 5). This surface layer and the concrete pad are placed on a continuous soil-cement layer of 2' that is on top of the soil foundation.

3.2.4 Soil Foundation Submodel

The size of the soil foundation submodel plays an important role in assessing the soil-structure-interaction (SSI) effect. Sensitivity studies on the submodel size

were performed to demonstrate that its chosen model size could simulate the behavior of a semi-infinite soil foundation underneath the 2' soil-cement layer. The lateral dimensions of the soil foundation submodel are finalized as 330' in U1 direction and 757' in U2 direction (see Figure 4), which are either equal or slightly larger than eleven times the pad size in the corresponding directions. It should be noted that the outside layer of elements on the four vertical sides of soil foundation submodel, with widths equal to the pad dimensions, are represented by edge columns. This model configuration indicates that the nodes at the inner row of the set of edge columns define the true model size with their degrees of freedom constrained to those at the outside row. Therefore, the actual geometry of the soil foundation submodel is only nine times (or slightly larger) the pad dimension. This selection of the lateral dimension of soil foundation submodel exceeded the recommended minimum as defined by the US Corps of Engineers soil-structure-interaction modeling guidelines [11].

In addition, a depth of 140', which was partitioned into six horizontal layers as shown in Figure 2, was selected for the soil foundation submodel. The 140' depth was chosen to reach a level below that the soil stiffness increases monotonically with depth. In addition, it was also based on satisfying the guidelines in American Society of Civil Engineers (ASCE) Standard [12]. In the close vicinity of the concrete pad, the top surface is further divided into compact aggregate and soil-cement layer, as illustrated in Figure 6.

3.3 Material Properties of Cask and Pad

The cask and the concrete pad are assumed to behave elastically when subjected to seismic excitations. Therefore, their elastic material properties were chosen in the model as shown in Table 1. The cask and pad moduli are based on assumed concrete strengths of 5,000 psi and 4,000 psi, respectively. The cask and pad are modeled as elastic bodies with zero damping.

Table 1. Elastic Material Properties of Cask and Pad

Structural Element	Young's Modulus, E (psi) (x 10^6)	Poisson's Ratio, ν	Density, ρ (lb-s^2/in.^{4})
Cask	4.0305	0.2	0.000318496 (Section 4)*
			0.000243043 (Section 3)*
			0.000243043 (Section 2)*
			0.000599072 (Section 1)*
Pad	3.6050	0.2	0.00022465

* Geometry definition of horizontal sections of the cask:

Section 1: from cask base to 8" above base

Section 2: from 8" above base to 24" above base

Section 3: from 24" above base to 118.38" above base

Section 4: from 118.38" above base to cask top

3.4 Soil Foundation

The site-specific soil profile data at the PFS Facility are categorized in terms of best estimate, lower bound and upper bound to provide a broad range of variation. For each set of soil profile data, the soil foundation was partitioned into thirteen horizontal layers to a depth of 700 feet. In the 3D coupled model, it was decided to use six horizontal layers to a depth of 140 feet to represent the soil foundation. Sensitivity studies were performed to demonstrate the adequacy of using this discretization scheme to incorporate the depth variation of soil properties such as shear wave velocity and damping profiles in the soil foundation submodel.

The same soil profile data (best estimate, lower bound and upper bound) were used in performing the cask analyses for the seismic event with a 2,000-year return period and the 1971 San Fernando Earthquake, Pacoima Dam record. However, different soil profile data were used for the seismic event with a 10,000-year return period in which the shear modulus and damping factor of the soil foundation are dependent on its shear strains.

3.4.1 Soil Material Properties

The 140-foot depth of the soil foundation was partitioned into six horizontal layers. With these graduations, the best estimate, the lower bound, and the upper bound strain-compatible soil properties for different seismic events were averaged for each horizontal layer and are shown in Tables 2 to 7 below. It should be noted that two damping values at each layer were presented in these tables. The damping ratio (%) is the material damping from free field site response analyses using the SHAKE program [9] reflecting the strain dependent soil property for the specific soil layer. These damping ratios were then used to represent the target damping value for the 3D coupled model solutions using the ABAQUS program [10], which utilizes the classical Rayleigh damping algorithm. Only the mass proportional damping response was implemented in the coupled analyses. The mass related damping parameters, a_0, in the tables were chosen such that the resultant damping will match the tabulated target damping value at the overall fundamental period of the soil foundation model. The stiffness proportional damping terms were not implemented (i.e. set to zero) to avoid very severe computational penalty associated with developing the very large stiffness matrix in the 3-D coupled model. This limitation tends to over predict the high frequency response of the soil/pad/cask system and can be regarded as somewhat conservative. Some sensitivity studies have been conducted by the project team using smaller 2-D models to evaluate potential errors introduced in the one parameter Rayleigh damping approach and found that the approach provides reasonable solutions.

Table 2. Best Estimate Soil Properties for Seismic Event with 2,000-year Return Period and the 1971 San Fernando Earthquake, Pacoima Dam Record

Layer No.	Layer Thickness (ft)		Young's Modulus (psi)	Poisson's Ratio	Density (pcf)	Damping Ratio (%)	Mass Related Damping Parameter, a_0
1	5	Aggregate (8")	20,000	0.2	120	NA	0.2000
		Soil-cement (2'-4") adjacent to pad	550,000	0.2	110	0.94	0.4073
		Soil-cement (2') underneath pad	270,000	0.2	100	0.94	0.4073
2	7		10,085	0.3	80	4.44	1.9252
3	14		31,951	0.3	97	2.70	1.1706
4	24		52,727	0.3	115	6.16	2.6693
5	40		198,139	0.3	120	1.74	0.7540
6	50		612,141	0.25	135	4.32	1.8720

Notes: 1. For shear wave propagation model of horizontal motion site response, fundamental period = 0.29 second.

2. For compressional wave propagation model of vertical motion site response, fundamental period = 0.19 second.

Table 3. Lower Bound Soil Properties for Seismic Event with 2,000-year Return Period and the 1971 San Fernando Earthquake, Pacoima Dam Record

Layer No.	Layer Thickness (ft)		Young's Modulus (psi)	Poisson's Ratio	Density (pcf)	Damping Ratio (%)	Mass Related Damping Parameter, a_0
1	5	Aggregate (8")	20,000	0.2	120	NA	0.2000
		Soil-cement (2'-4") adjacent to pad	550,000	0.2	110	1.08	0.3460
		Soil-cement (2') underneath pad	270,000	0.2	100	1.08	0.3460
2	7		6,833	0.3	80	5.72	1.8420
3	14		19,507	0.3	97	3.40	1.0960
4	24		21,917	0.3	115	9.17	2.9550
5	40		170,667	0.3	120	3.02	0.9720
6	50		306,187	0.25	135	3.97	1.2790

Notes: 1. For shear wave propagation model of horizontal motion site response, fundamental period = 0.39 second.

2. For compressional wave propagation model of vertical motion site response, fundamental period = 0.24 second.

Table 4. Upper Bound Soil Properties for Seismic Event with 2,000-year Return Period and the 1971 San Fernando Earthquake, Pacoima Dam Record

Layer No.	Layer Thickness (ft)		Young's Modulus (psi)	Poisson's Ratio	Density (pcf)	Damping Ratio (%)	Mass Related Damping Parameter, a_0
1	5	Aggregate (8")	20,000	0.2	120	NA	0.2000
		Soil-cement (2'-4") adjacent to pad	550,000	0.2	110	0.91	0.6020
		Soil-cement (2') underneath pad	270,000	0.2	100	0.91	0.6020
2	7		17,737	0.3	80	3.25	2.1520
3	14		51,725	0.3	97	2.10	1.3880
4	24		113,176	0.3	115	4.43	2.9300
5	40		705,183	0.3	120	2.64	1.7490
6	50		1,224,151	0.25	135	4.28	2.8310

Notes: 1. For shear wave propagation model of horizontal motion site response, fundamental period = 0.19 second.

2. For compressional wave propagation model of vertical motion site response, fundamental period = 0.12 second.

Table 5. Best Estimate Soil Properties for Seismic Event with 10,000-year Return Period

Layer No.	Layer Thickness (ft)		Young's Modulus (psi)	Poisson's Ratio	Density (pcf)	Damping Ratio (%)	Mass Related Damping Parameter, a_0
1	5	Aggregate (8")	20,000	0.2	120	NA	0.2000
		Soil-cement (2'-4") adjacent to pad	550,000	0.2	110	1.00	0.4054
		Soil-cement (2') underneath pad	270,000	0.2	100	1.00	0.4054
2	7		4,647	0.3	80	8.20	3.3240
3	14		27,148	0.3	97	4.00	1.6215
4	24		38,957	0.3	115	9.35	3.7902
5	40		186,651	0.3	120	3.05	1.2364
6	50		612,141	0.25	135	3.90	1.5809

Notes: 1. For shear wave propagation model of horizontal motion site response, fundamental period = 0.31 second.

2. For compressional wave propagation model of vertical motion site response, fundamental period = 0.19 second.

Table 6. Lower Bound Soil Properties for Seismic Event with 10,000-year Return Period

Layer No.	Layer Thickness (ft)		Young's Modulus (psi)	Poisson's Ratio	Density (pcf)	Damping Ratio (%)	Mass Related Damping Parameter, a_0
1	5	Aggregate (8")	20,000	0.2	120	NA	0.2000
		Soil-cement (2'-4") adjacent to pad	550,000	0.2	110	1.25	0.3653
		Soil-cement (2') underneath pad	270,000	0.2	100	1.25	0.3653
2	7		1,226	0.3	80	13.25	3.8722
3	14		13,090	0.3	97	5.05	1.4758
4	24		17,034	0.3	115	12.00	3.5069
5	40		96,103	0.3	120	3.40	0.9936
6	50		344,329	0.25	135	3.90	1.1397

Notes: 1. For shear wave propagation model of horizontal motion site response, fundamental period = 0.43 second.

2. For compressional wave propagation model of vertical motion site response, fundamental period = 0.24 second.

Table 7. Upper Bound Soil Properties for Seismic Event with 10,000-year Return Period

Layer No.	Layer Thickness (ft)		Young's Modulus (psi)	Poisson's Ratio	Density (pcf)	Damping Ratio (%)	Mass Related Damping Parameter, a_0
1	5	Aggregate (8")	20,000	0.2	120	NA	0.2000
		Soil-cement (2'-4") adjacent to pad	550,000	0.2	110	1.00	0.5027
		Soil-cement (2') underneath pad	270,000	0.2	100	1.00	0.5027
2	7		10,496	0.3	80	5.70	2.8651
3	14		47,910	0.3	97	3.05	1.5331
4	24		71,864	0.3	115	7.70	3.8705
5	40		302,771	0.3	120	2.00	1.0053
6	50		956,470	0.25	135	3.90	1.9604

Notes: 1. For shear wave propagation model of horizontal motion site response, fundamental period = 0.25 second.

2. For compressional wave propagation model of vertical motion site response, fundamental period = 0.12 second.

3.5 Seismic Input at Base of Soil Foundation

Three sets of seismic loading were used as input excitations to the coupled model in performing the dynamic analyses of casks. A seismic event with a duration of 30 seconds, which is based on the response spectra specific to the PFS site for a 2,000-year return period, was used to generate the design basis response of casks. This seismic event is prescribed by one vertical component and two horizontal components of statistically independent accelerations. The peak ground accelerations for the three components are 0.728 g (horizontal, east - west), 0.707 g (horizontal, north - south), and 0.721 g (vertical) [2]. The original time histories of seismic accelerations for this event provided by the NRC are shown in part (a) of Figures 7 - 9.

A sensitivity study on the cask response was also performed using the 1971 San Fernando Earthquake, Pacoima Dam record whose time histories of the three components of accelerations are shown in part (a) of Figures 10 - 12. The peak ground accelerations for the two horizontal components are 0.641 g and that for the vertical component is 0.433 g [3]. It is apparent from the earthquake record that there are very low levels of seismic excitations after the first 20 seconds of this 41.8-second event, therefore the time histories of the first 20 seconds only are plotted in these figures and used in the dynamic analyses.

A similar site-specific time history of seismic accelerations for a 10,000-year return period was used to provide an upper bound assessment of cask response. The peak ground accelerations for the three components, which envelop the PFS earthquake hazard spectra [2], are 1.25 g (horizontal, east - west), 1.23 g (horizontal, north - south), and 1.33 g (vertical). Part (a) of Figures 13 - 15 shows the original time histories of seismic accelerations for this event that were provided by the NRC.

In every set of seismic loading, each one of the three acceleration components was treated with a deconvolution procedure to produce a modified time history of deconvoluted accelerations with properly adjusted frequencies and magnitudes. The net outcome is that when all three components of deconvoluted accelerations are applied simultaneously at the base of soil foundation in the coupled model, the dynamic characteristics of the original seismic motions is preserved and the desired surface shaking intensity can be achieved.

The deconvoluted accelerations for the three seismic events, which were used in the analyses, are shown in part (b) of Figures 7 - 15. The analysis results of the free-field surface accelerations, which are plotted in part (c) of these figures, indicated that they are very similar to the original seismic surface accelerations.

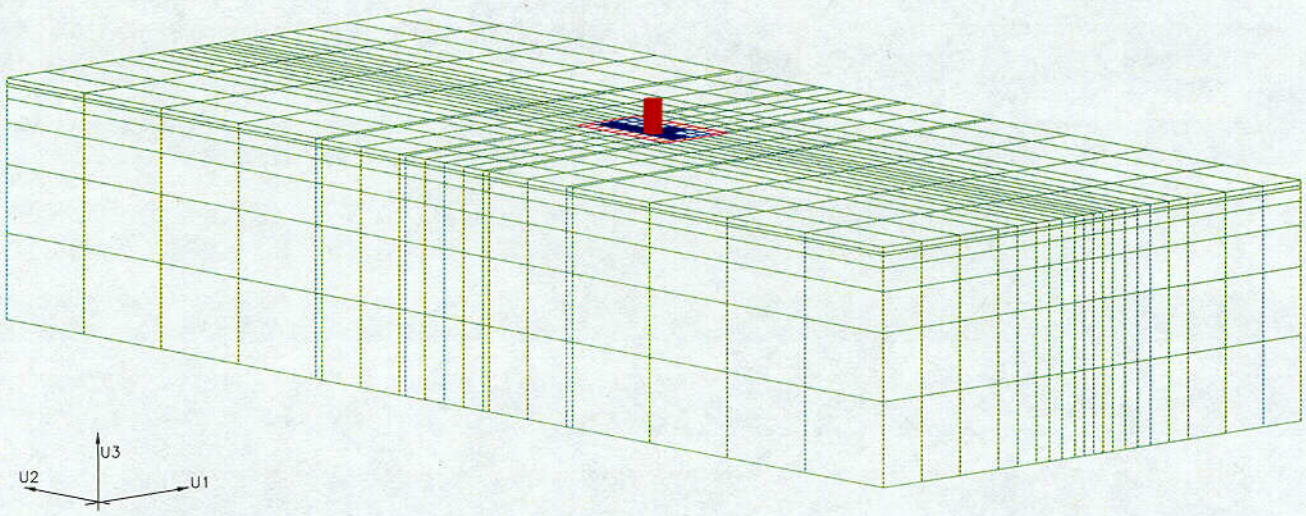


Figure 1. The layout of entire 3D coupled model at PFS Facility

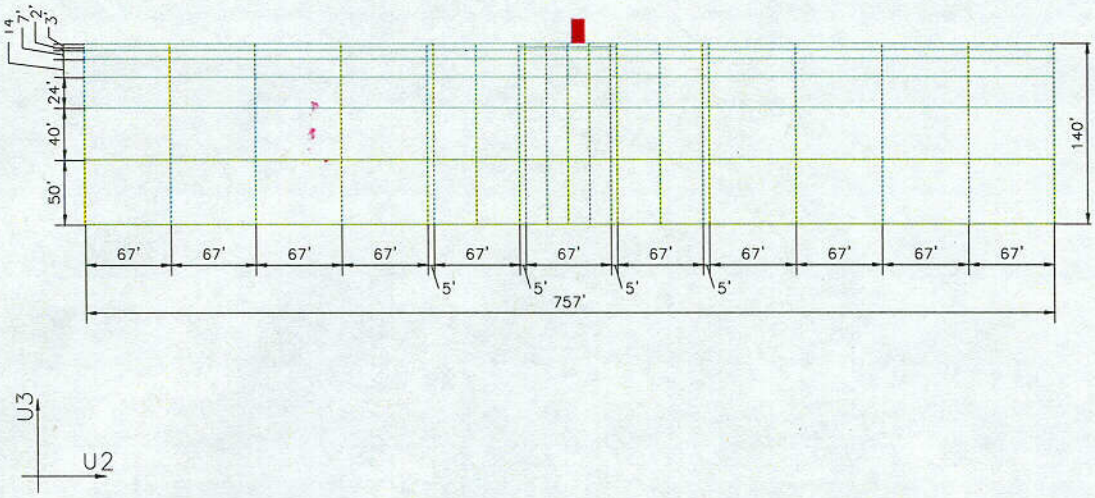


Figure 2. Model layout viewed in U1 direction

C01

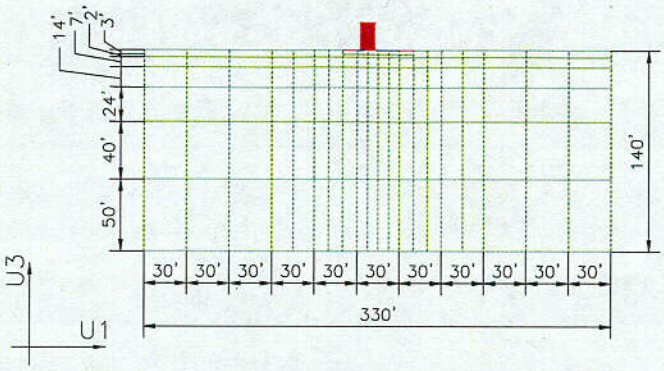


Figure 3. Model layout viewed in U2 direction

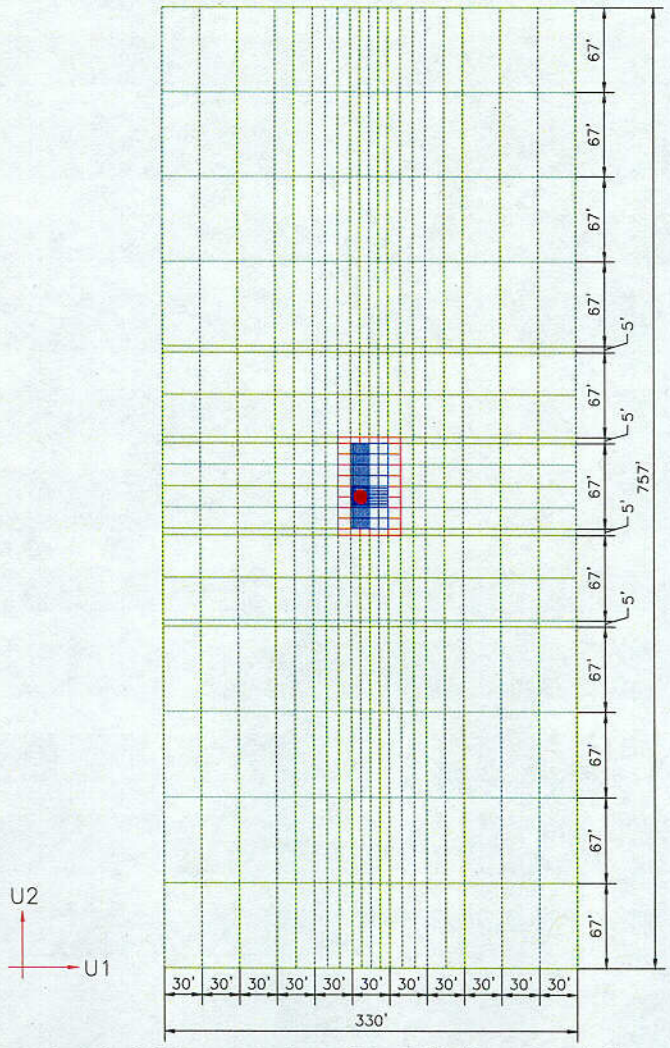


Figure 4. Model layout viewed in U3 direction (plan view)

C02

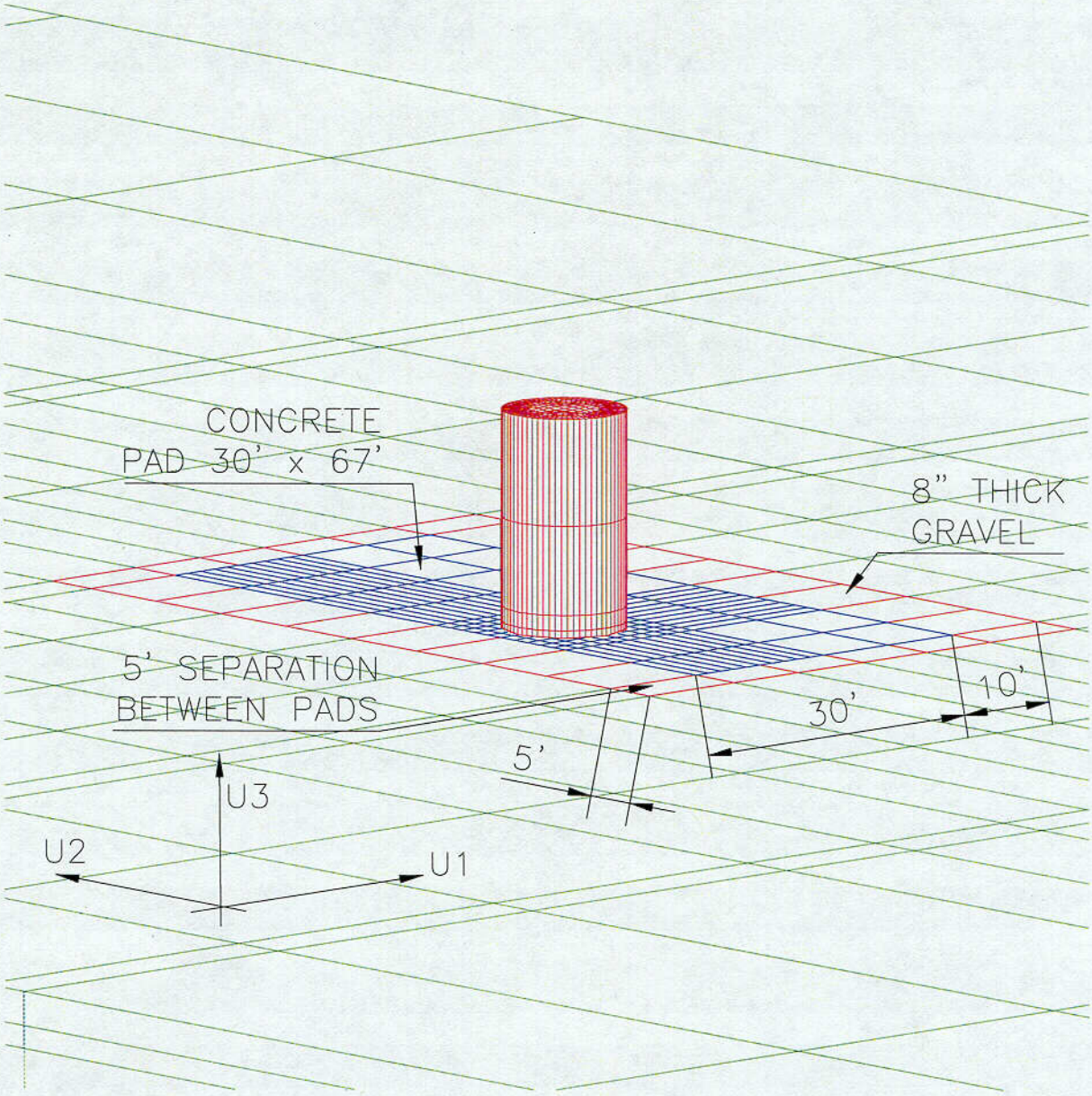


Figure 5. A cylindrical HI-STORM 100 cask on a full-sized concrete pad

C03

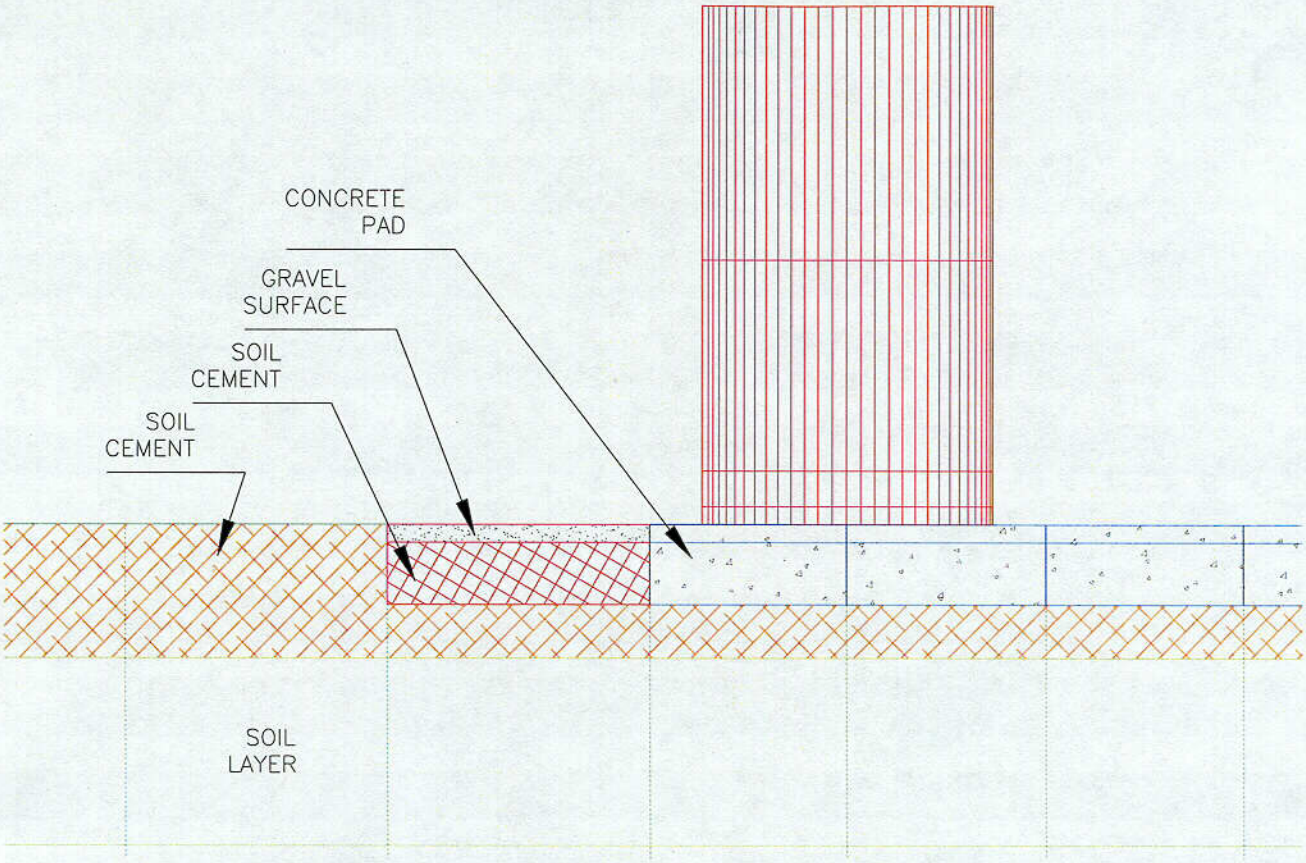
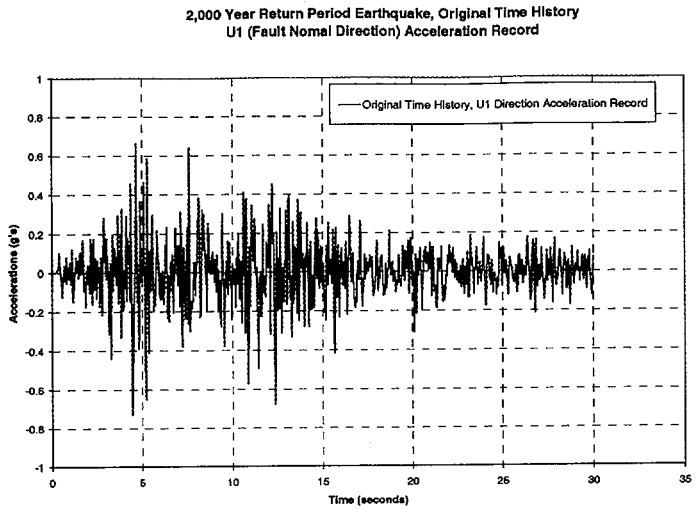
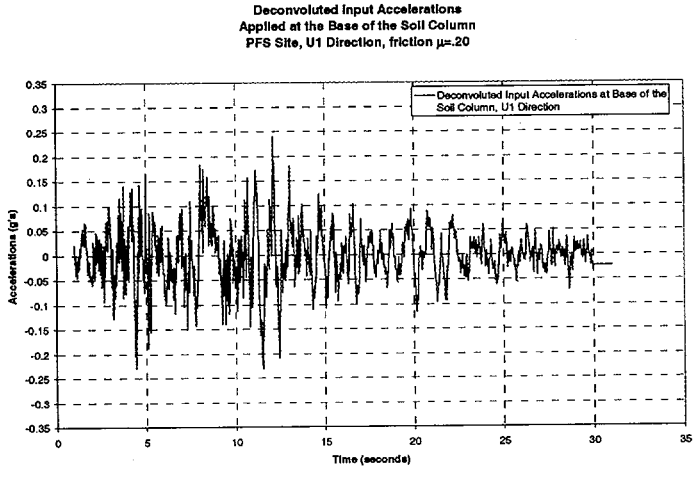


Figure 6. A detailed surface layout above soil foundation

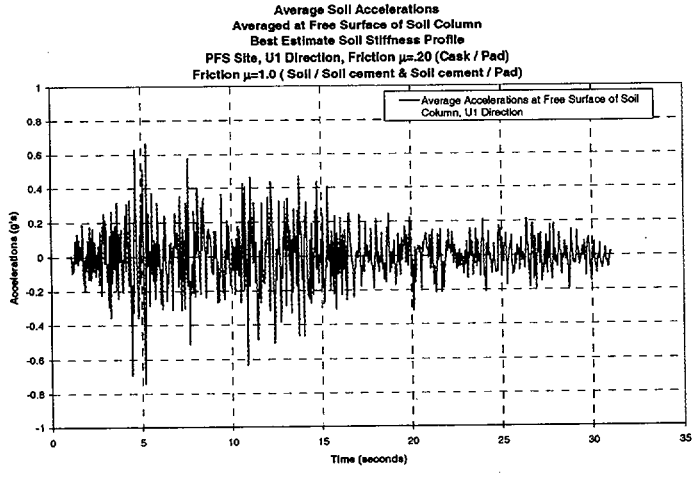
C04



(a) Original time histories

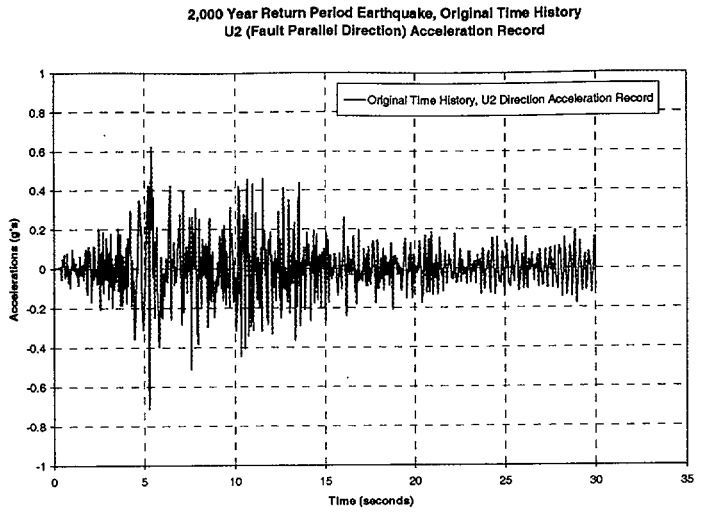


(b) Deconvoluted base input time histories

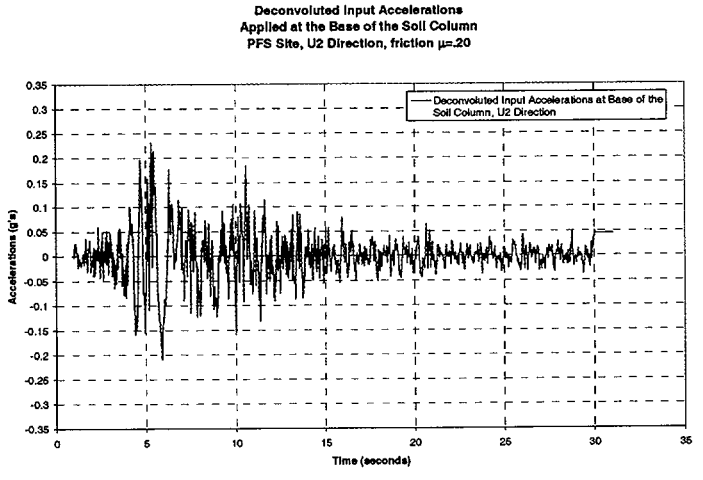


(c) Time histories of free-field analysis results

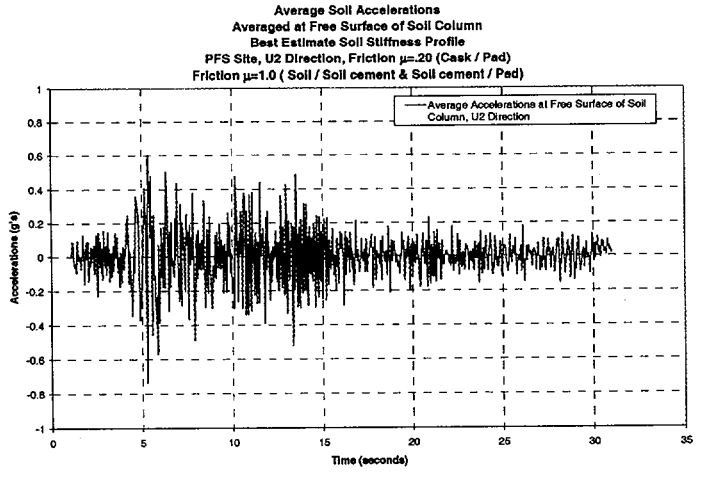
Figure 7. PFS accelerations for seismic event with 2,000-year return period in the horizontal U1 direction for best estimate soil profile data



(a) Original time histories

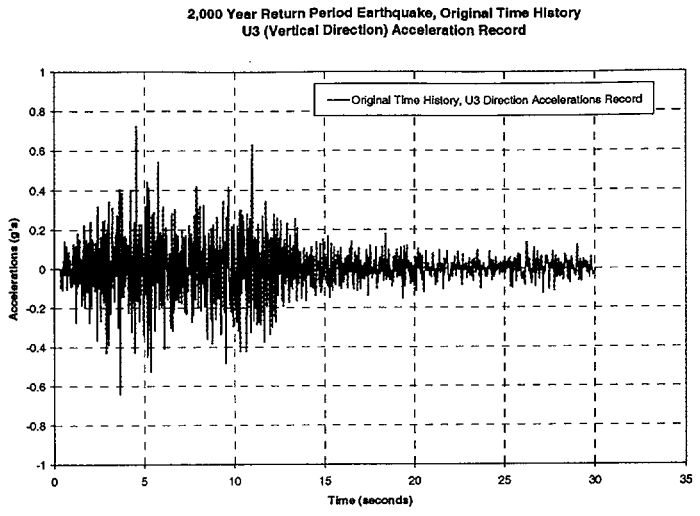


(b) Deconvoluted base input time histories

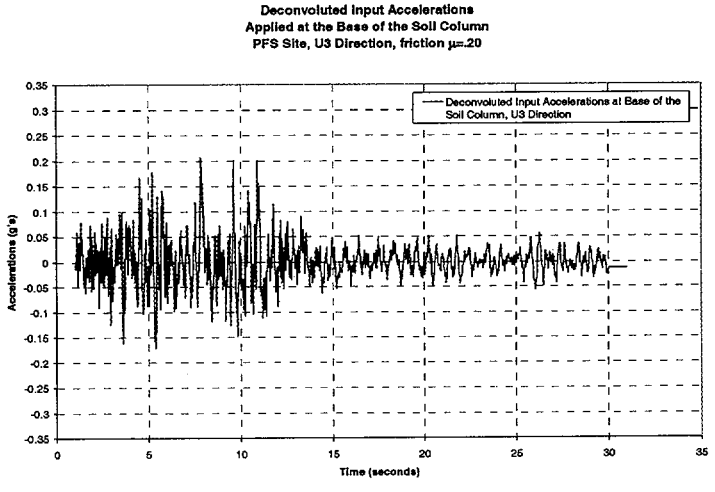


(c) Time histories of free-field analysis results

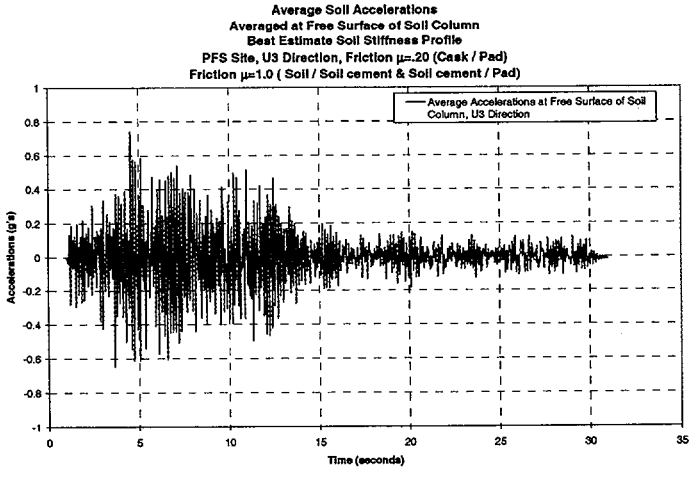
(a) Figure 8. PFS accelerations for seismic event with 2,000-year return period in the horizontal U2 direction for best estimate soil profile data



(a) Original time histories

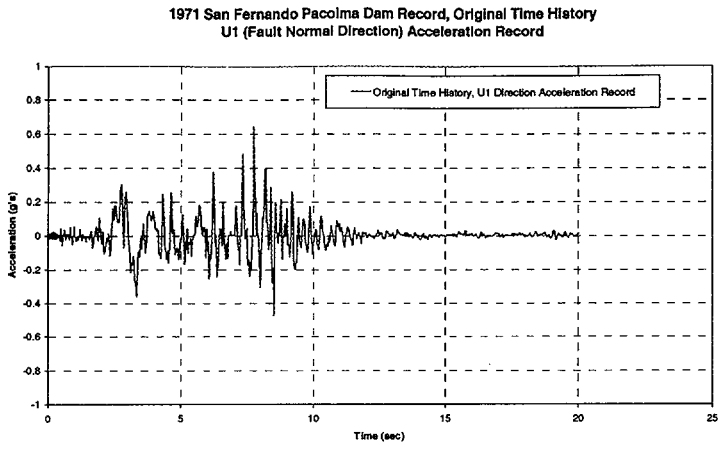


(b) Deconvoluted base input time histories

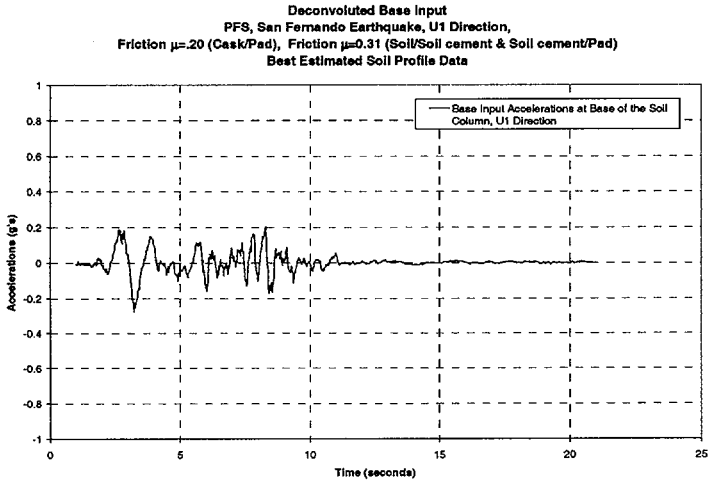


(c) Time histories of free-field analysis results

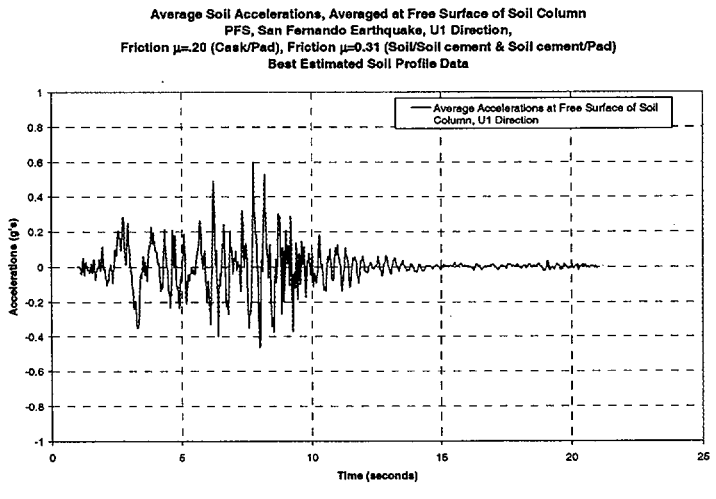
Figure 9. PFS accelerations for seismic event with 2,000-year return period in the vertical U3 direction for best estimate soil profile data



(a) Original time histories

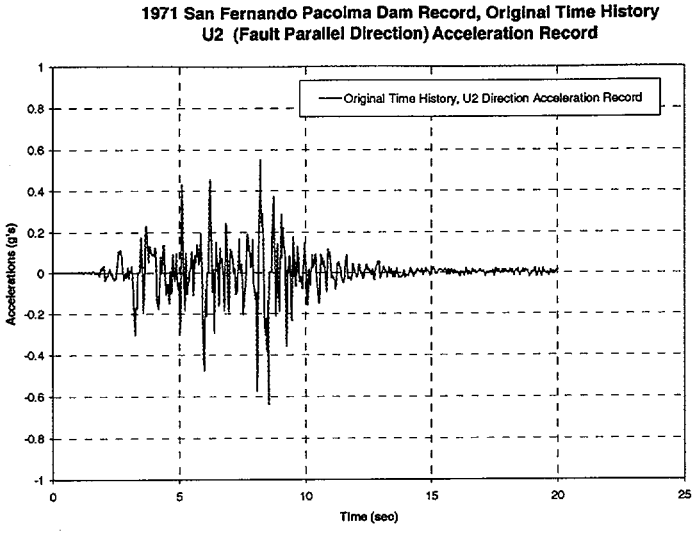


(b) Deconvoluted base input time histories

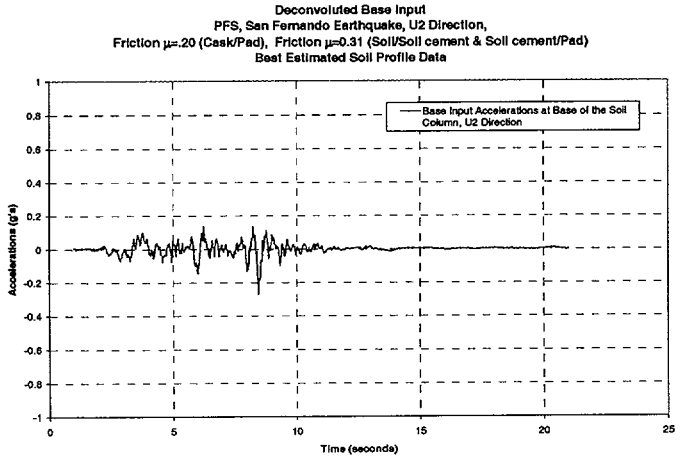


(c) Time histories of free-field analysis results

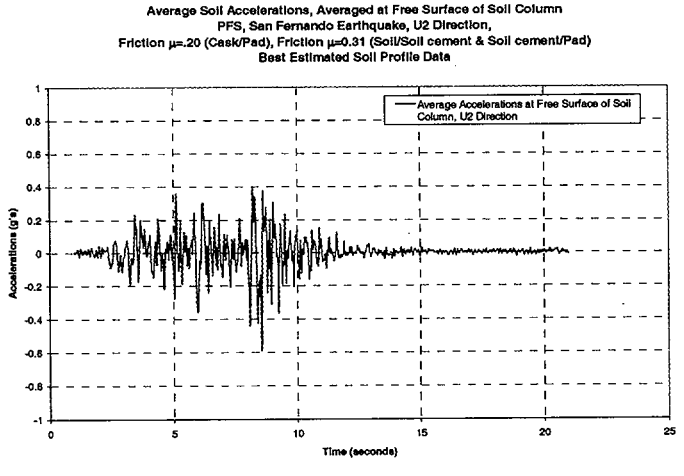
Figure 10. Accelerations for 1971 San Fernando Pacoima Dam record in the horizontal U1 direction for best estimate soil profile data



(a) Original time histories

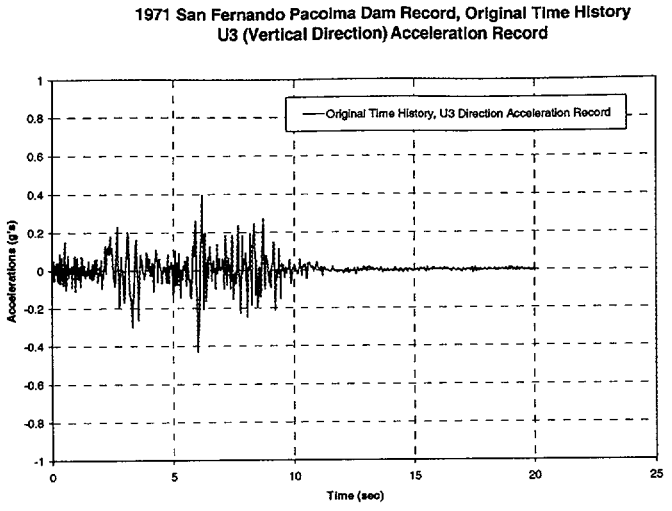


(b) Deconvoluted base input time histories

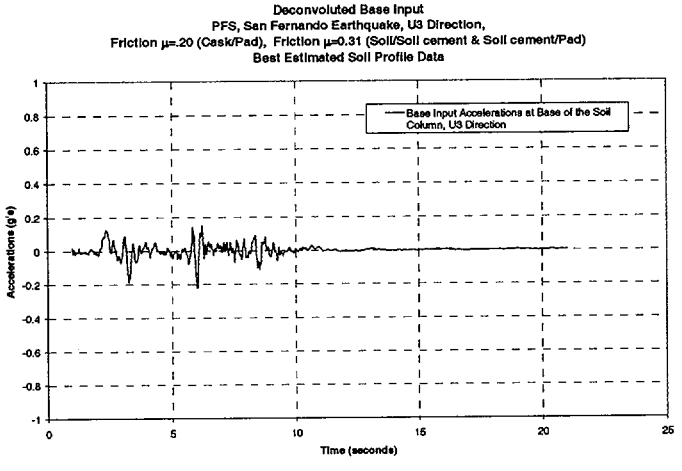


(c) Time histories of free-field analysis results

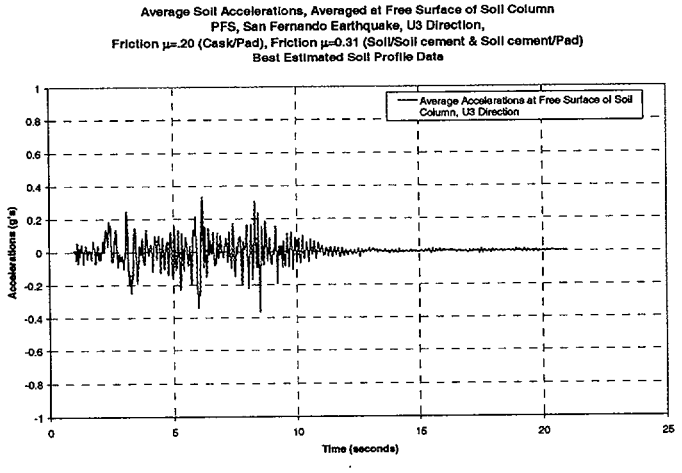
Figure 11. Accelerations for 1971 San Fernando Pacoima Dam record in the horizontal U2 direction for best estimate soil profile data



(a) Original time histories

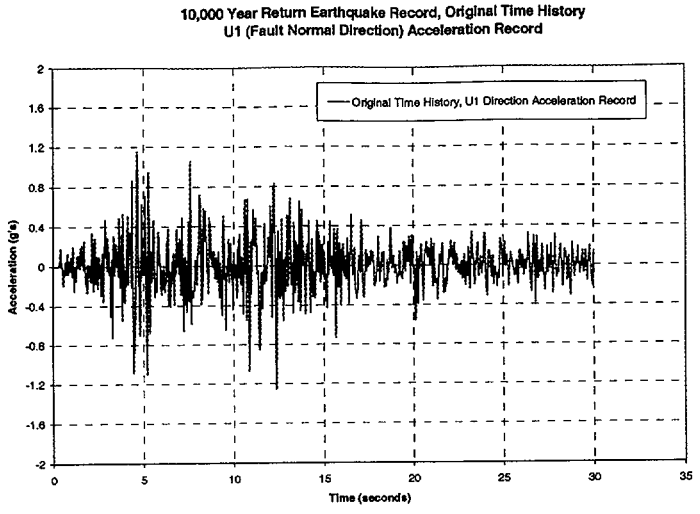


(b) Deconvoluted base input time histories

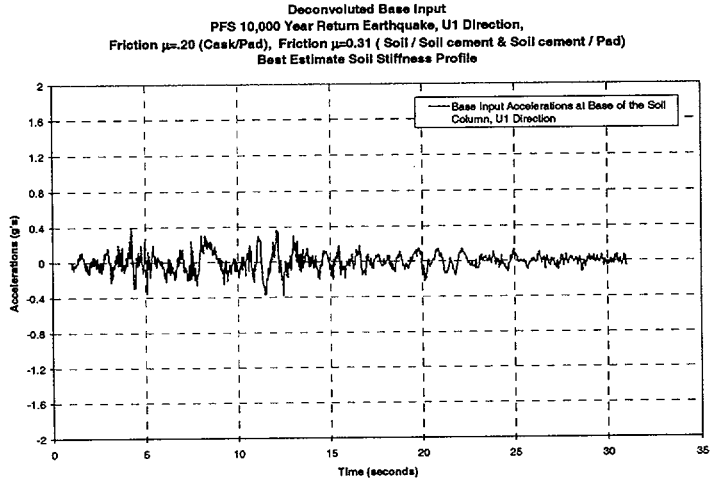


(c) Time histories of free-field analysis results

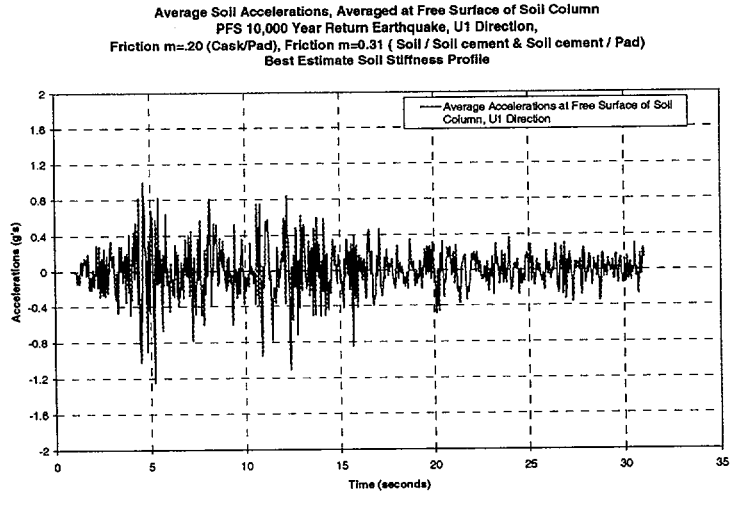
Figure 12. Accelerations for 1971 San Fernando Pacoima Dam record in the vertical U3 direction for best estimate soil profile data



(a) Original time histories

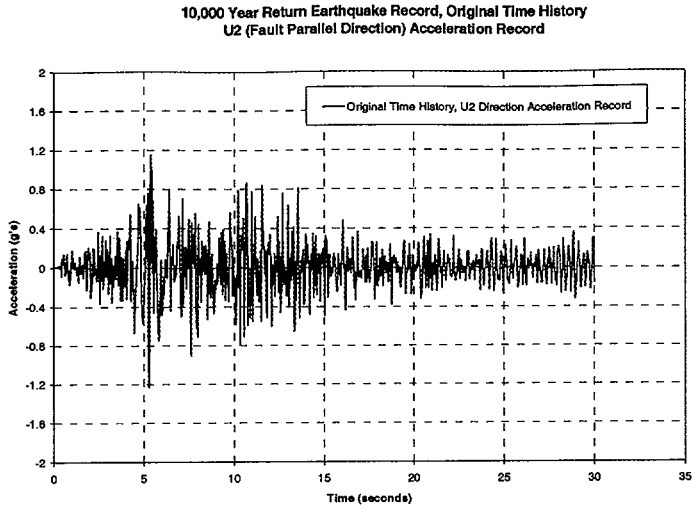


(b) Deconvoluted base input time histories

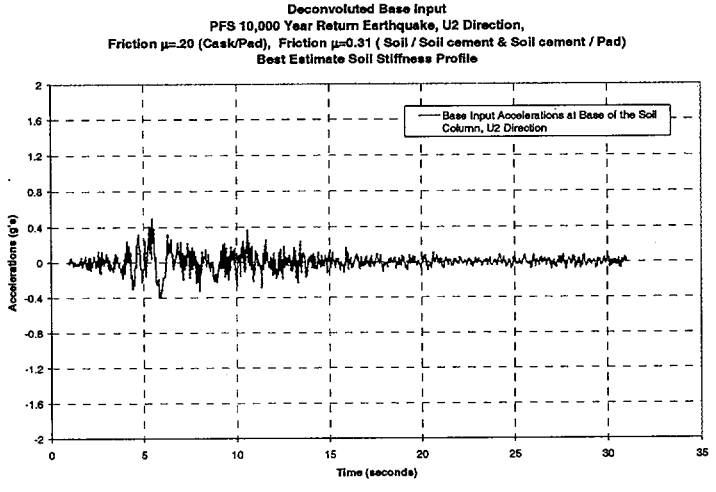


(c) Time histories of free-field analysis results

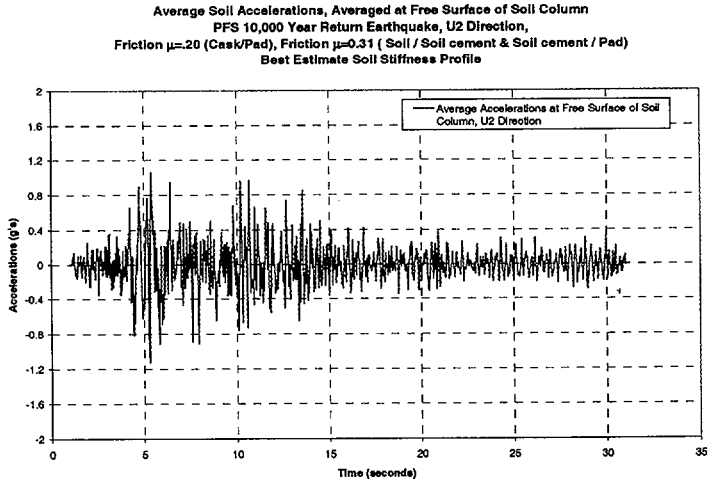
Figure 13. PFS accelerations for seismic event with 10,000-year return period in the horizontal U1 direction for best estimate soil profile data



(a) Original time histories

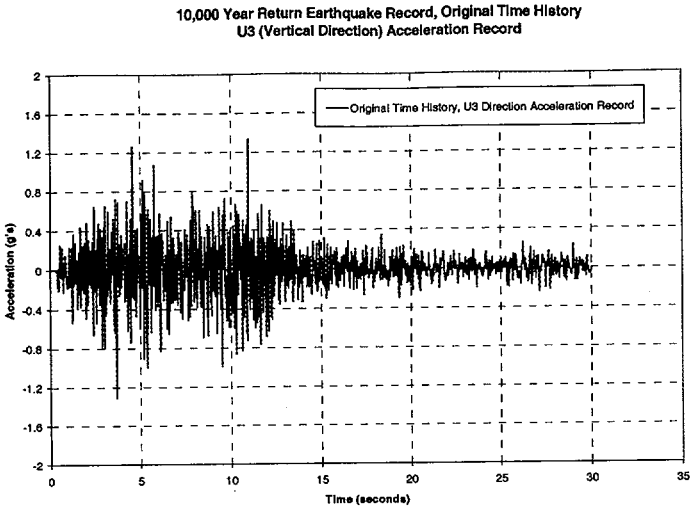


(b) Deconvoluted base input time histories

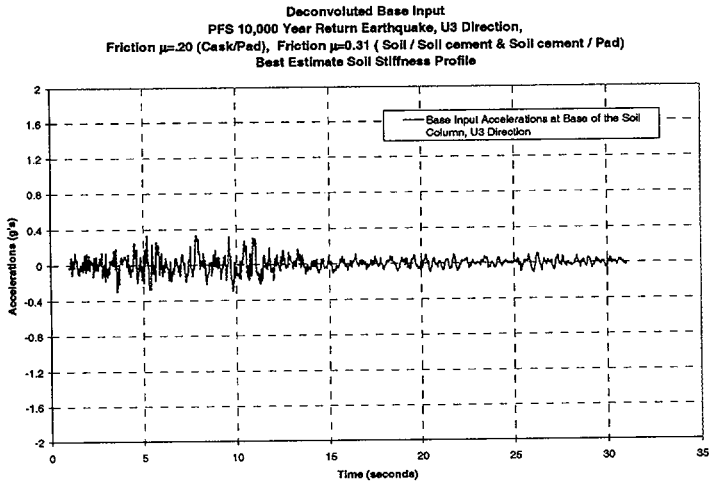


(c) Time histories of free-field analysis results

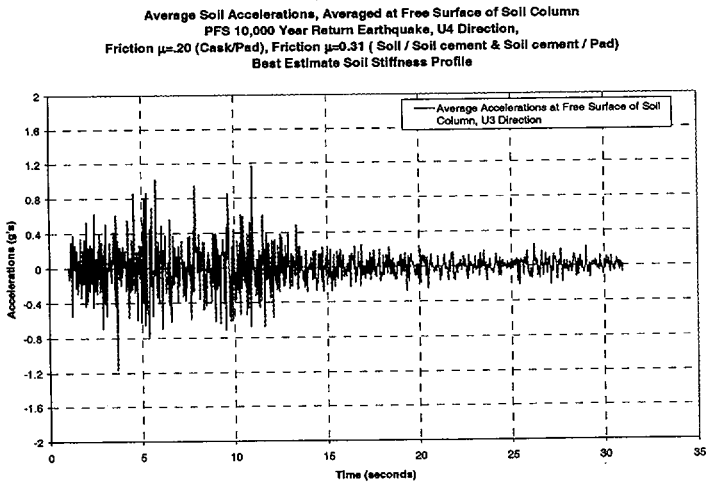
Figure 14. PFS accelerations for seismic event with 10,000-year return period in the horizontal U2 direction for best estimate soil profile data



(a) Original time histories



(b) Deconvoluted base input time histories



(c) Time histories of free-field analysis results

Figure 15. PFS accelerations for seismic event with 10,000-year return period in the vertical U3 direction for best estimate soil profile data

4. ANALYSIS RESULTS

4.1 Summary of Analysis Results

This research project involves investigating the seismic response of cylindrical HI-STORM 100 casks using a coupled 3-D finite element model of a cylindrical cask, a flexible concrete pad, a soil-cement layer, and a soil foundation. The coupled model has three interfaces at cask/pad, pad/soil-cement layer, and soil-cement layer/soil foundation. The friction at these interfaces plays a dominant role in the dynamic response of the cask in a seismic event. This report contains analysis results for various selected cases with different combinations of lower and upper bounds of coefficients of friction at these interfaces. It was found that the cask response is very sensitive to the coefficient of friction at the cask/pad interface. A lower bound coefficient of friction of 0.20 (for investigating cask sliding) and an upper bound coefficient of friction of 0.80 (for examining the possibility of cask tipping-over) were used at this interface. Coefficients of friction of 1.00 and 0.31 were also assumed at the other two interfaces. The different combinations of interfacial coefficients of friction together with the analysis results from the coupled model are compiled in Tables 8 – 10.

A total of three sets of seismic loading were used as input excitations to the coupled model. Two time histories of seismic accelerations, which are based on the response spectra specific to the PFS site for a 2,000-year and a 10,000-year return period, were used to calculate the dynamic response of the cask. A sensitivity study was also performed using the 1971 San Fernando Earthquake, Pacoima Dam record. Each set of seismic loading has one vertical and two horizontal components of statistically independent accelerations. Each one of the three seismic acceleration components was treated with a deconvolution procedure to produce a modified time history of deconvoluted accelerations with properly adjusted frequencies and magnitudes in order to preserve their dynamic characteristics and to achieve the desired surface shaking intensity. All three components of deconvoluted accelerations were applied simultaneously at the base of soil foundation in the coupled model.

Sensitivity studies were performed to investigate the effect of chosen soil profile data on the dynamic response of casks. The best estimate, the lower bound and the upper bound soil profile data were used separately in the seismic analyses of PFS casks.

The seismic responses of the cask are expressed in terms of three components of displacements and two components of rotations. The two horizontal displacements, U1 and U2, and the vertical component, U3, which are referenced to the top surface of concrete pad, describe the translational movements of the cask. The rotational movements of the cask are measured by the two rotational angles with respect to the vertical axis in U1 and U2 directions, respectively.

Before executing the explicit dynamic calculations for each loading configuration, a static load of all submodels was applied for duration of one second to perform implicit calculations in order to create initial conditions of the finite element model for subsequent dynamic computations. Therefore, there is a one-second shift in the analysis results of seismic response of the cask.

In addition, a zero displacement boundary condition was assumed in U1 and U2 directions at the cask base in the static load initialization step. The coupled model would not be properly executed without this assumption because of the huge memory required to perform the implicit calculations with this complicated model. This assumption was then removed at the start of dynamic computations.

The analysis effort was started by investigating the dynamic cask response using different interfacial coefficients of friction for a seismic event with a 2,000-year return period and the best estimate soil profile data. The analysis results in Table 8 indicate that the maximum horizontal displacements of the cask are obtained for the case with a coefficient of friction of 0.20 at the cask/pad interface and that of 0.31 at the interfaces of pad/soil-cement layer and soil-cement layer/soil foundation. This combination of interfacial coefficients of friction was then chosen as the governing case for all subsequent seismic analyses to investigate the maximum horizontal displacements of casks. Table 8 also indicates that the combination of interfacial coefficients of friction of 0.80 and 1.00 generates the maximum rotational angles of the cask with respect to the vertical axis and was therefore selected for all subsequent analyses for this investigation.

The maximum horizontal sliding displacements at the top and base of the cask and its maximum rotational angle with respect to the vertical axis in U1 and U2 directions for the three seismic events are listed in Tables 8 - 10. A detailed evaluation of these tables indicate that the case of using the lower bound soil profile data and the interfacial combination of 0.20 and 0.31 produces a higher cask rotational angle in Table 10 for the seismic event with a 10,000-year return period, and therefore, this soil profile data was selected to investigate the maximum cask rotational angle. For the 1971 San Fernando Earthquake, Pacoima Dam record in Table 9, the results of cask rotation angle are very similar for all three cases of soil profile data, and the best estimate soil profile data was selected in investigation.

The cask does not experience much displacement in the vertical direction in all three seismic events. The cask base is never entirely lifted off the top surface of pad throughout the seismic event with a 2,000-year return period and the 1971 San Fernando Earthquake, Pacoima Dam record. However, during the seismic event with a 10,000-year return period, the analysis results reveal that the cask base will entirely lift off the top surface of pad 0.26 inches maximum for a total duration of less than 0.30 seconds. Detailed examinations of analysis results also indicate that the maximum vertical displacement at any point along the perimeter of the cask base is less than 2.7 inches above the pad top surface. Therefore, the analysis results of the cask vertical displacements are not included in Tables 8 - 10.

Two special cases of interest were also investigated for the seismic event with a 2,000-year return period and the best estimate soil profile data, as indicated in Table 8. In one case, the special ground surface preparation with compacted aggregate and soil-cement layers was removed from the coupled model. In the other case, the dead loads of the seven adjacent casks and neighboring pads are included in the coupled model. The maximum horizontal sliding displacements of cask for both cases were found to be less than those from the original coupled model.

The dynamic coupling or the soil-structure-interaction (SSI) effect of the cylindrical cask with the soil foundation was examined in detail using the acceleration results in U1 direction for the combination of interfacial coefficients of friction of 0.20 and 0.31. Figure 16 shows the analysis output locations at A' and B' on the free surface, and D' on the top of soil-cement layer. In addition, there are analysis output locations at four points, A, B, C, and D on the soil surface, and four points, D, E, F, and G at various depths along the central axis of the pad for demonstration purposes. The SSI effect is demonstrated in Figure 17 with the acceleration results at A' and D'. The acceleration results at four locations on the soil surface and at various depths along the central axis of the pad are shown in Figure 18 and 19, respectively. Noticeable differences in accelerations are observed in these figures to demonstrate the presence of the SSI effect and to justify the development of the coupled finite element model in the research effort. The SSI effect was further investigated by plotting the corresponding response spectra in Figures 20 - 22.

4.2 Analysis Results of All Selected Cases

The analysis results of the cylindrical HI-STORM 100 casks for all selected cases under investigation are reported in Appendices I - III, one for each of three seismic events. The reported results include the two horizontal and one vertical displacement components at the top and base of the cask with respect to the pad, plan view trajectory plots of the horizontal displacements, and the two rotational angles with respect to the vertical axis in U1 and U2 directions.

Table 8. Summary table of seismic analysis results for Private Fuel Storage (PFS) casks in the seismic event with a 2,000-year return period

Soil Profile Data (Model Type)	Interfacial Coefficient of Friction: μ1 at cask/pad and μ2 at pad/soil-cement layer and soil-cement layer/soil foundation	Location on Cask	Maximum Horizontal Sliding Displacement / Time				Maximum Rotational Angle (degrees)	
			U1		U2			
			in.	sec.	in.	sec.	East-West U1	North-South U2
Best Estimate (Model Type 1)	μ1 = 0.20	Top	**3.01**	11.9	**2.85**	14.2	0.02	0.01
	μ2 = 1.00	Base	2.99	11.9	2.84	14. 2		
	μ1 = 0.20	Top	**3.93**	12.9	**3.98**	14.2	0.02	0.01
	μ2 = 0.31	Base	3.92	12.9	3.96	14.2		
	μ1 = 0.80	Top	**1.97**	11.0	**2.35**	5.6	0.22	0.40
	μ2 = 1.00	Base	1.46	7.9	1.10	5.7		
Best Estimate (Model Type 2)	μ1 = 0.20	Top	1.28	5.3	**1.76**	13.84	0.03	0.01
	μ2 = 0.31	Base	**1.30**	5.3	1.75	13.8		
Best Estimate (Model Type 3)	μ1 = 0.20	Top	**3.20**	12.9	**3.61**	11.8	0.03	0.01
	μ2 = 0.31	Base	3.11	12.9	3.59	11.8		
Lower Bound (Model Type 1)	μ1 = 0.20	Top	**2.34**	11.4	**1.85**	11.7	0.02	0.01
	μ2 = 0.31	Base	2.31	11.4	1.84	11.8		
Upper Bound (Model Type 1)	μ1 = 0.20	Top	**2.35**	5.3	**3.92**	13.6	0.01	0.01
	μ2 = 0.31	Base	2.34	5.3	3.91	13.7		

Notes:

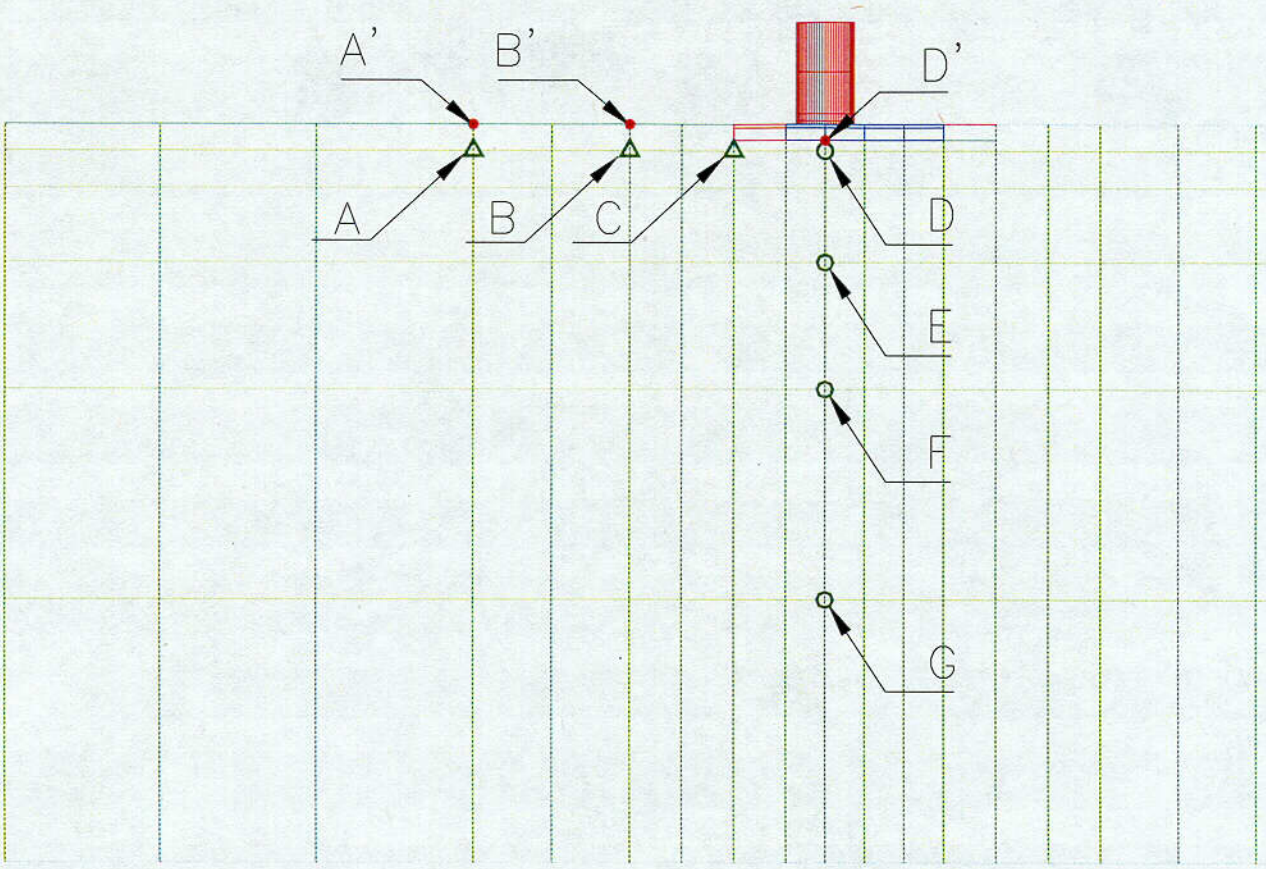
1. Model Type 1: The coupled model illustrated in Figure 1.
2. Model Type 2: The coupled model without compacted aggregate and soil-cement layers (concrete pad directly on soil foundation).
3. Model Type 3: The coupled model includes the dead loads of 7 adjacent casks and neighboring concrete pads.

Table 9. Summary table of seismic analysis results for Private Fuel Storage (PFS) casks for the 1971 San Fernando Earthquake, Pacoima Dam record

Soil Profile Data	Interfacial Coefficient of Friction: μ1 at cask/pad and μ2 at pad/soil-cement layer and soil-cement layer/soil foundation	Location on Cask	Maximum Horizontal Sliding Displacement / Time				Maximum Rotational Angle (degrees)	
			U1		U2			
			in.	sec.	in.	sec.	East-West U1	North-South U2
Best Estimate	μ1 = 0.20 μ2 = 0.31	Top	**3.00**	6.3	**1.64**	8.7	0.01	0.01
		Base	3.00	6.2	1.64	8.7		
Lower Bound	μ1 = 0.20 μ2 = 0.31	Top	**2.75**	6.2	**2.30**	8.7	0.02	0.01
		Base	2.73	6.2	2.29	8.8		
Upper Bound	μ1 = 0.20 μ2 = 0.31	Top	**2.62**	6.2	**1.12**	8.2	0.01	0.01
		Base	2.62	6.2	1.12	8.2		
Best Estimate	μ1 = 0.80 μ2 = 1.00	Top	**0.57**	8.8	**0.59**	8.6	0.06	0.07
		Base	0.43	8.8	0.35	8.7		

Table 10. Summary table of seismic analysis results for Private Fuel Storage (PFS) casks in the seismic event with a 10,000-year return period

Soil Profile Data	Interfacial Coefficient of Friction: μ1 at cask/pad and μ2 at pad/soil-cement layer and soil-cement layer/soil foundation	Location on Cask	Maximum Horizontal Sliding Displacement / Time				Maximum Rotational Angle (degrees)	
			U1		U2			
			in.	sec.	in.	sec.	East-West U1	North-South U2
Best Estimate	μ1 = 0.20 μ2 = 0.31	Top	**9.80**	11.4	**6.78**	10.2	0.03	0.01
		Base	9.79	11.4	6.78	10.2		
Lower Bound	μ1 = 0.20 μ2 = 0.31	Top	**15.94**	11.5	**6.84**	9.2	0.10	0.05
		Base	15.82	11.5	6.80	9.2		
Upper Bound	μ1 = 0.20 μ2 = 0.31	Top	**12.19**	11.4	**6.00**	9.8	0.06	0.04
		Base	12.19	11.4	5.97	9.8		
Lower Bound	μ1 = 0.80 μ2 = 1.00	Top	**7.20**	11.7	**7.39**	14.3	0.65	1.16
		Base	5.11	8.1	7.08	14.3		



Designation	Description
A	Point at free field location (top of soil surface)
B	10' from edge of pad (top of soil surface)
C	Edge of pad (top of soil surface)
D	Center of pad (top of soil surface)
A'	Point at free field location (free surface)
B'	10' from edge of pad (free surface)
D'	Center of pad (top of soil-cement layer)
E	Depth of 12' below free surface
F	Depth of 26' below free surface
G	Depth of 50' below free surface

Figure 16. Location definition of designation points

C05

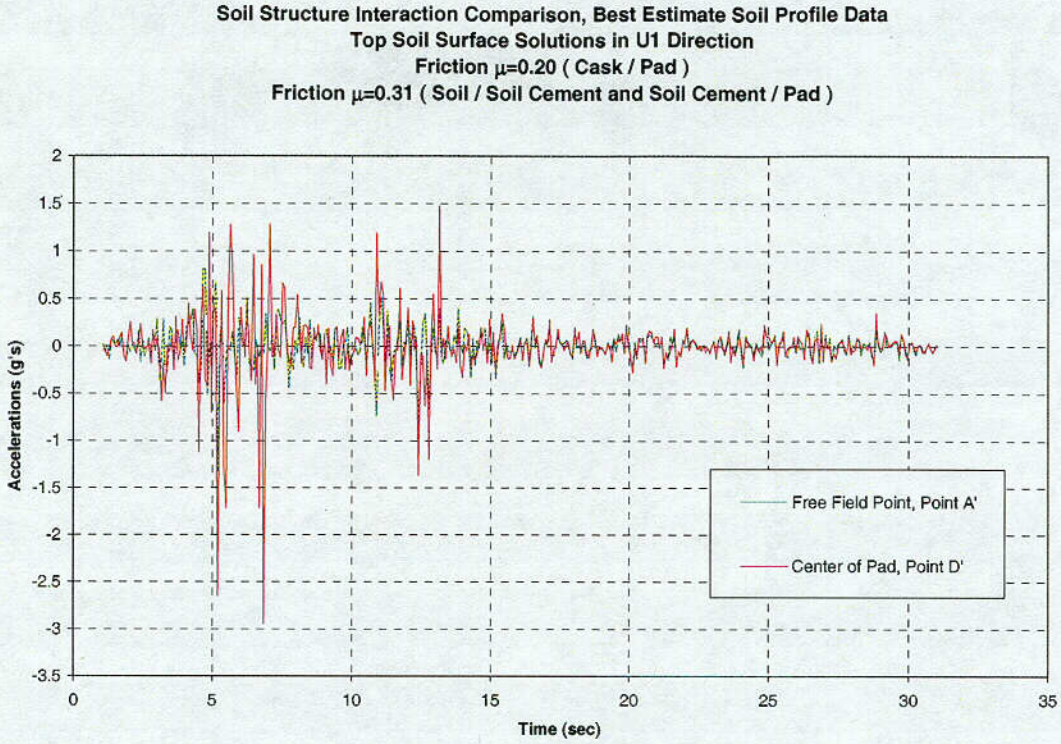


Figure 17. Time histories of accelerations in U1 direction at points A' and D' to demonstrate the SSI effect

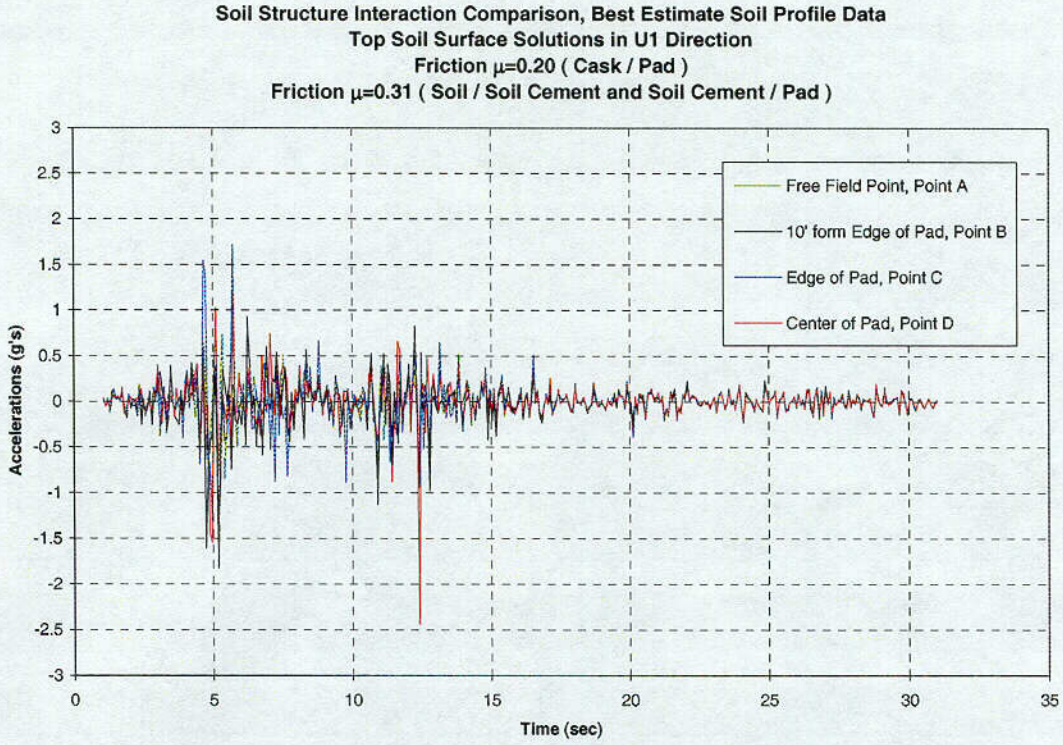


Figure 18. Time histories of U1 accelerations at four locations on top of soil surface to demonstrate the SSI effect

C06

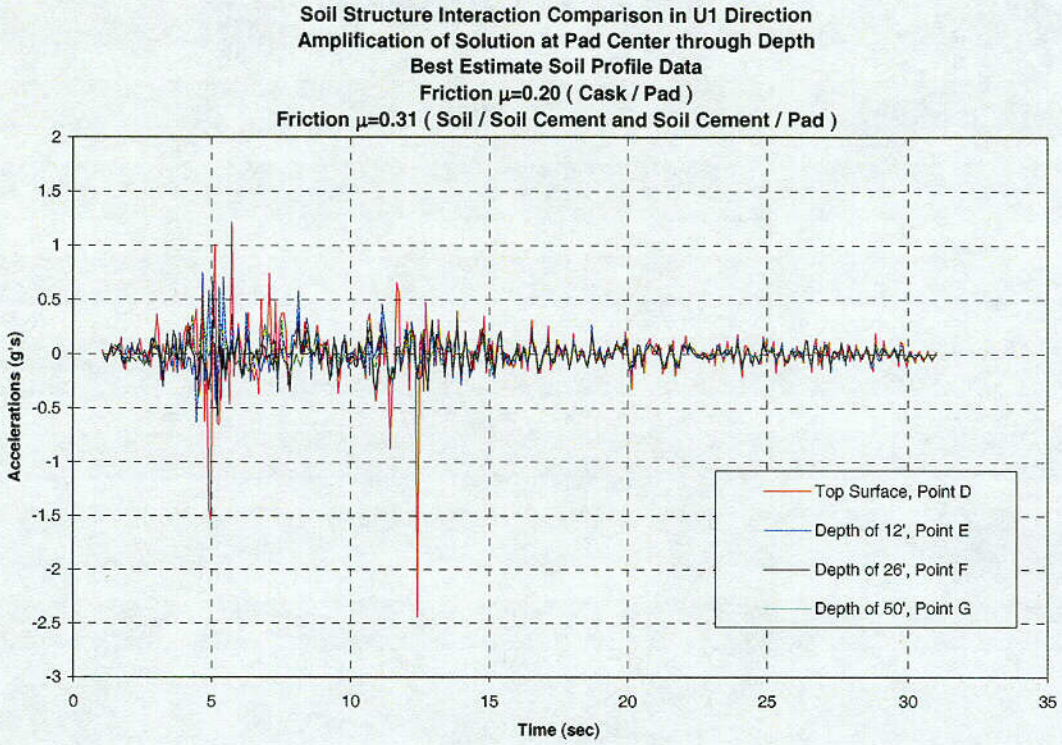


Figure 19. Time histories of U1 accelerations at four depths along the central axis of pad to demonstrate the amplification effect

C07

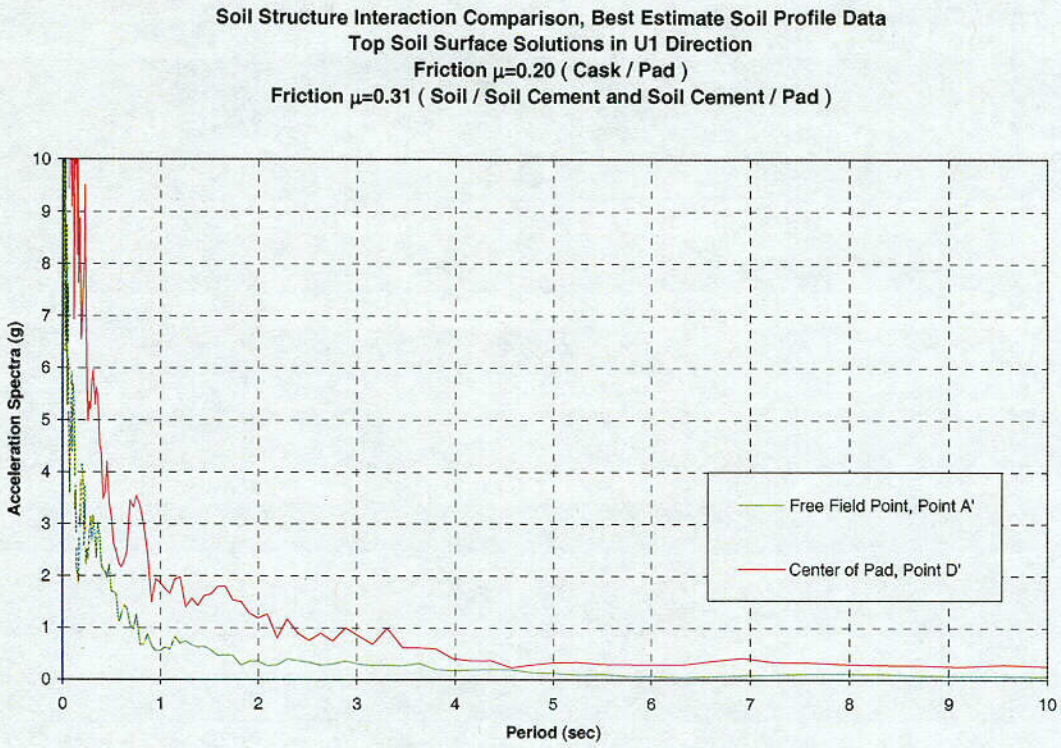


Figure 20a

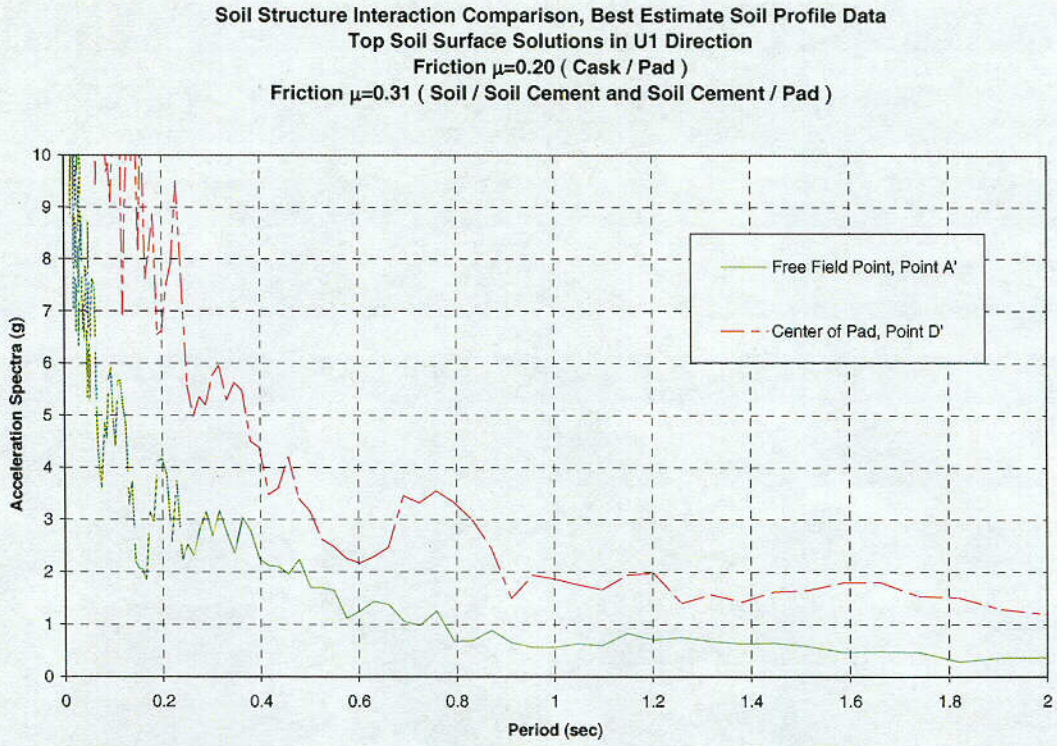


Figure 20b.

Response spectra in U1 direction at points A' and D' to demonstrate the SSI effect

C08

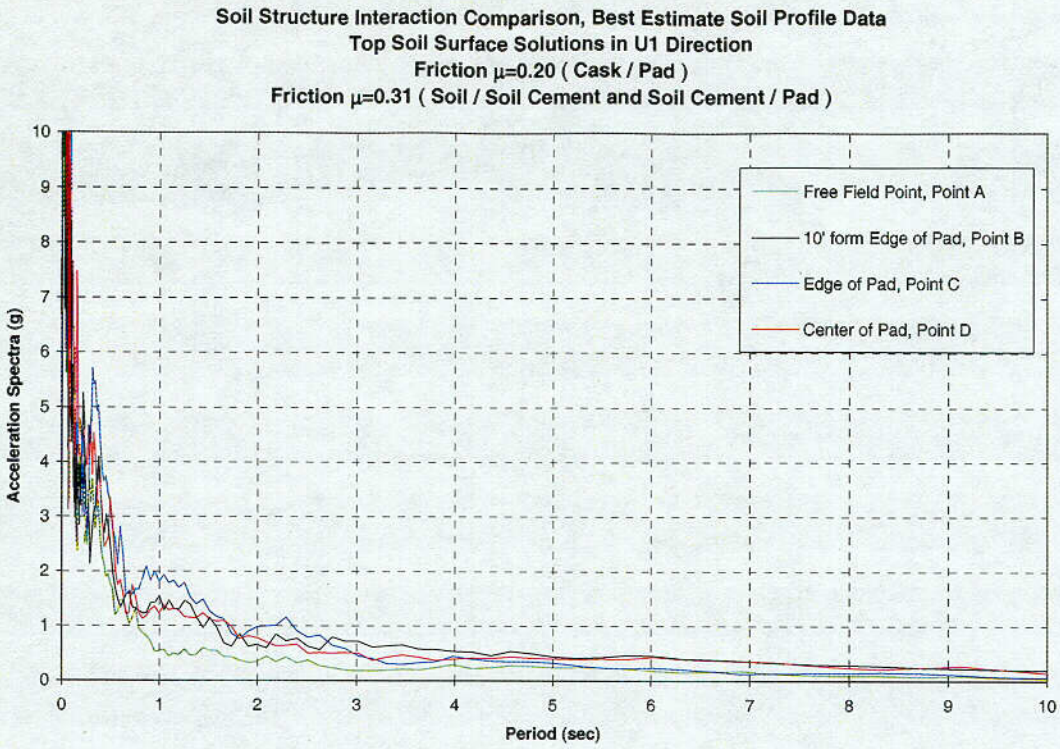


Figure 21a.

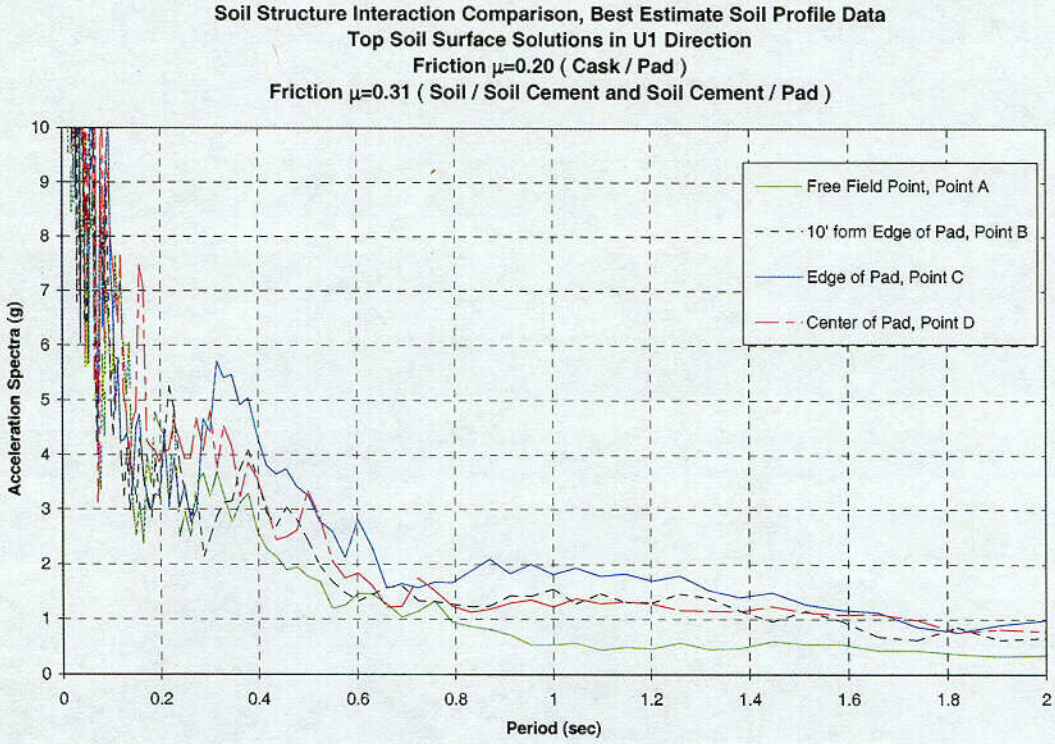


Figure 21b.

Response spectra in U1 direction at four locations on top of soil surface to demonstrate the SSI effect

C09

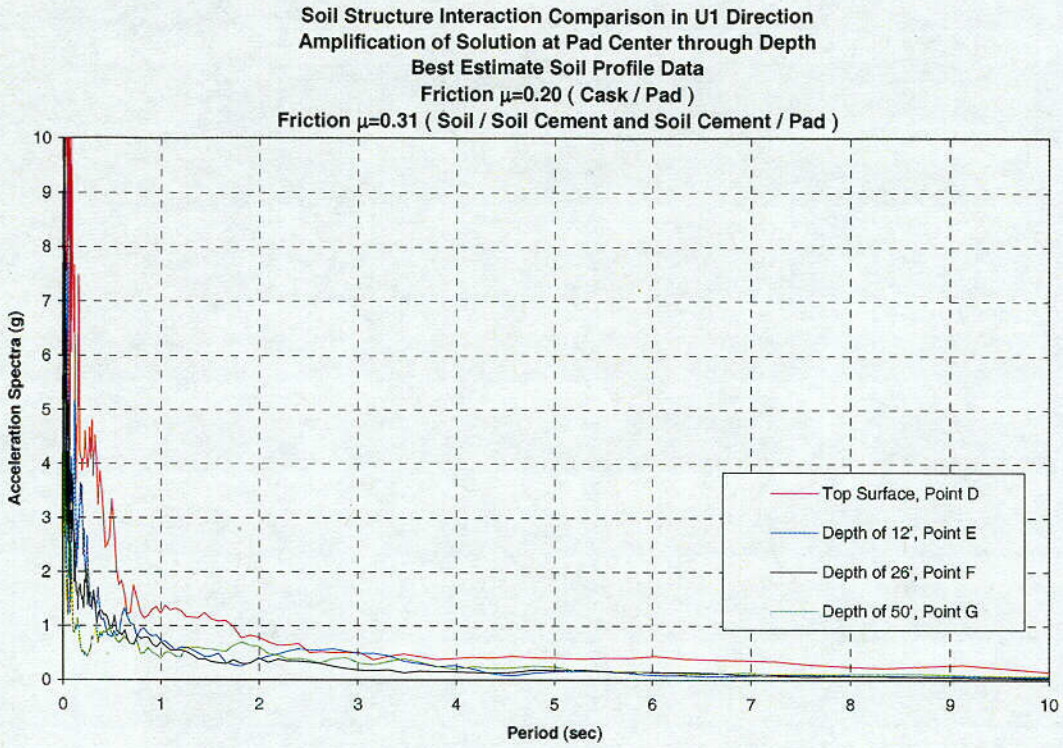


Figure 22a.

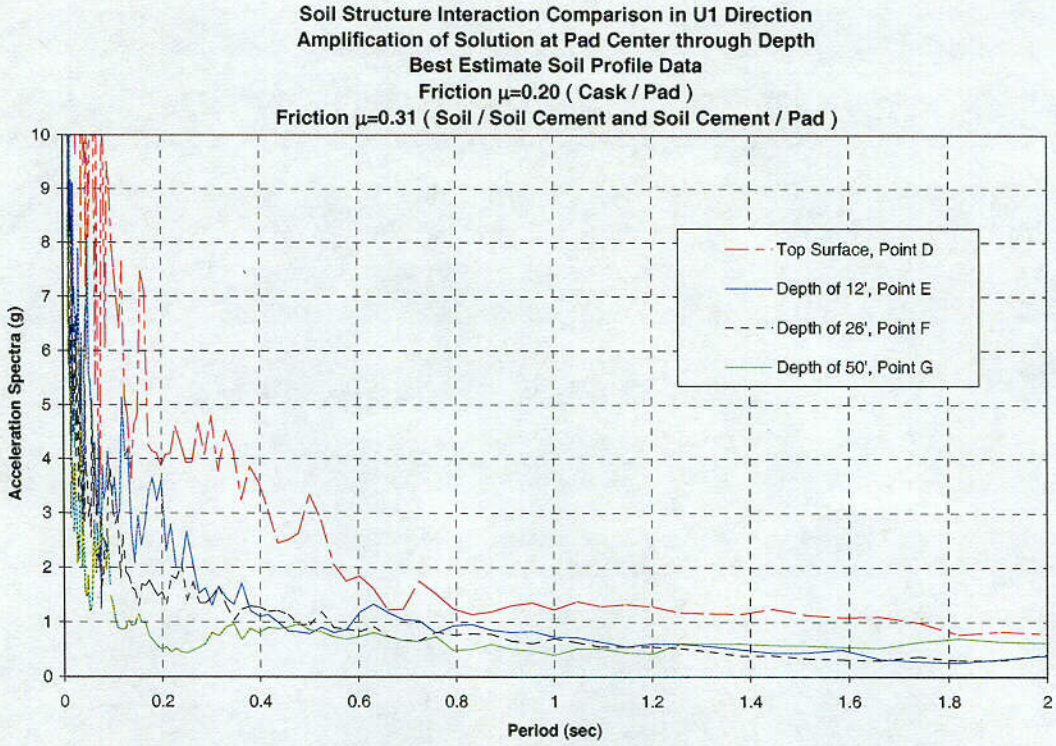


Figure 22b.

Response spectra in U1 direction at four depths along the central axis of pad to demonstrate the amplification effect

C10

5. SUMMARY

This research project investigates the seismic response of freestanding dry cask storage systems. This report contains the seismic analysis results for cylindrical HI-STORM 100 casks at the Private Fuel Storage (PFS) Facility. The research team consisting of analysts and engineers at Sandia National Laboratories (SNL), ANATECH, and Earth Mechanics developed the three-dimensional coupled finite element model, using the ABAQUS / Explicit code, to examine the dynamic and nonlinear behavior of the cask and to simulate the effect of soil-structure-interaction. The coupled model consists of a cylindrical cask, a flexible concrete pad, and a soil-cement layer under and adjacent to the pad and a soil foundation whose material properties are based on the site-specific soil profile data.

A total of three sets of seismic loading were used as input excitations to the coupled model. Two artificial seismic time histories of accelerations, which are based on the response spectra specific to the PFS site for a 2,000-year and a 10,000-year return period, were used to calculate the dynamic response of the cask. A sensitivity study was also performed using the actual 1971 San Fernando Earthquake, Pacoima Dam record. Each set of seismic loading has one vertical and two horizontal components of statistically independent accelerations. Each one of the three seismic acceleration components was treated with a deconvolution procedure to produce a modified time history of deconvoluted accelerations with properly adjusted frequencies and magnitudes in order to preserve their dynamic characteristics and to achieve the desired surface shaking intensity. All three components of deconvoluted accelerations were applied simultaneously at the base of soil foundation in the coupled model.

The coupled model has three interfaces at cask/pad, pad/ soil-cement layer, and soil-cement layer/soil foundation. The horizontal sliding displacements and the rotational angles of casks are found to be dependent on the selection of coefficient of friction at these interfaces. Sensitivity studies of cask response were therefore performed with different combinations of lower and upper bound interfacial coefficients of friction for the seismic event with a 2,000-year return period and the best estimate soil profile data. The results of sensitivity studies indicate that the combination of coefficients of friction of 0.20 at the cask/pad interface and 0.31 at the other two interfaces generates the maximum horizontal sliding displacements of the cask, and the corresponding combination of interfacial coefficients of friction of 0.80 and 1.00 produces the maximum cask rotational angles. These two combinations were used to investigate the dynamic behavior of casks for the all three sets of seismic loading and the three cases of soil profile data.

The separation distance between neighboring casks is 47.50 inches and half of this distance equal to 23.75 inches has been regarded as the cask collision criterion. The results from all seismic analyses indicate that the maximum horizontal cask sliding displacements are 15.94 inches (for the seismic event with a 10,000-year return period), 3.98 inches (for the seismic event with a 2,000-year return period), and 3.00 inches (for the 1971 San Fernando Earthquake, Pacoima Dam record). Therefore, no cask collision will occur in all cases under investigation. In addition, the analysis results show that the maximum cask rotation with respect to the vertical axis in either horizontal direction is less than 1.5 degrees, which is significantly less than the cask rotation for tipping over

(approximately 29 degrees). Therefore, the PFS casks are not anticipated to tip over during an earthquake return period of either 2,000 years or 10,000 years.

6. REFERENCES

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APPENDIX I

ANALYSIS RESULTS FOR THE SEISMIC EVENT WITH A 2,000-YEAR RETURN PERIOD

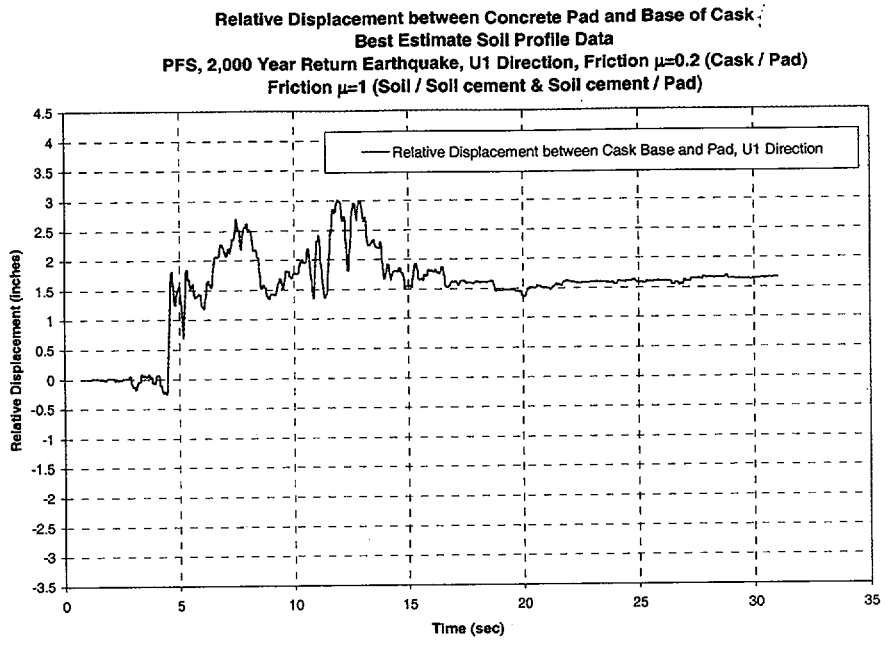


Figure I 1.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

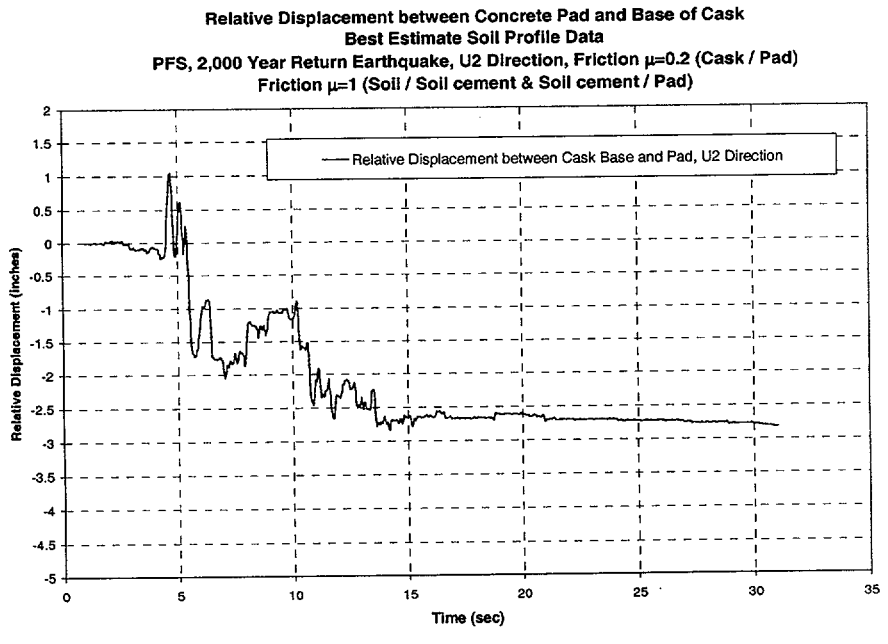


Figure I 1.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

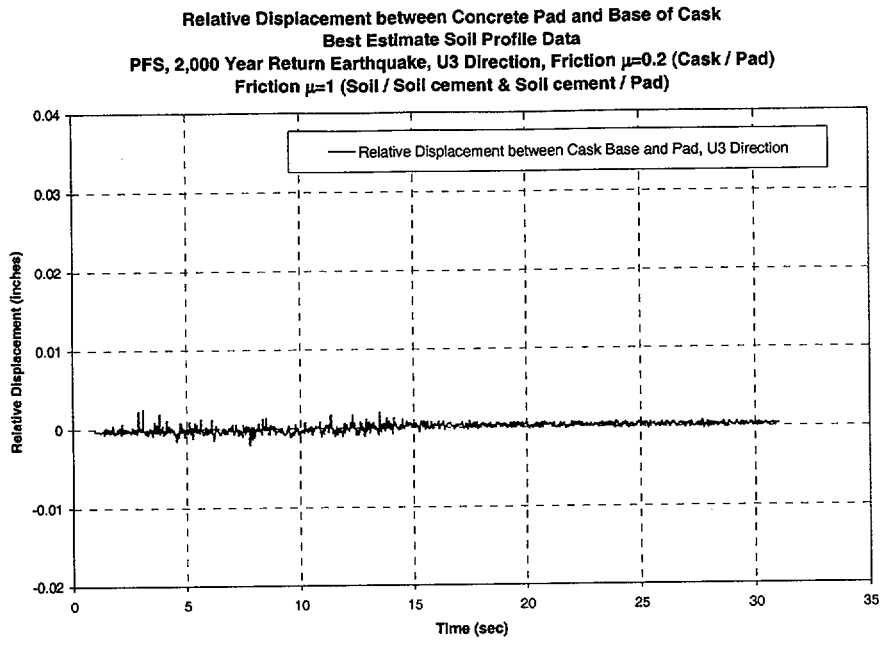


Figure I 1.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

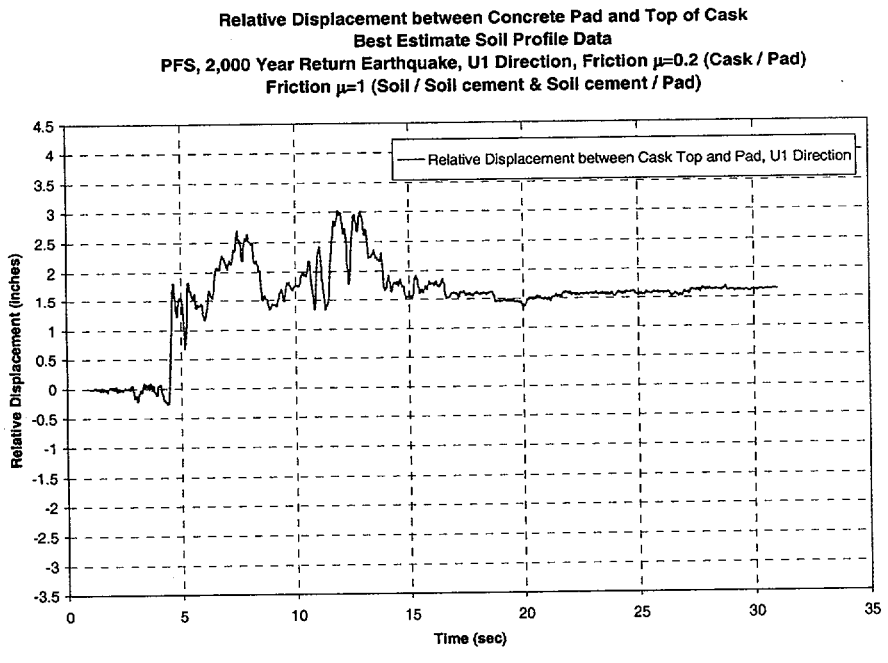


Figure I 1.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

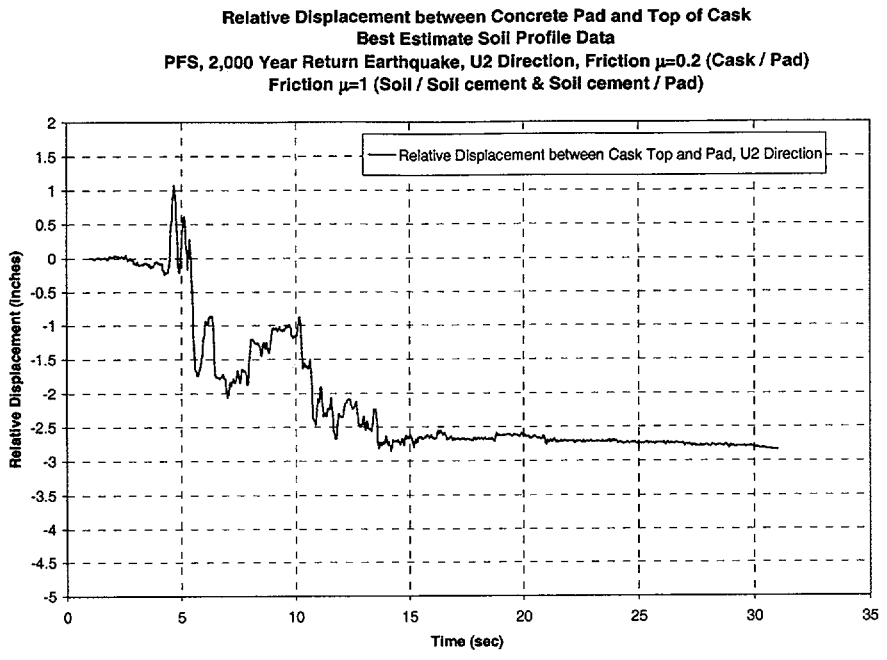


Figure I 1.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

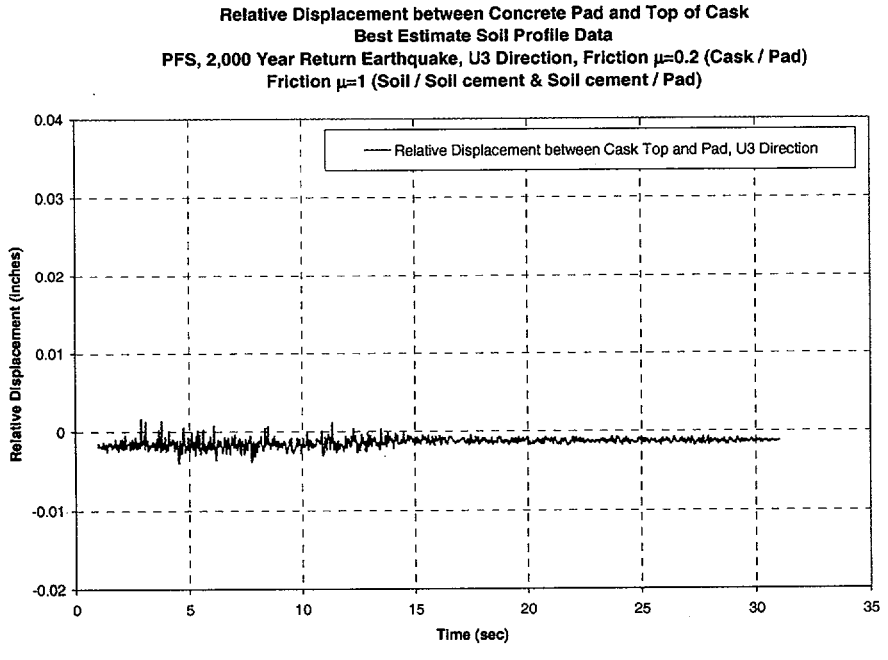


Figure I 1.6. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

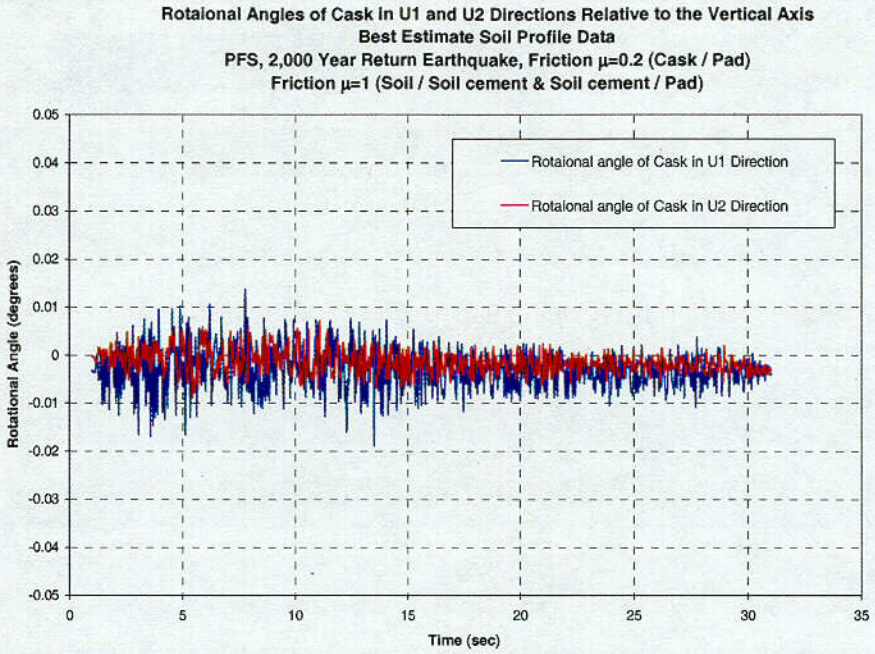


Figure I 1.7. Time history of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, Friction μ=0.20 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

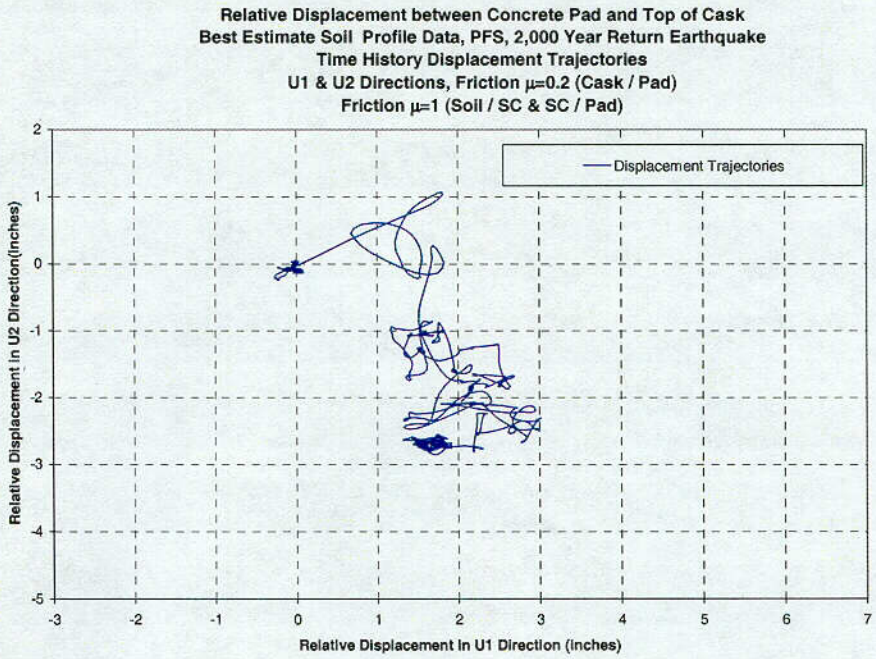
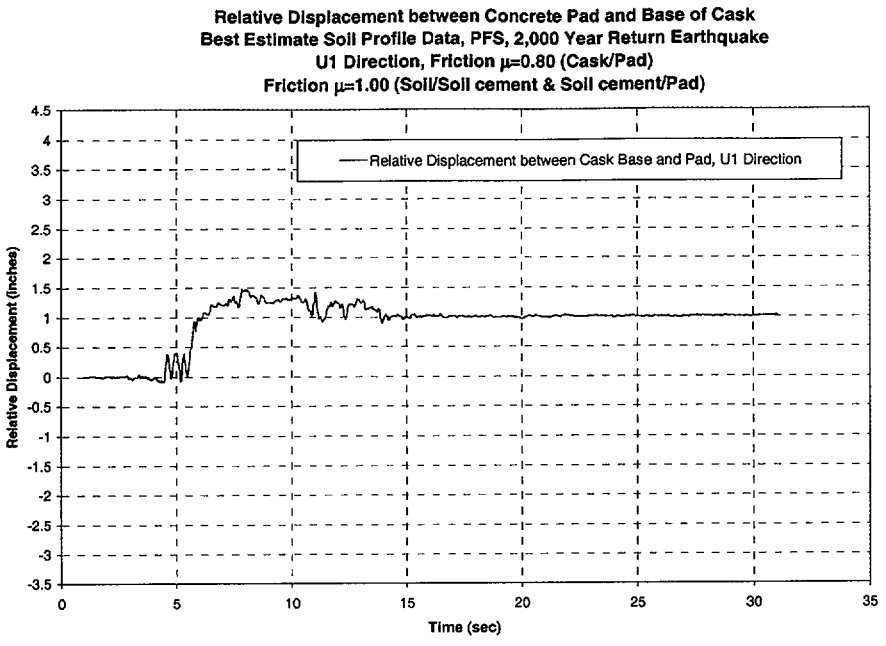


Figure I 1.8. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

C11



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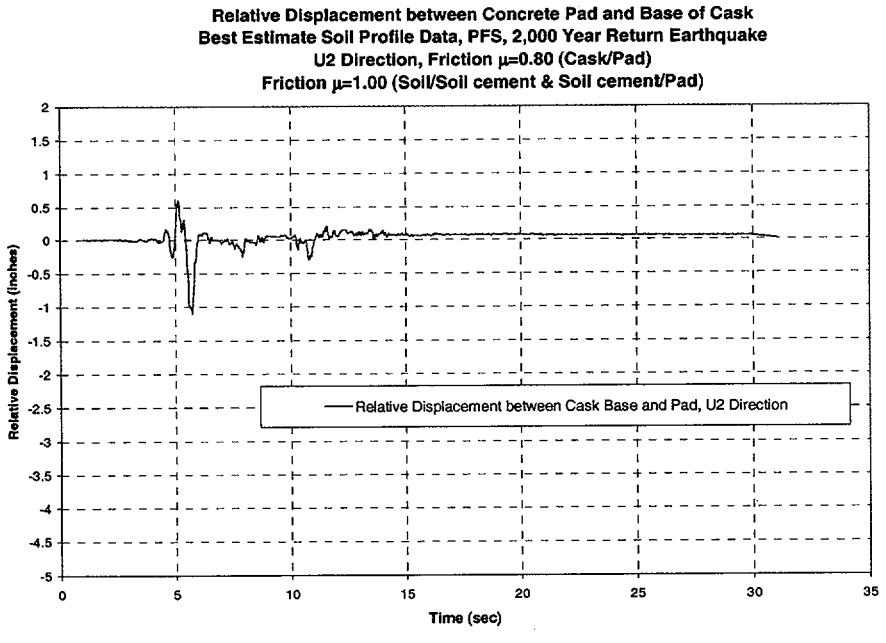

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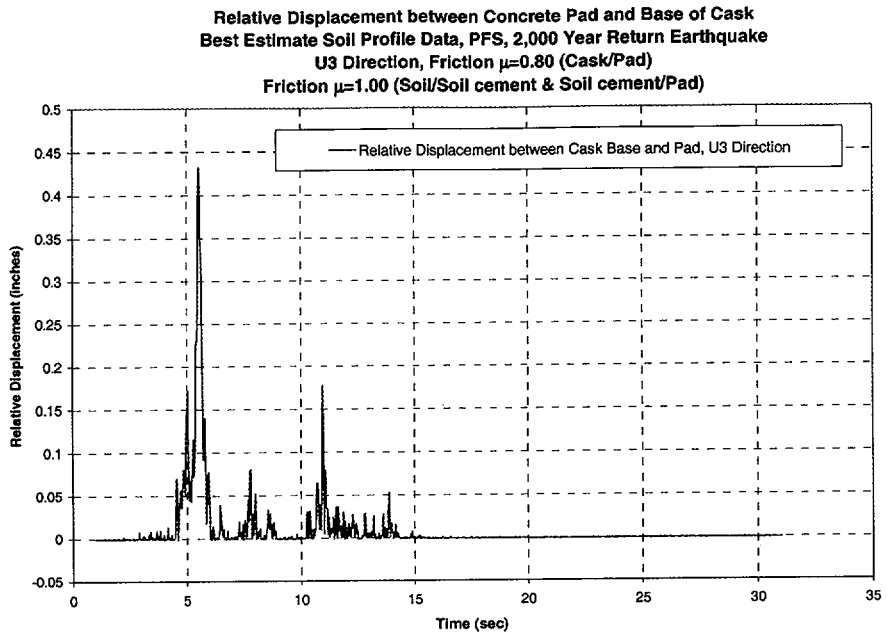

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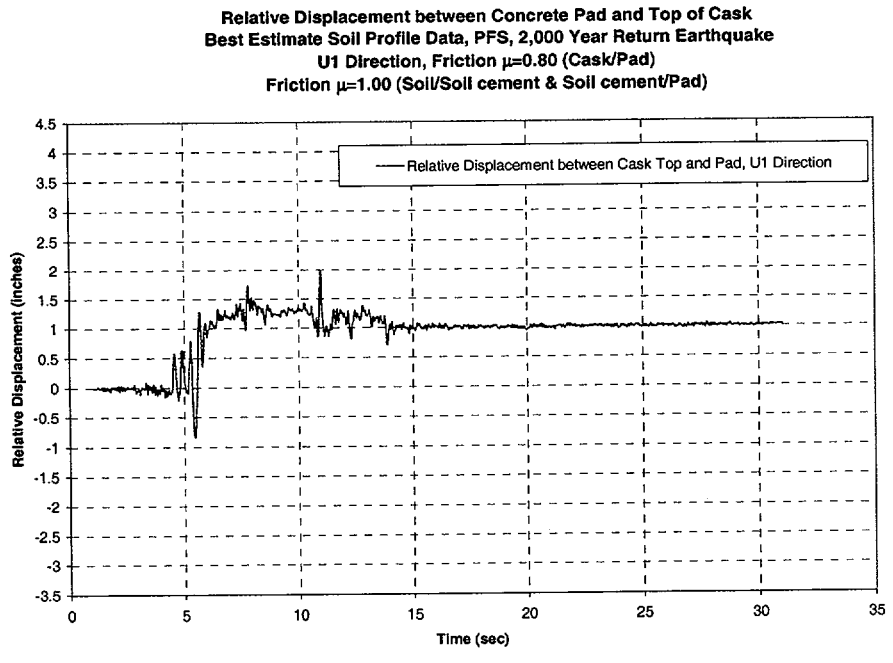

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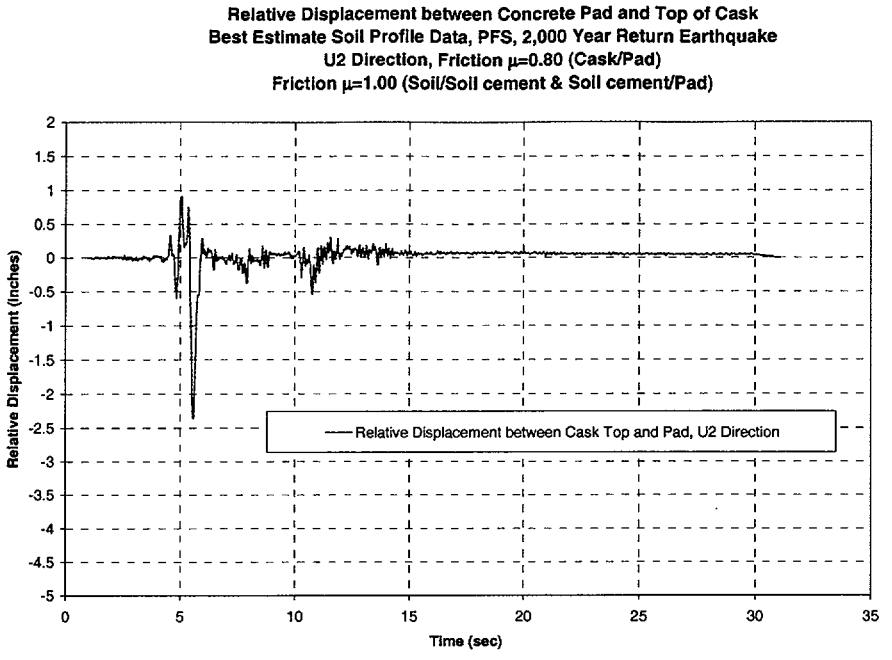
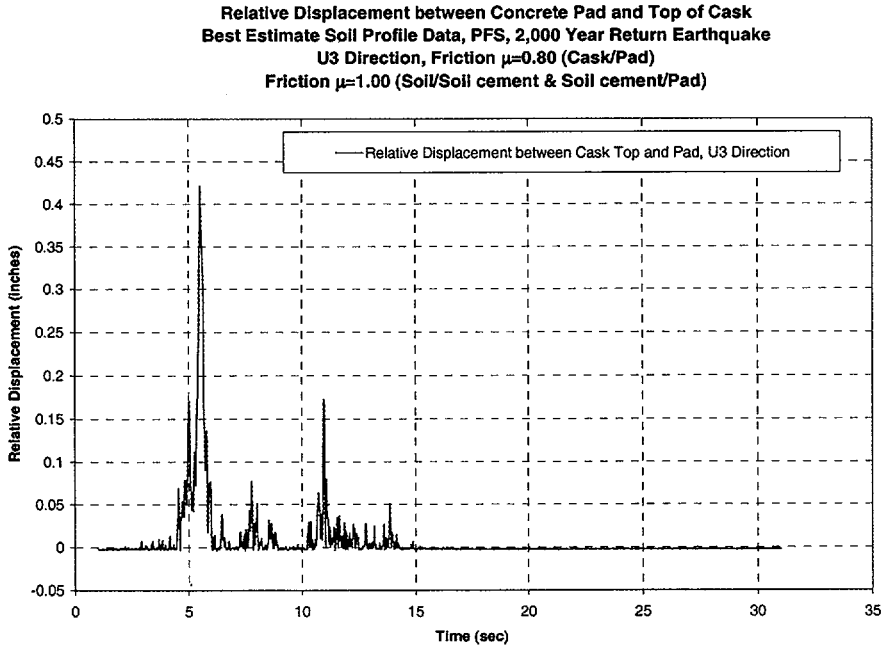


Figure I 2.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U2 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)



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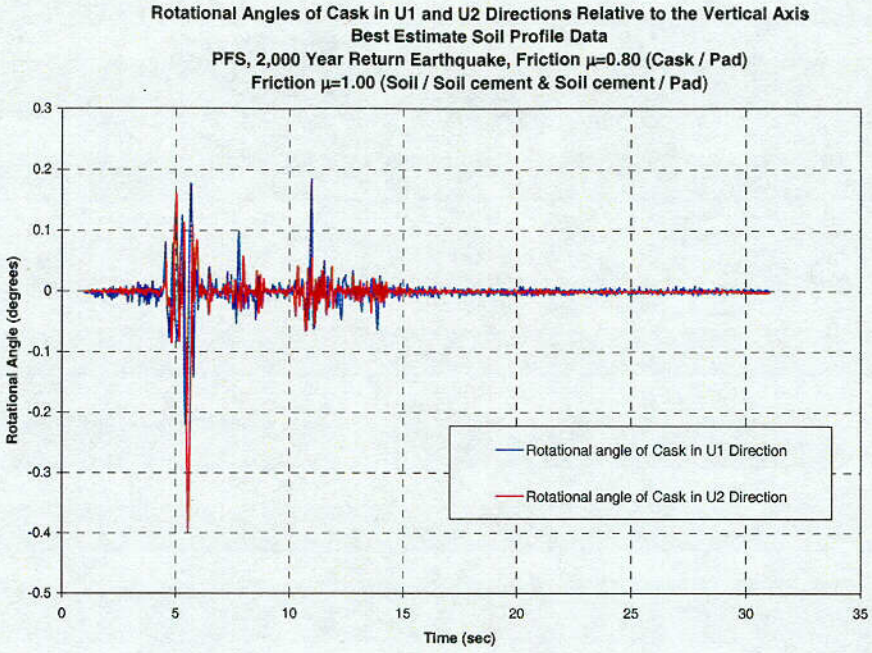


Figure I 2.7. Time history of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

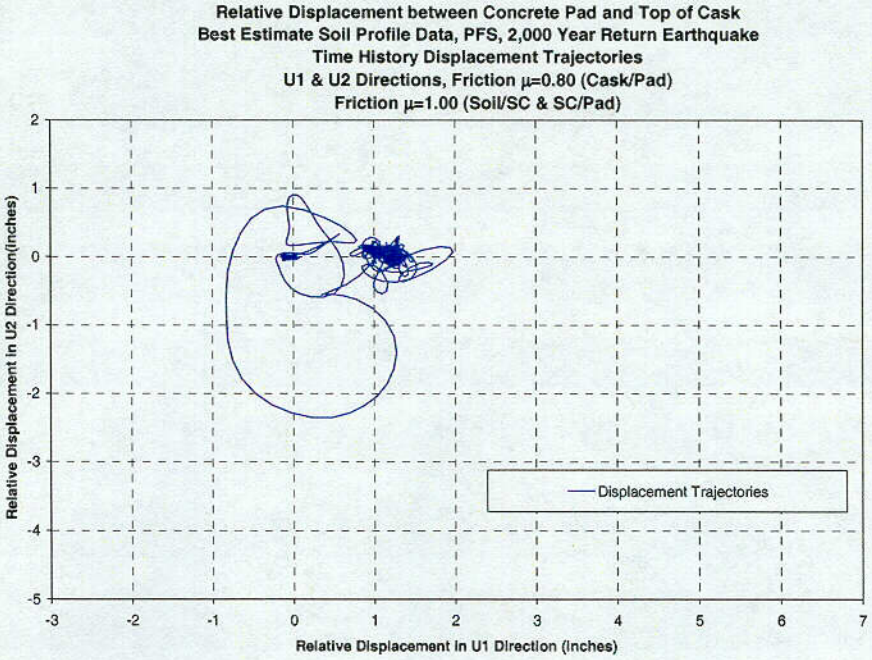


Figure I 2.8. Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

C12

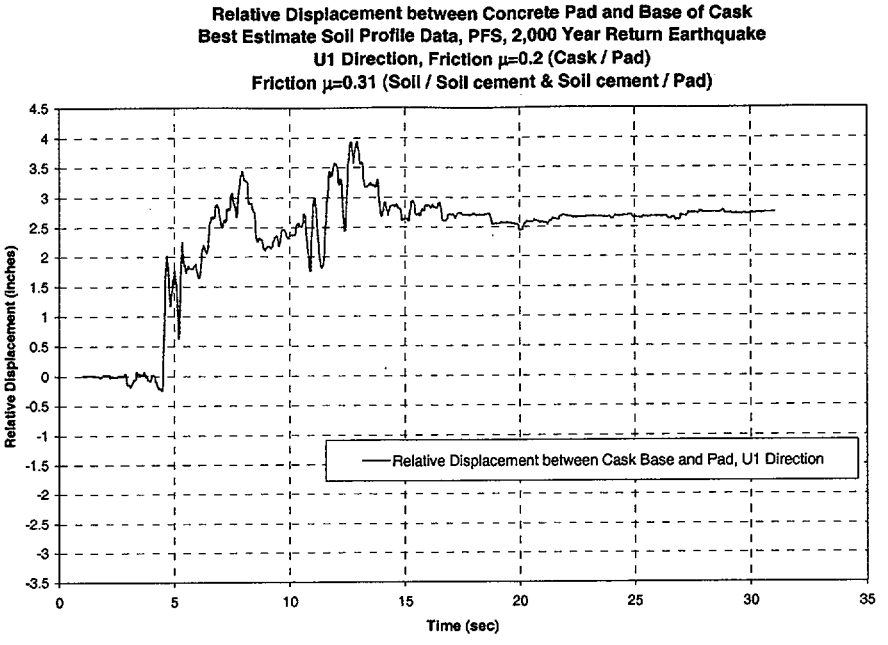
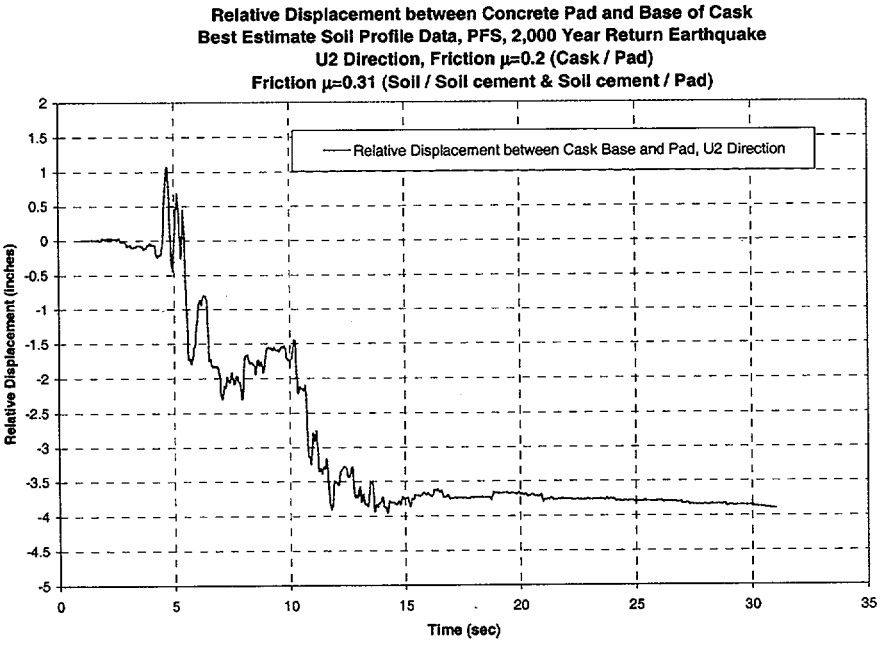


Figure I 3.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)



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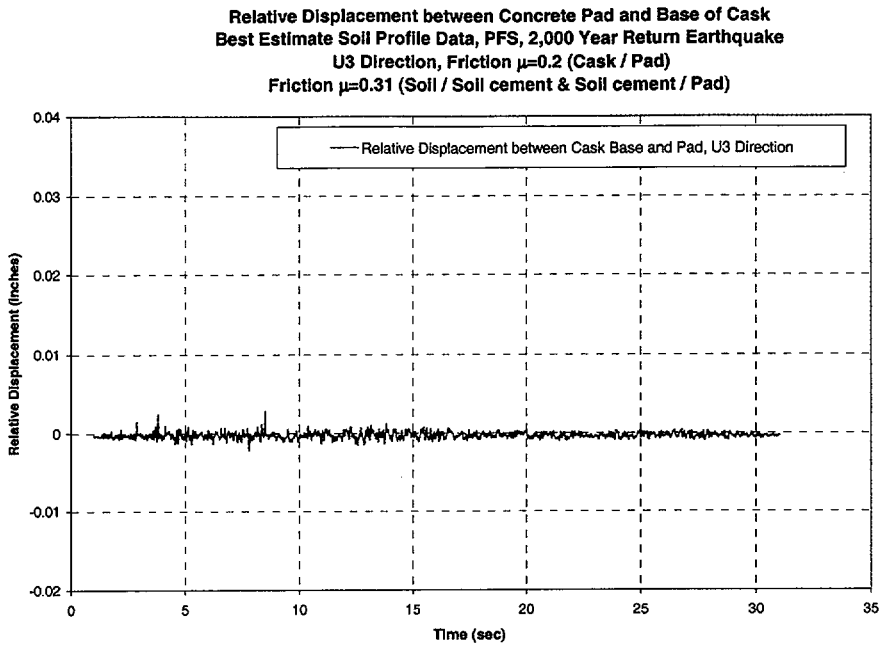

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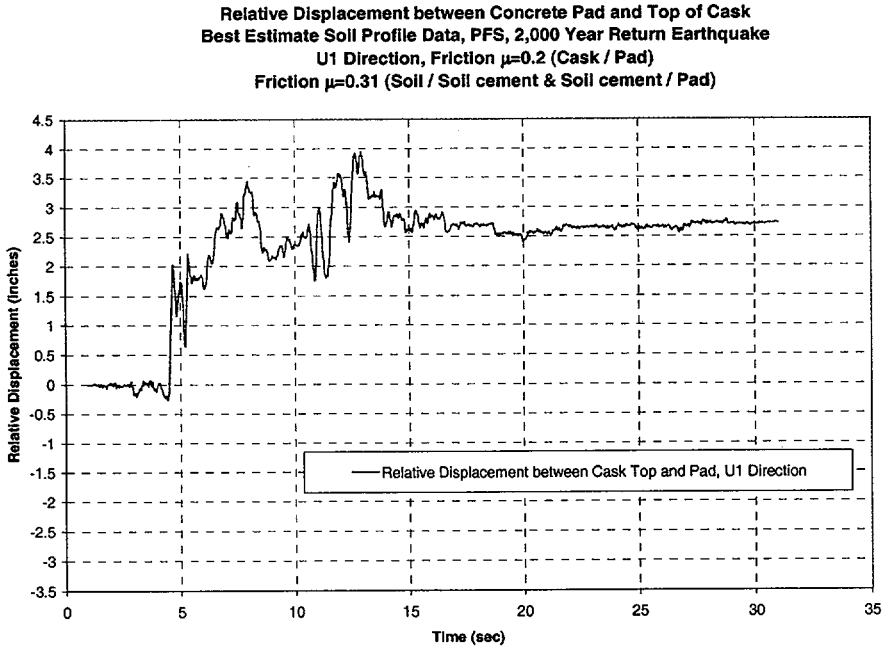

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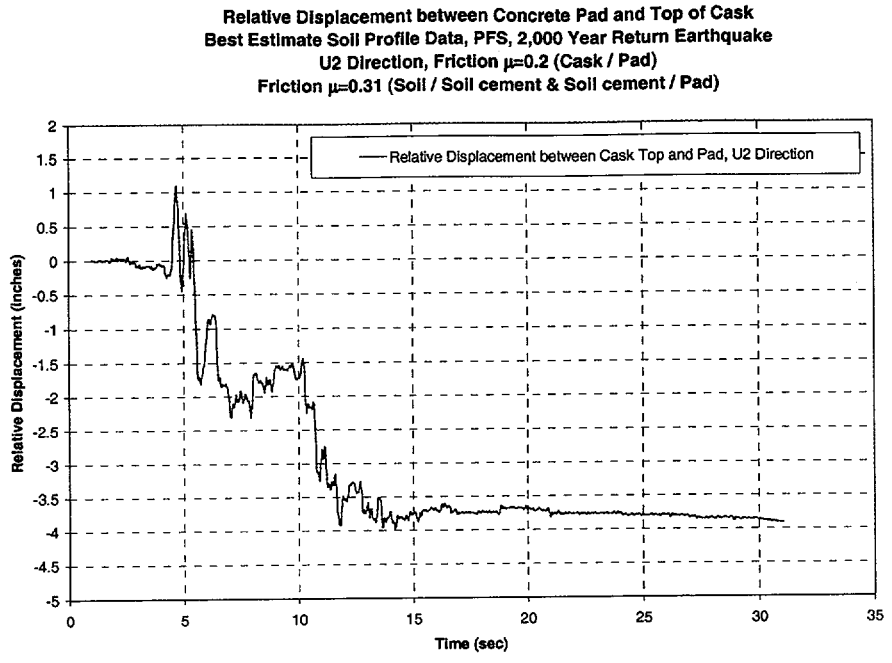
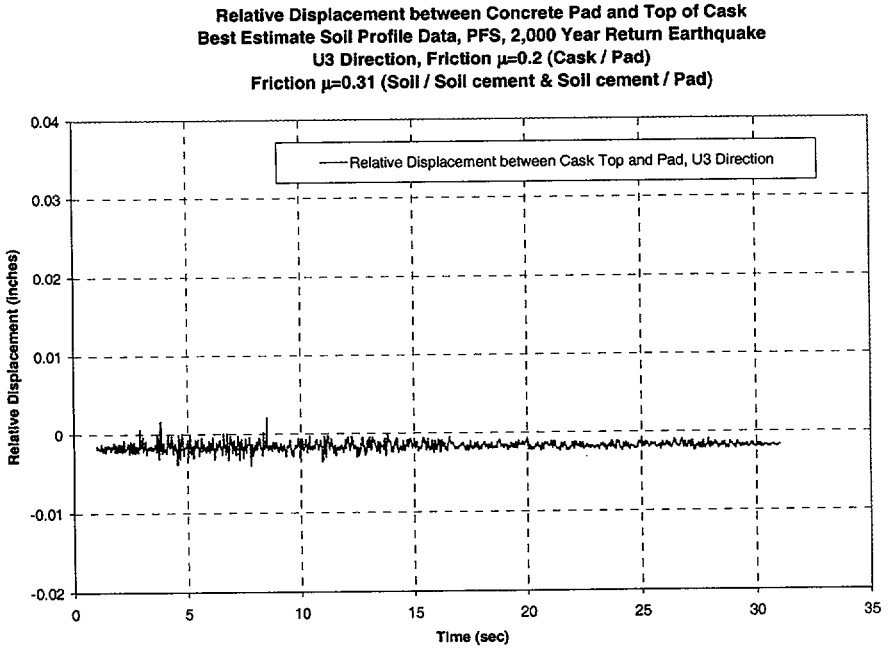


Figure I 3.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)



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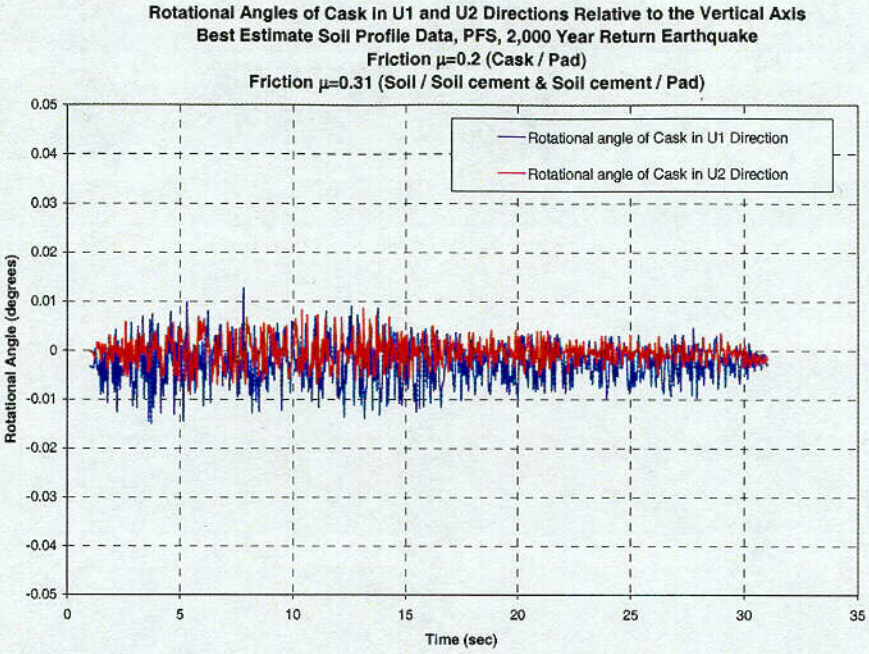


Figure I 3.7. Time history of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

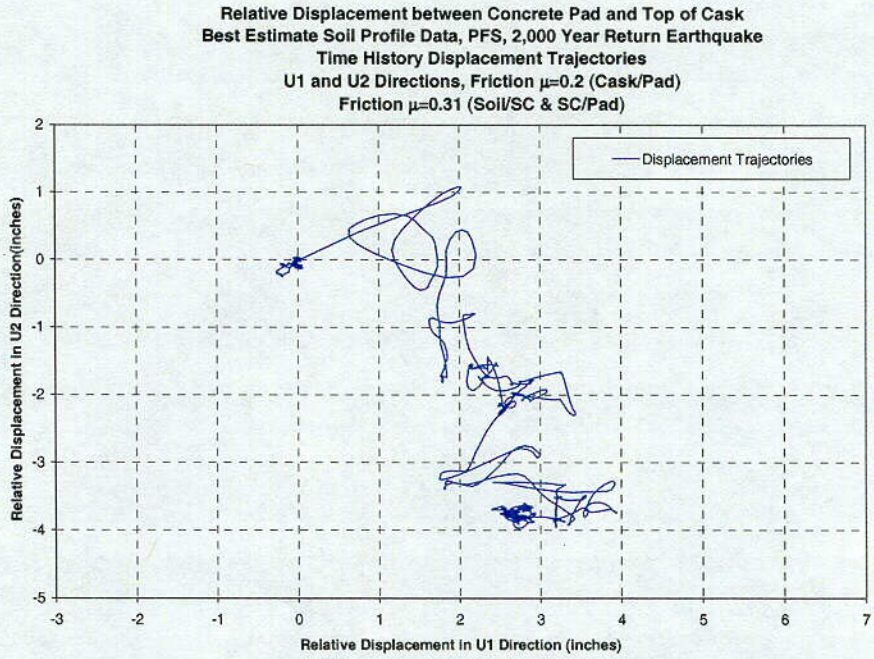


Figure I 3.8. Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

C13

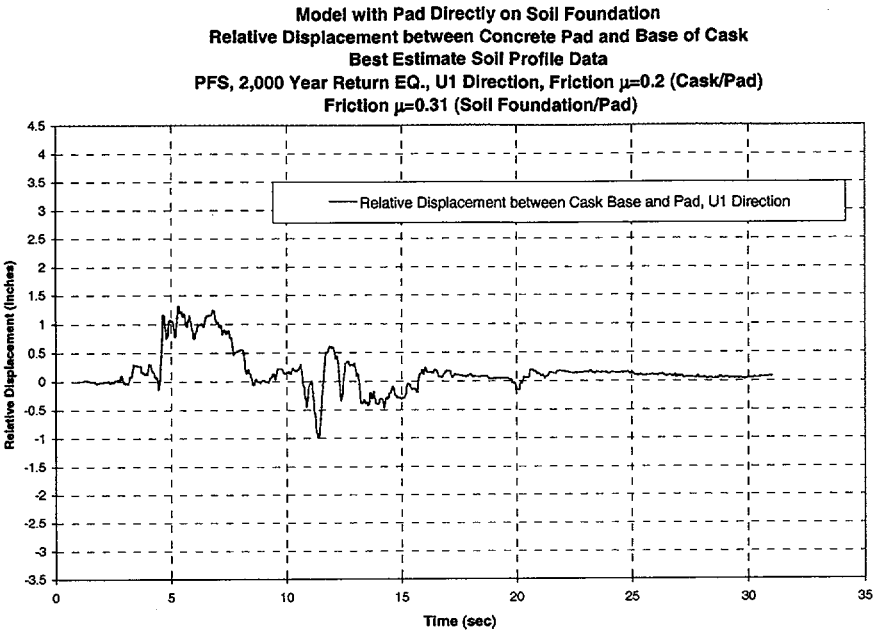


Figure I 4.1. Model with pad resting directly on soil foundation, Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

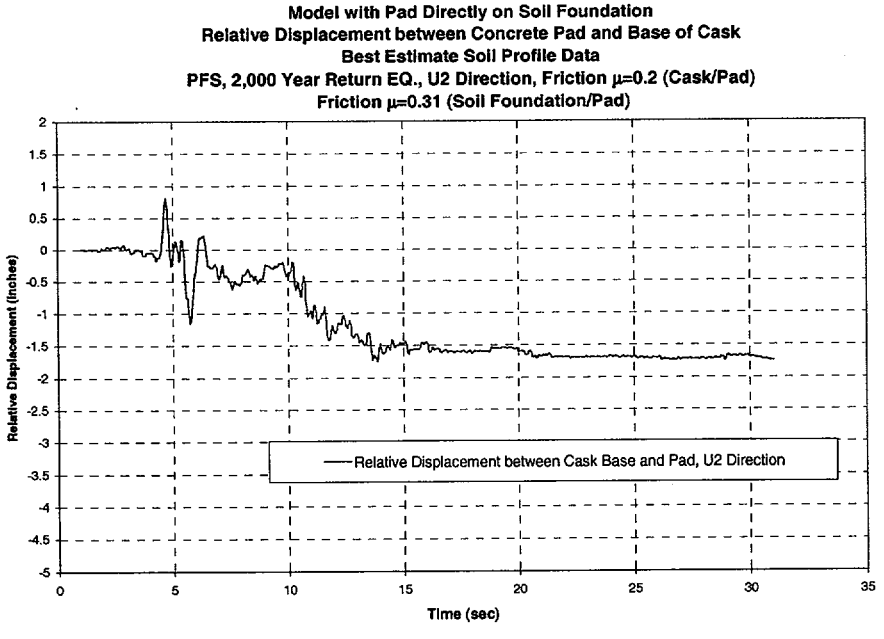


Figure I 4.2. Model with pad resting directly on soil foundation, Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

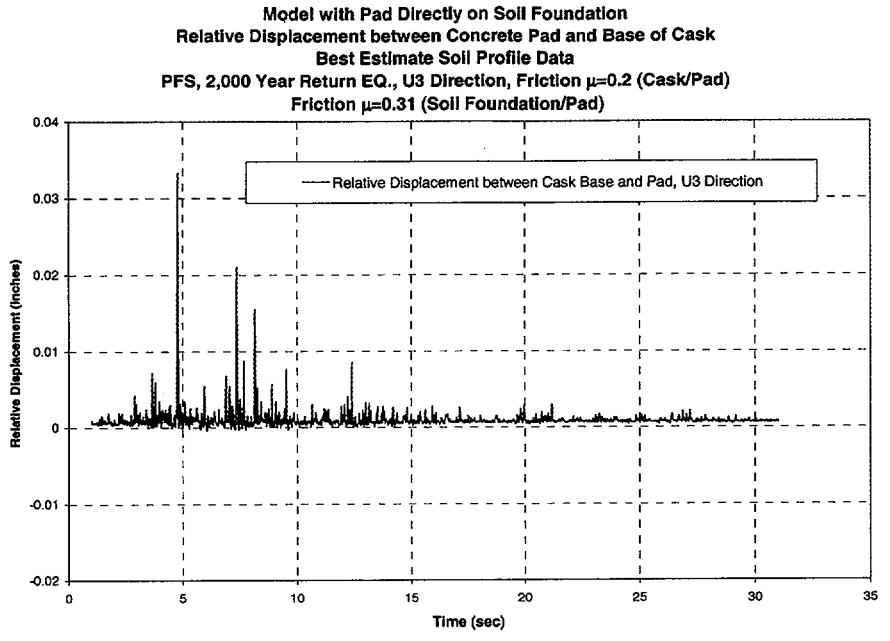


Figure I 4.3. Model with pad resting directly on soil foundation, Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

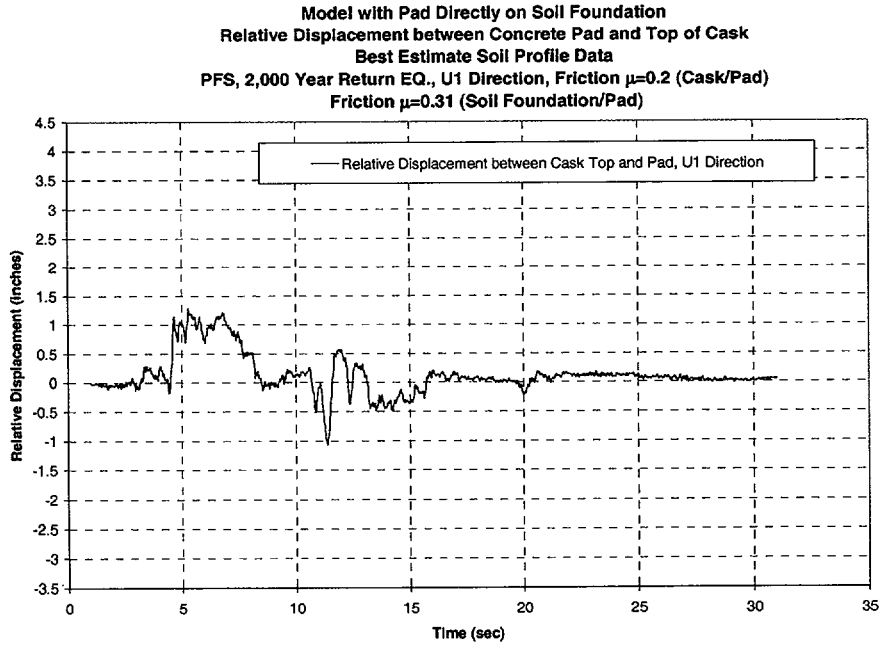


Figure I 4.4. Model with pad resting directly on soil foundation, Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

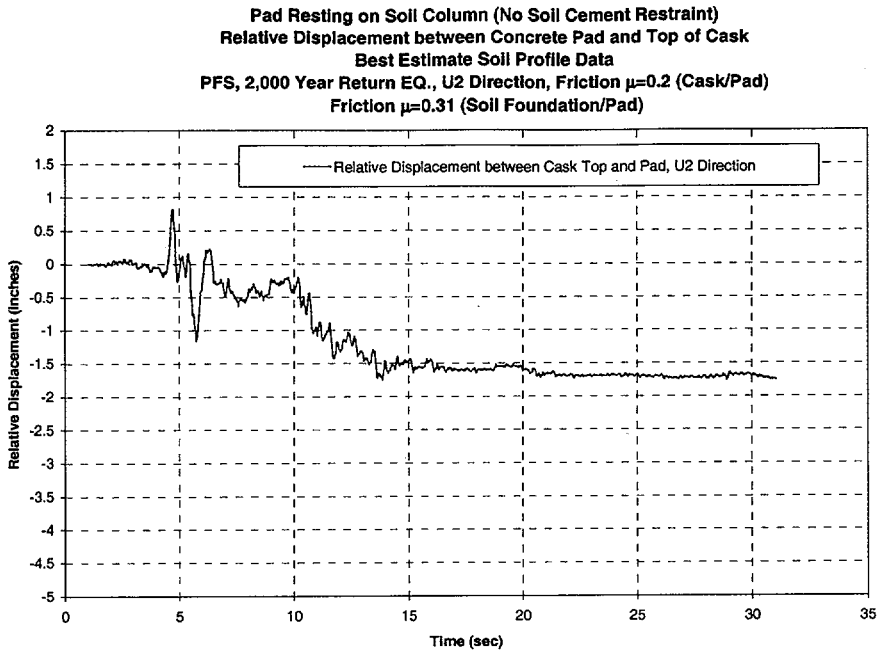


Figure I 4.5. Model with pad resting directly on soil foundation, Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

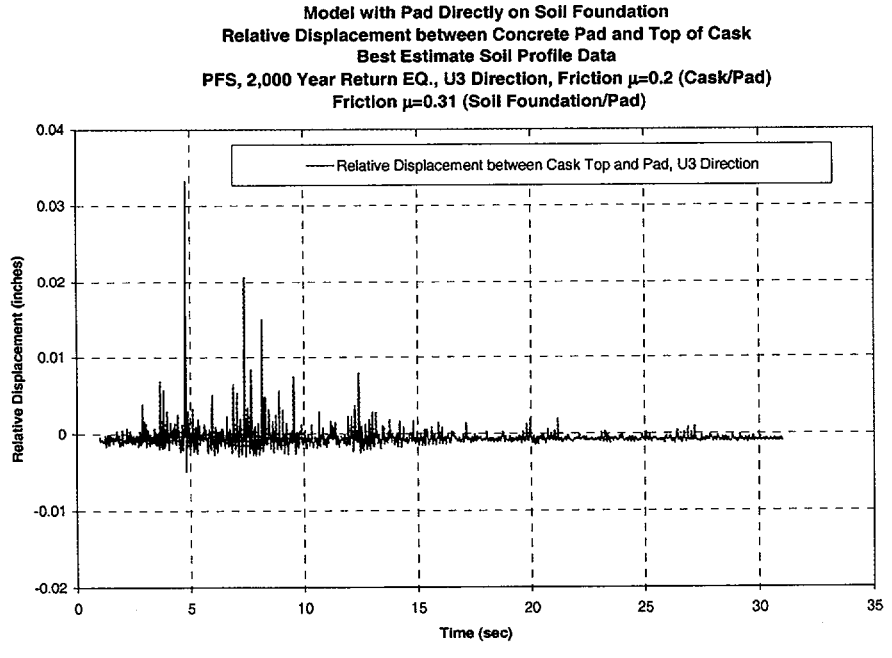
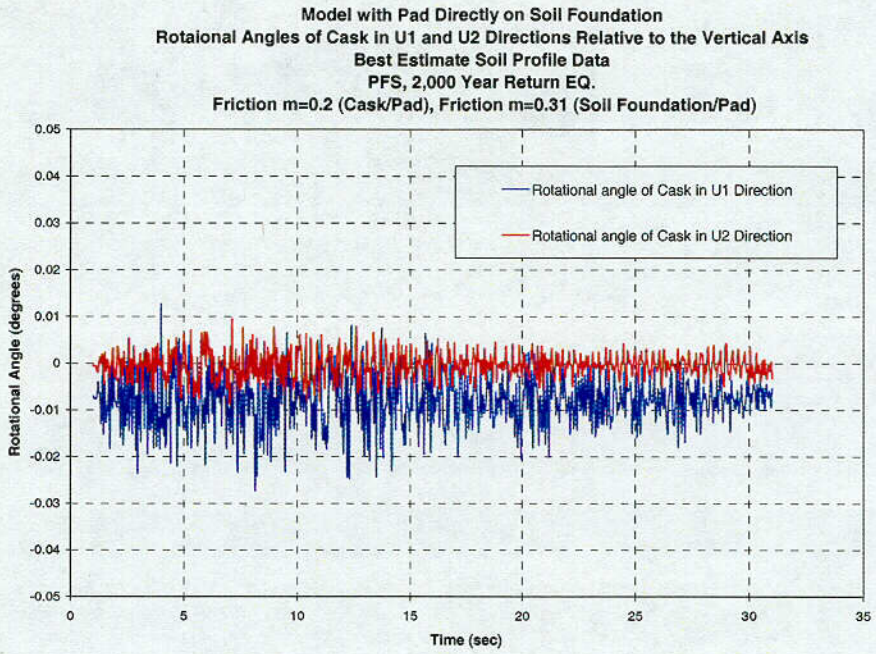


Figure I 4.6. Model with pad resting directly on soil foundation, Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)



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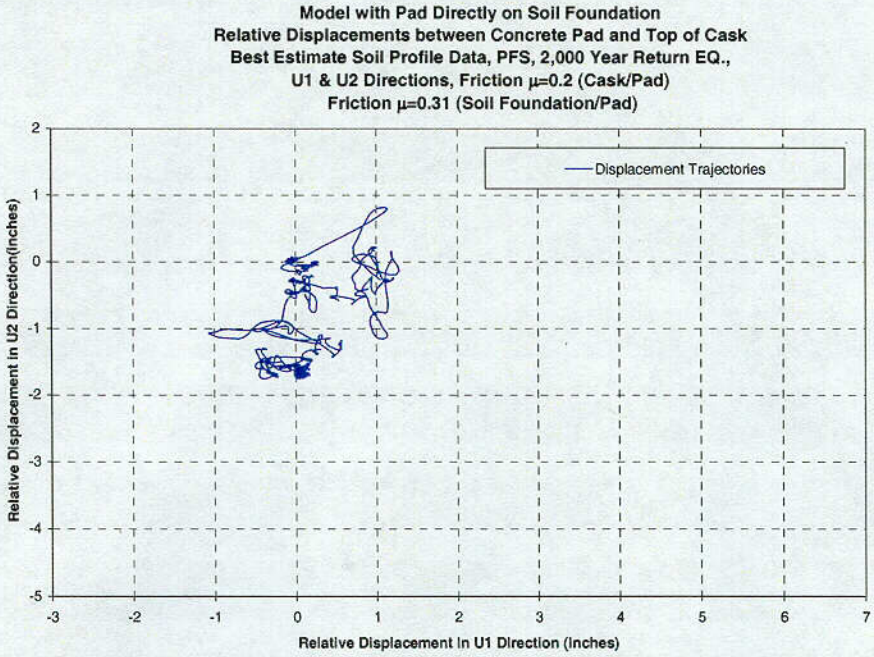

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C14

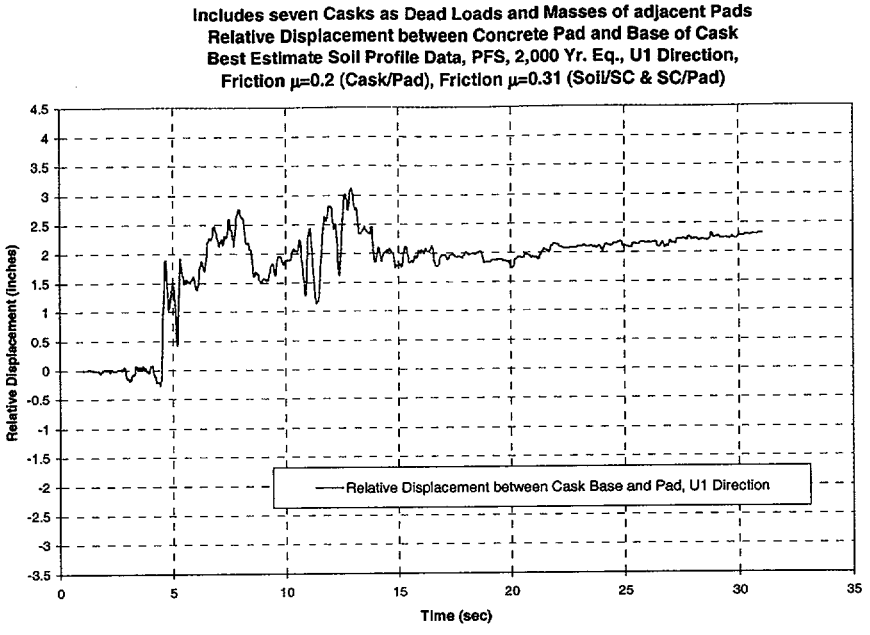


Figure I 5.1. Model including dead loads of 7 adjacent casks and adjoining pads, Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

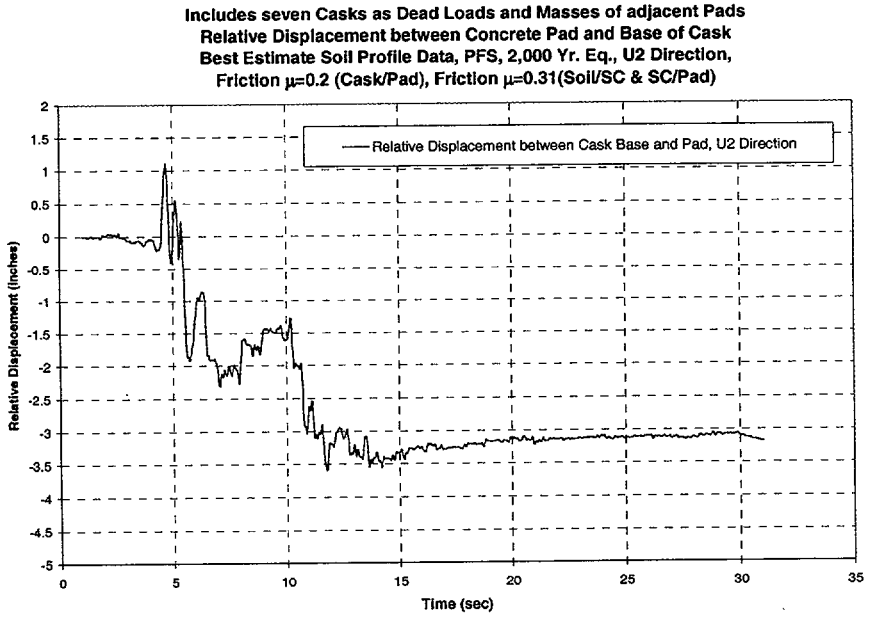
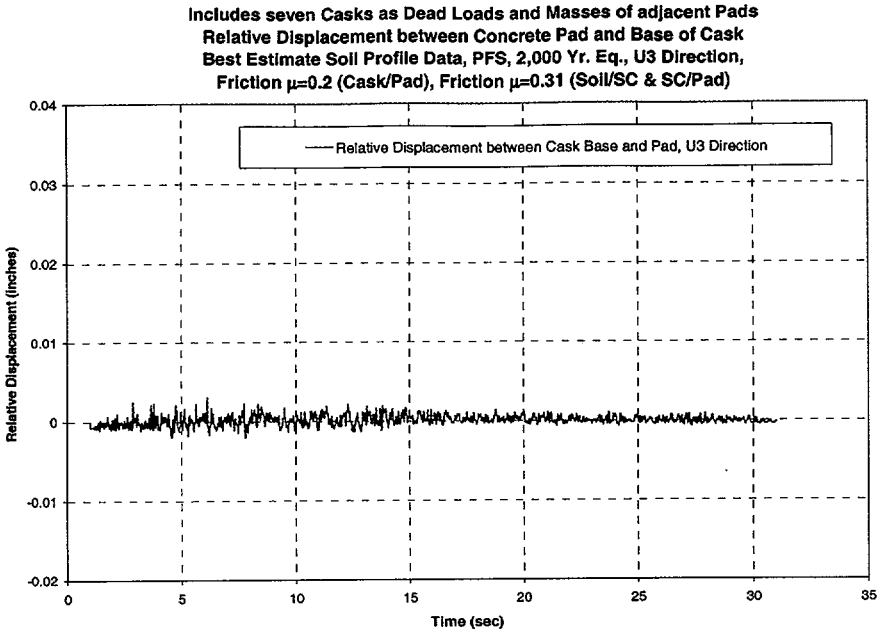


Figure I 5.2. Model including dead loads of 7 adjacent casks and adjoining pads, Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)



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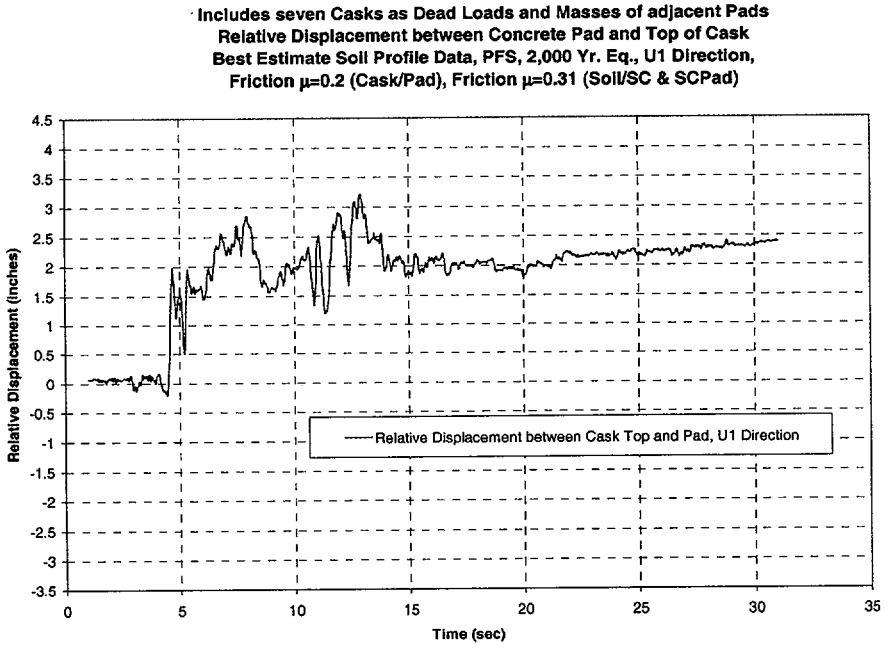
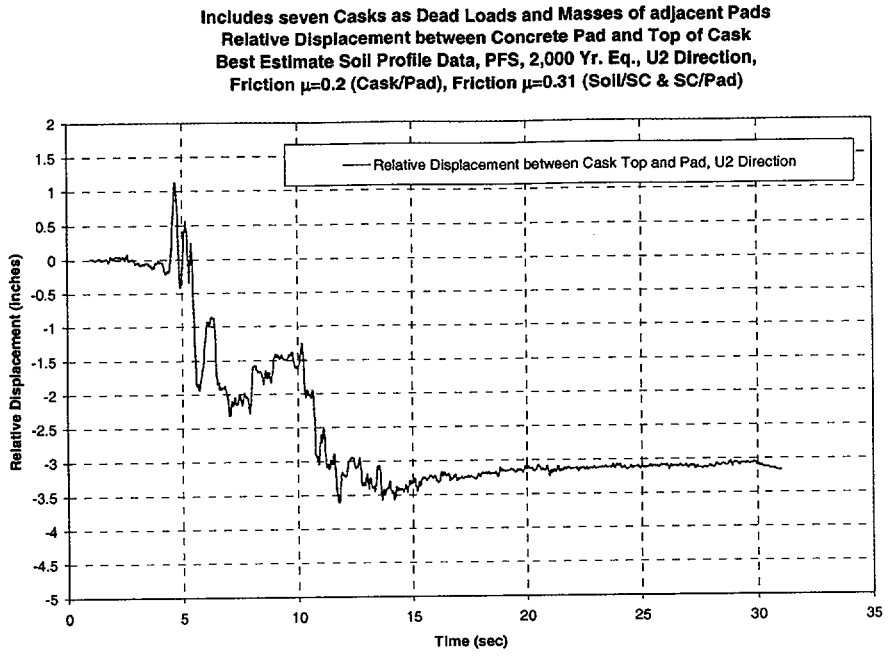


Figure I 5.4. Model including dead loads of 7 adjacent casks and adjoining pads, Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)



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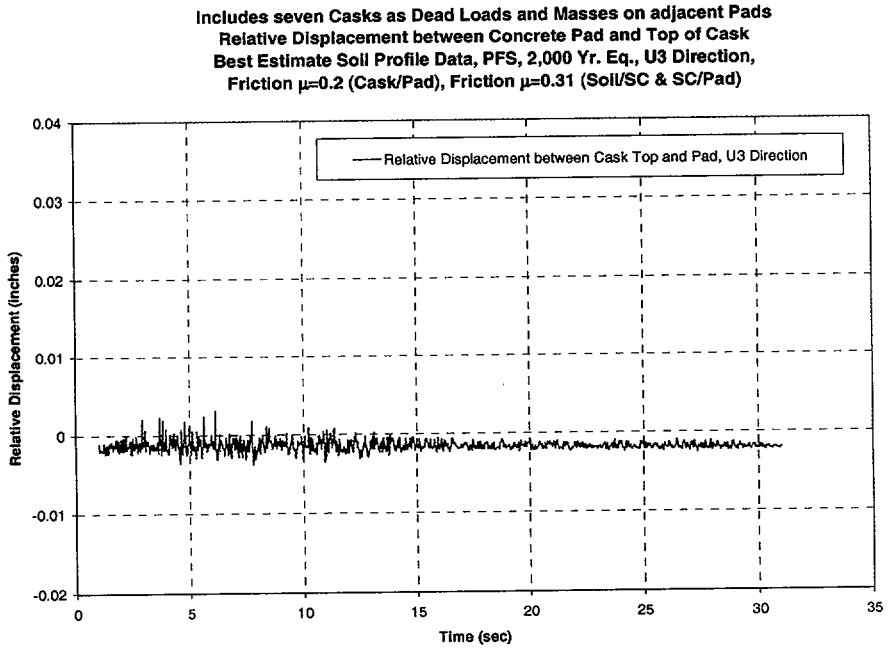

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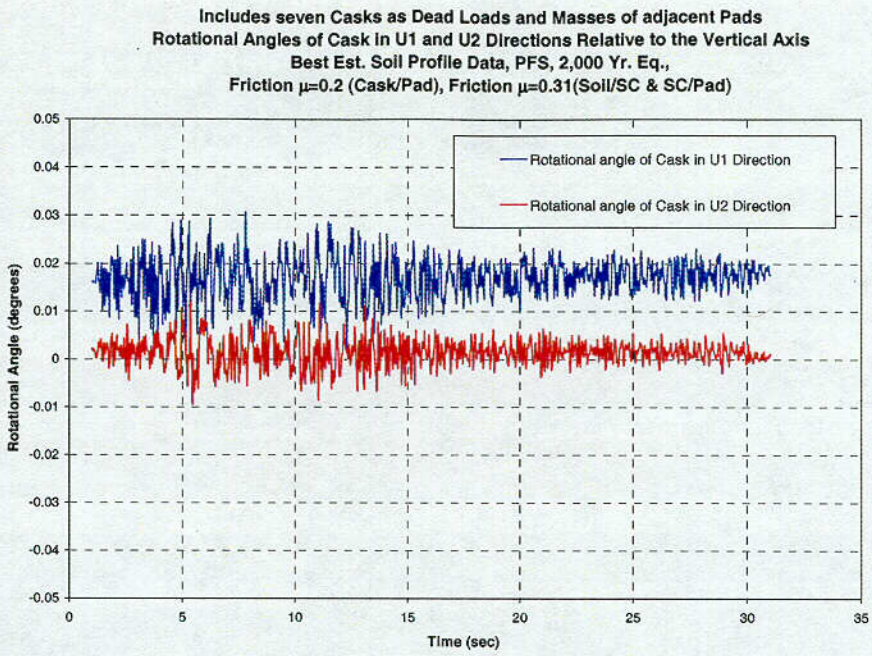

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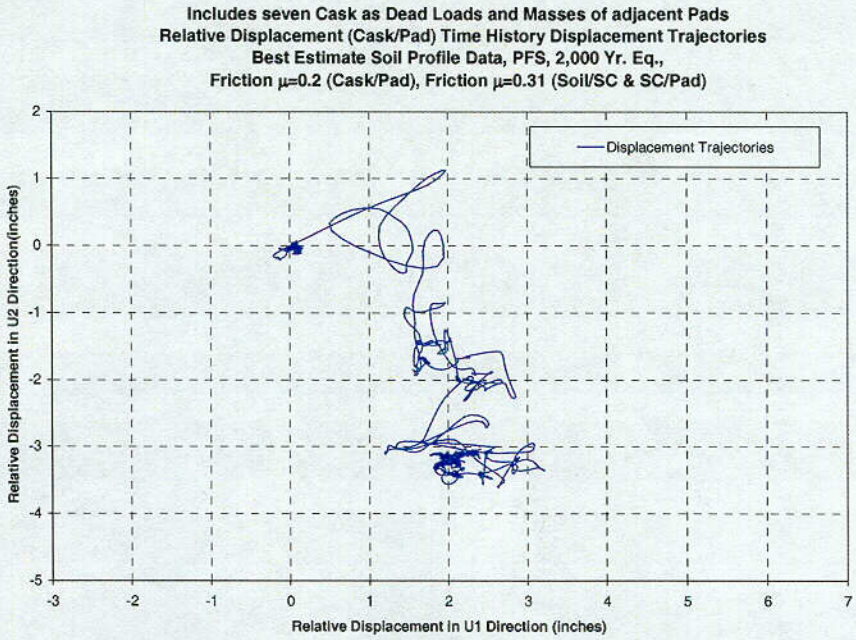

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C15

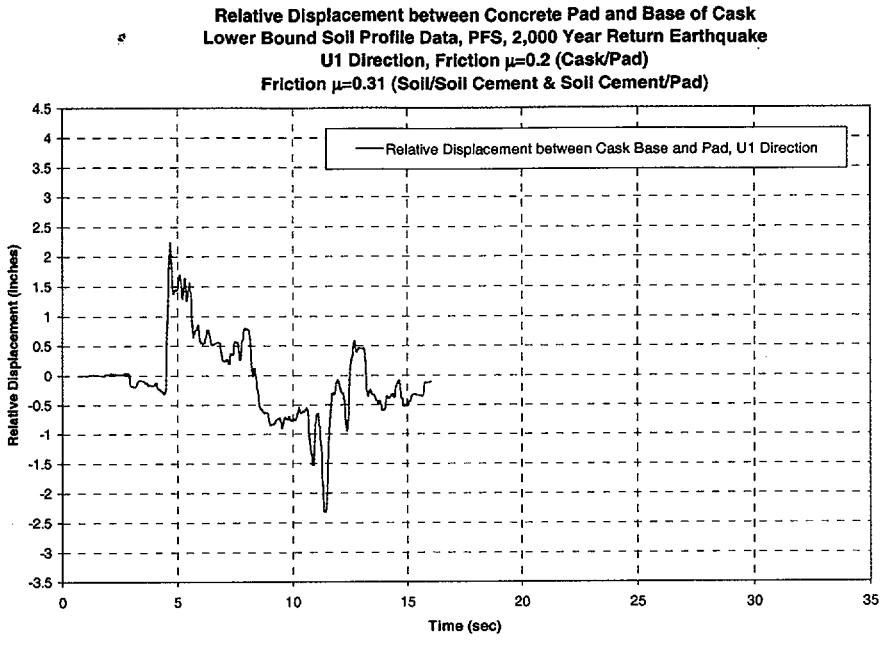


Figure I 6.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

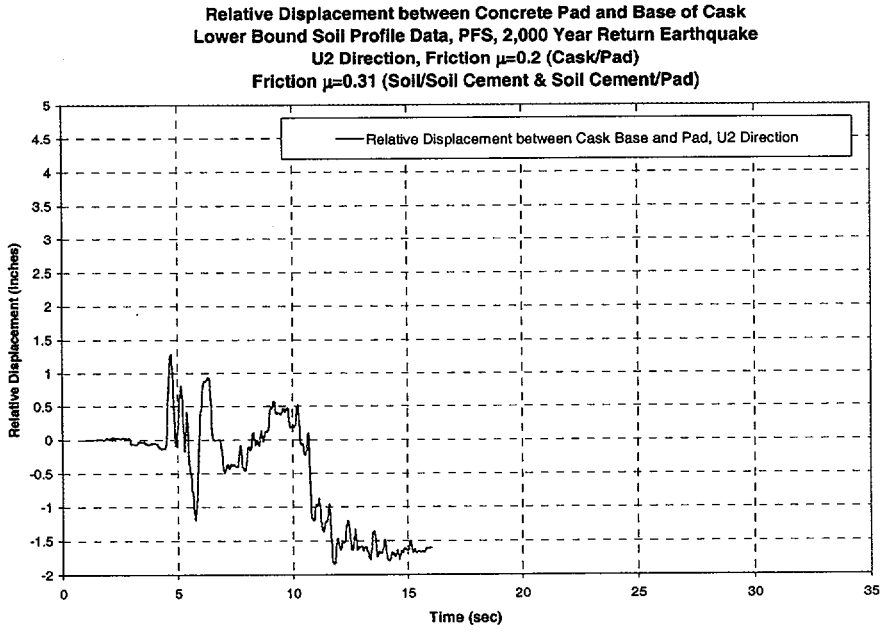


Figure I 6.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

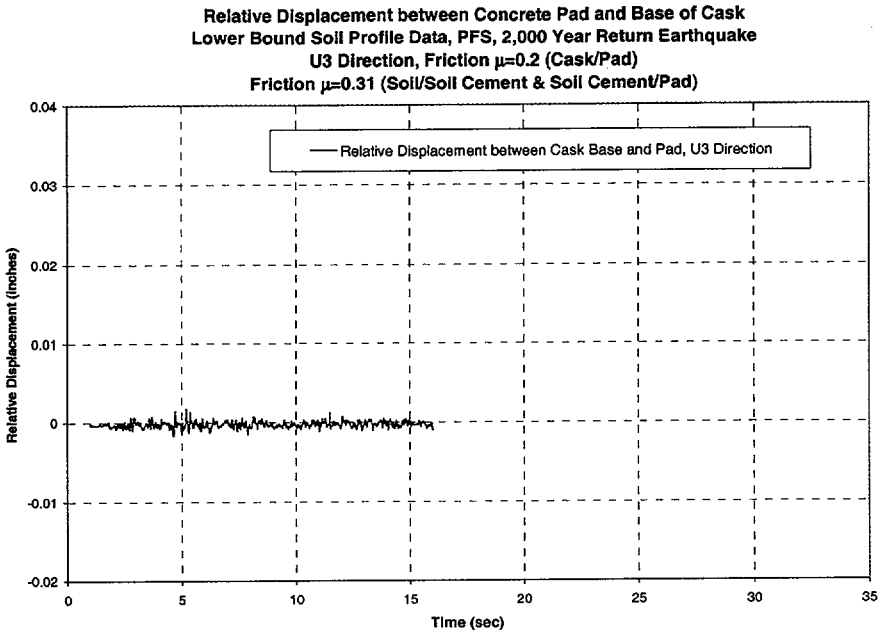


Figure I 6.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

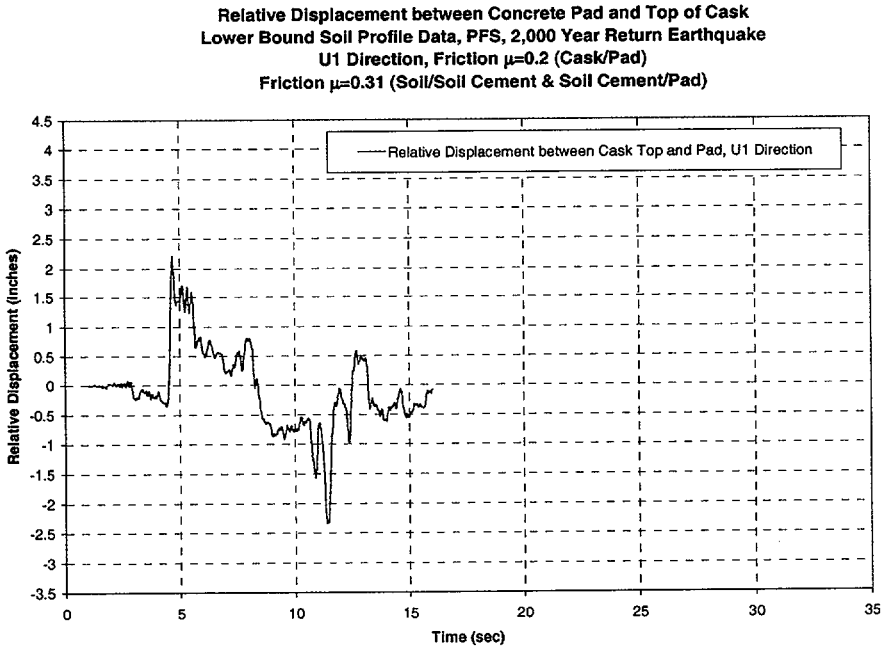
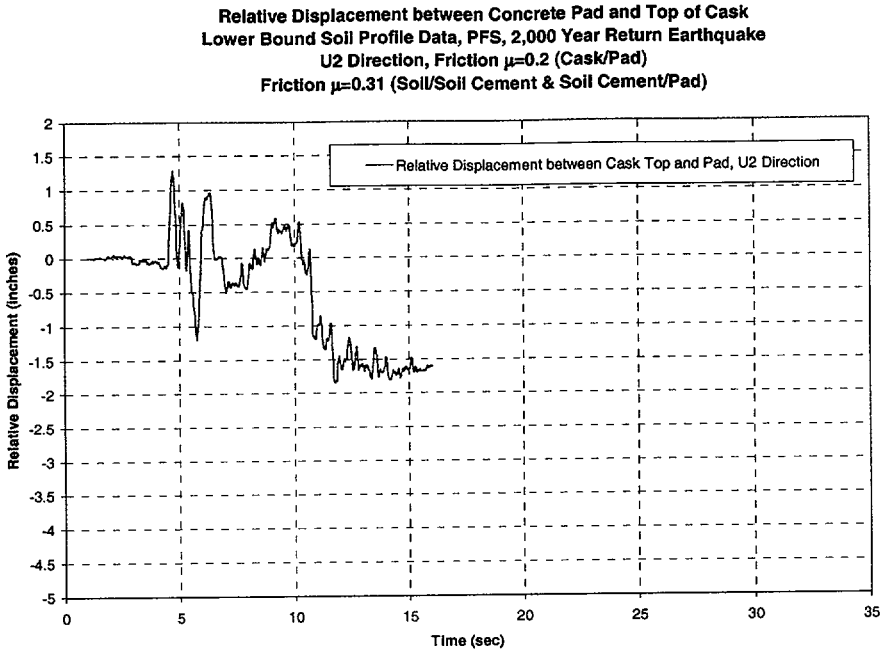


Figure I 6.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)



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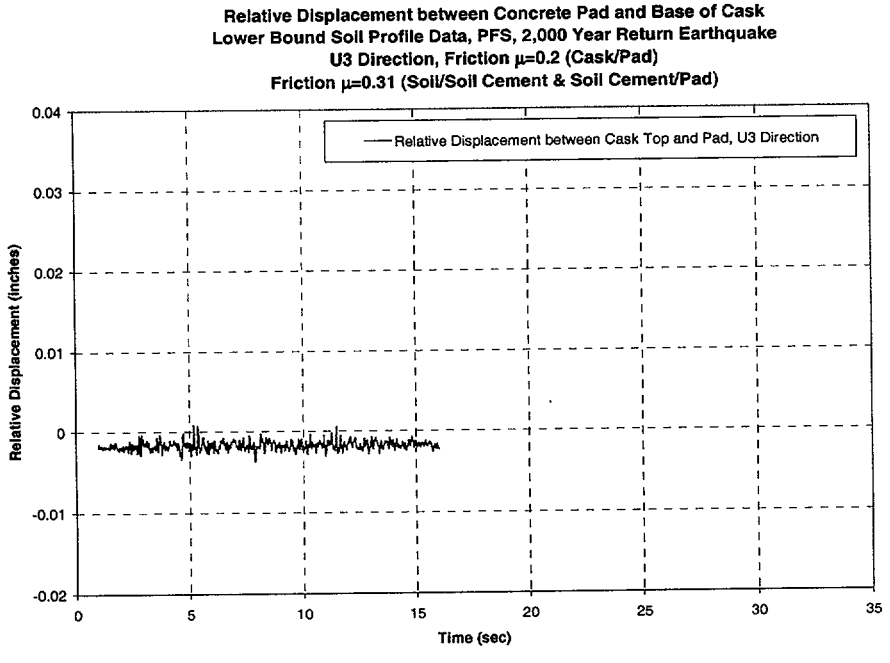

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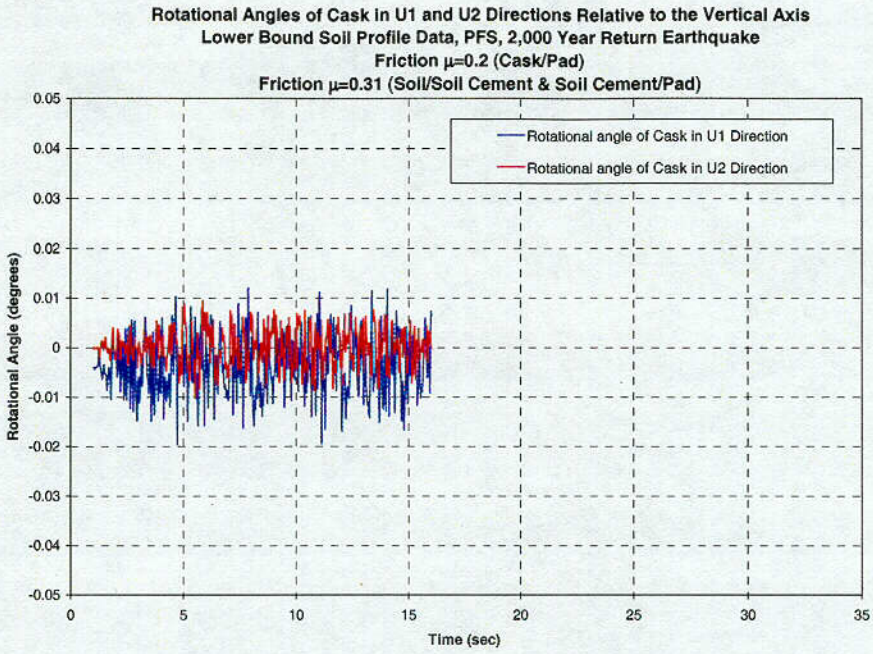


Figure I 6.7. Time history of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Lower Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

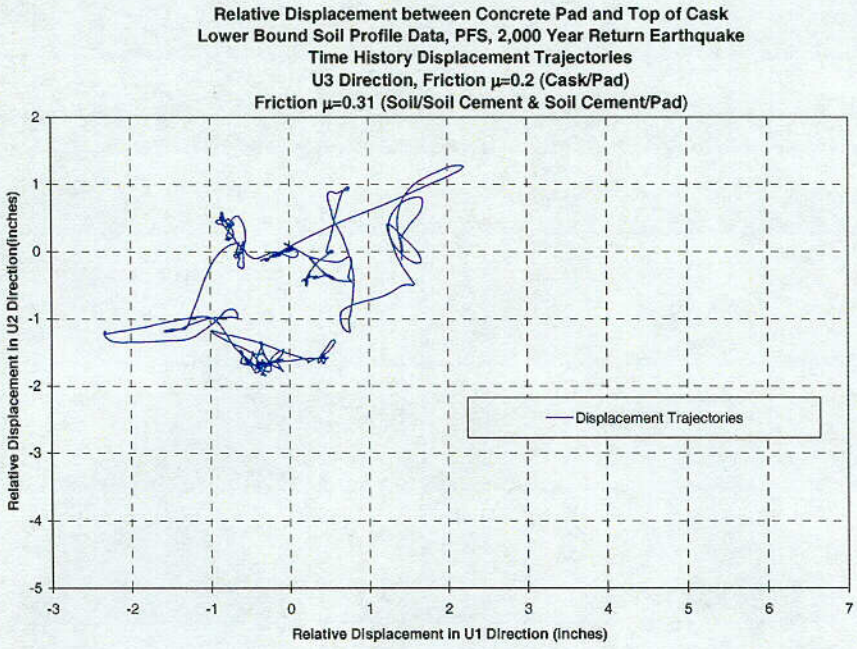


Figure I 6.8. Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

C16

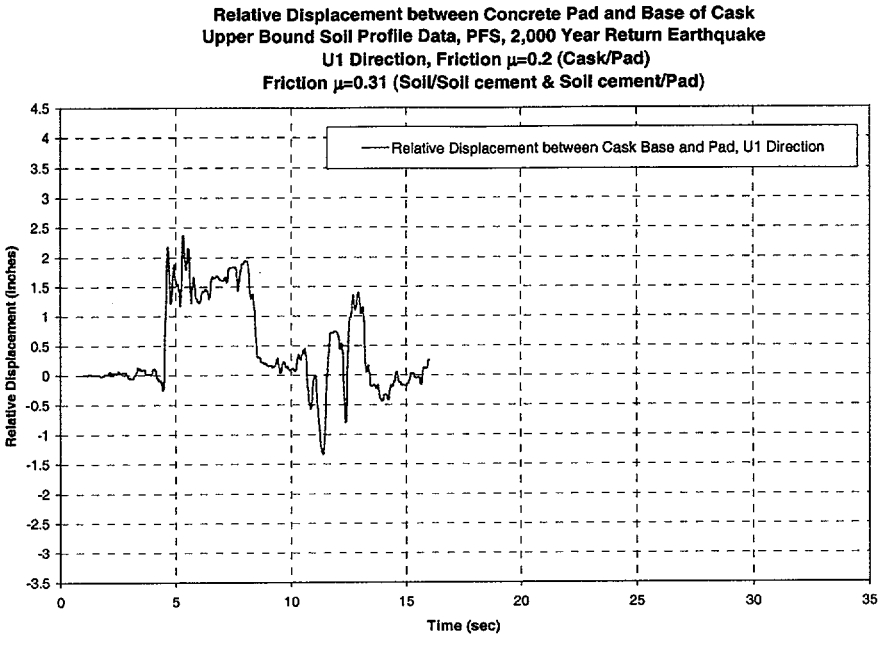


Figure I 7.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Upper Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

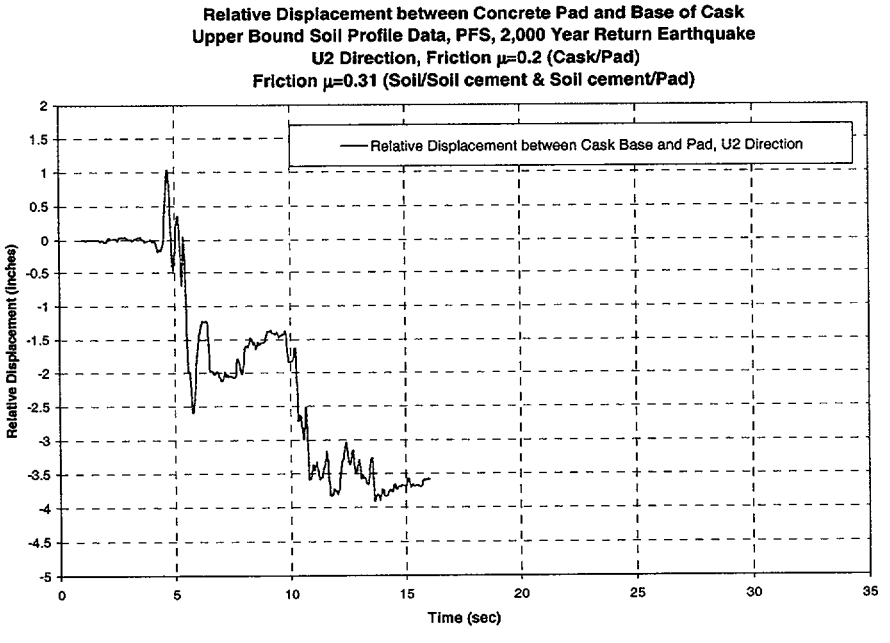
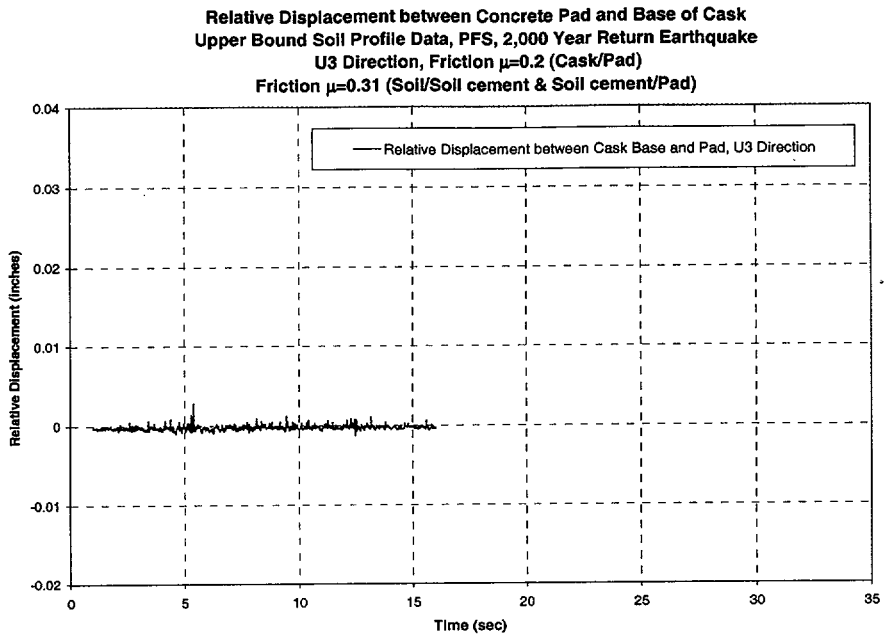


Figure I 7.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Upper Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)



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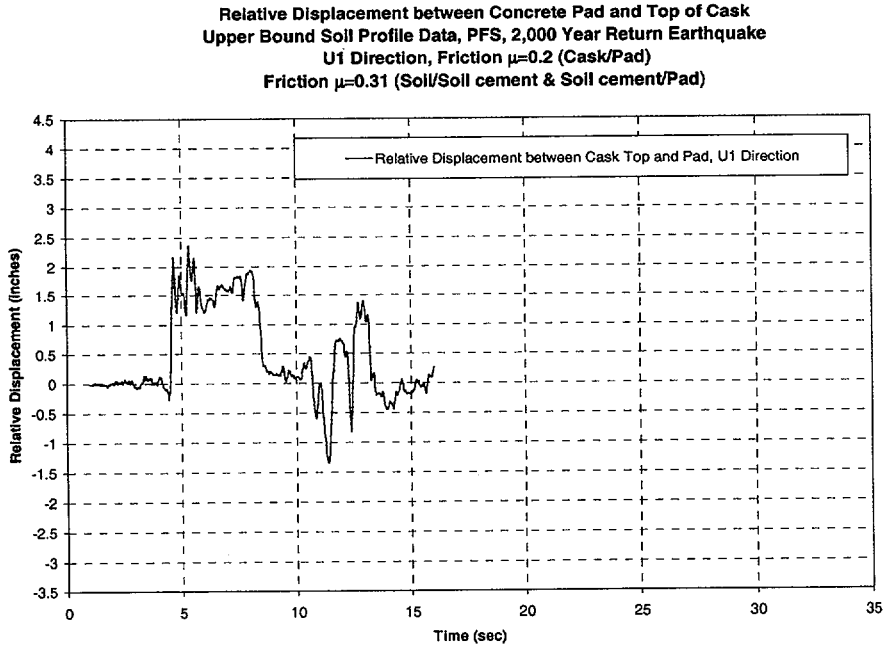
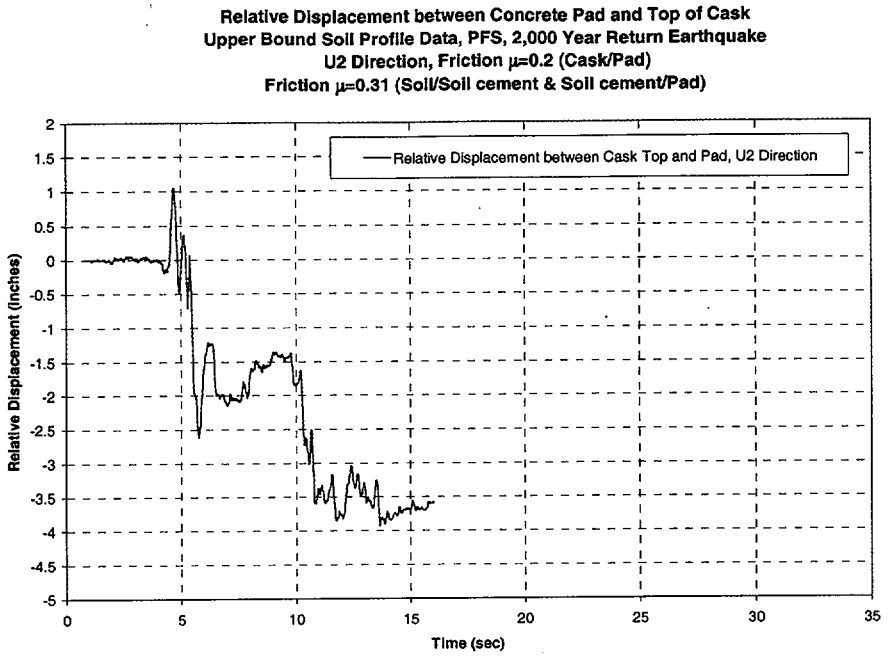


Figure I 7.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)



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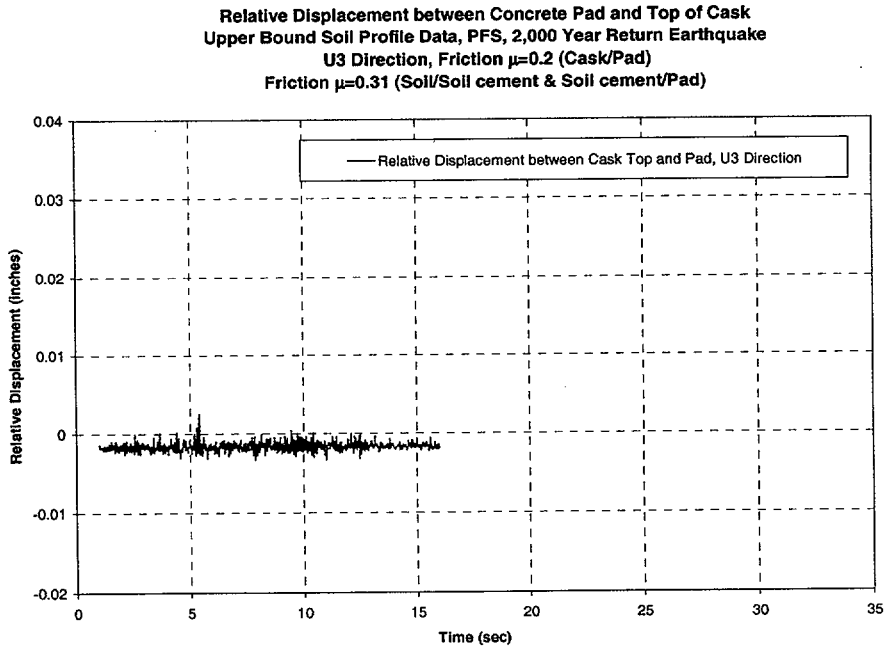

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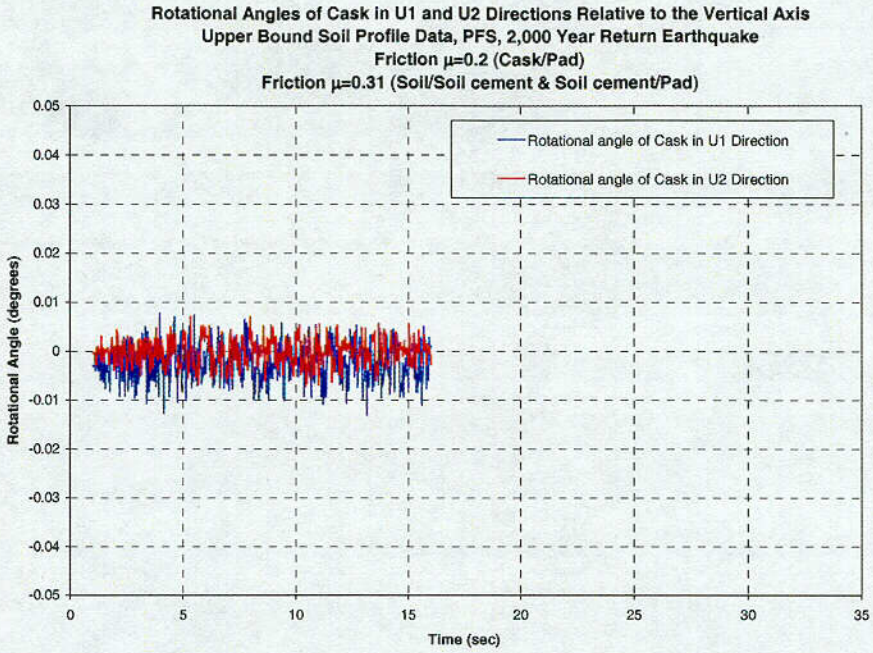

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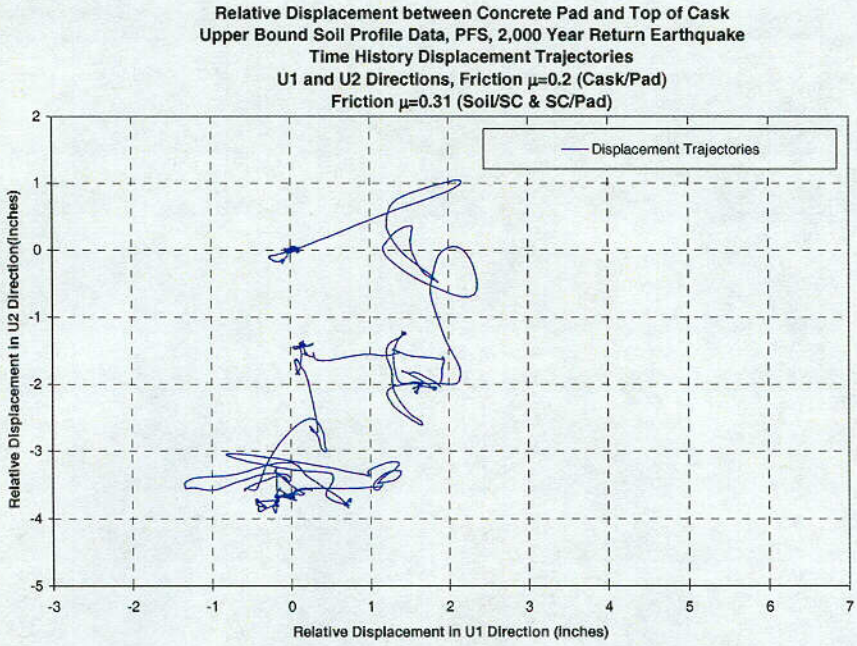

Figure I 7.8. Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, PFS, 2,000 Year Return Earthquake, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

C17

APPENDIX II

ANALYSIS RESULTS FOR THE 1971 SAN FERNANDO EARTHQUAKE, PACOIMA DAM RECORD

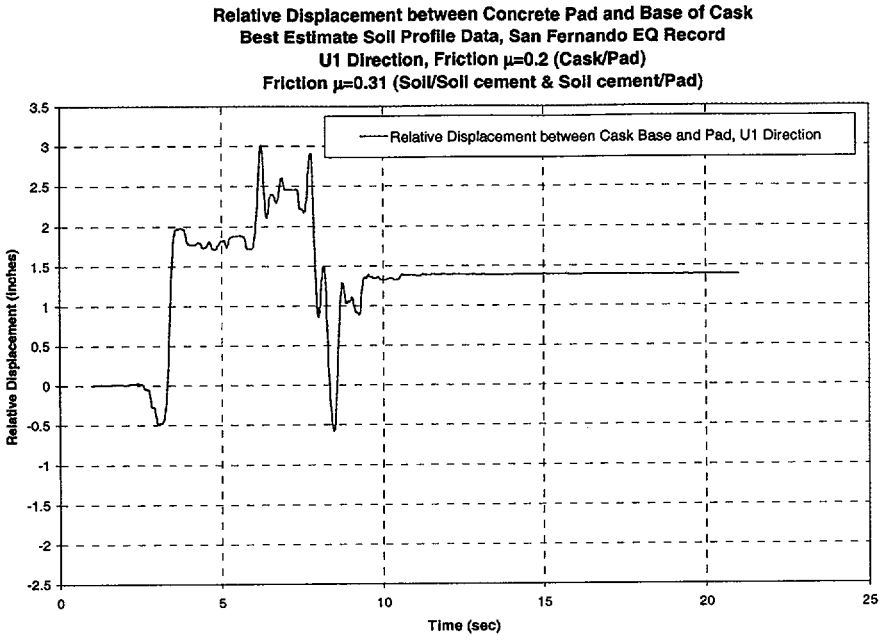

Figure II 1.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

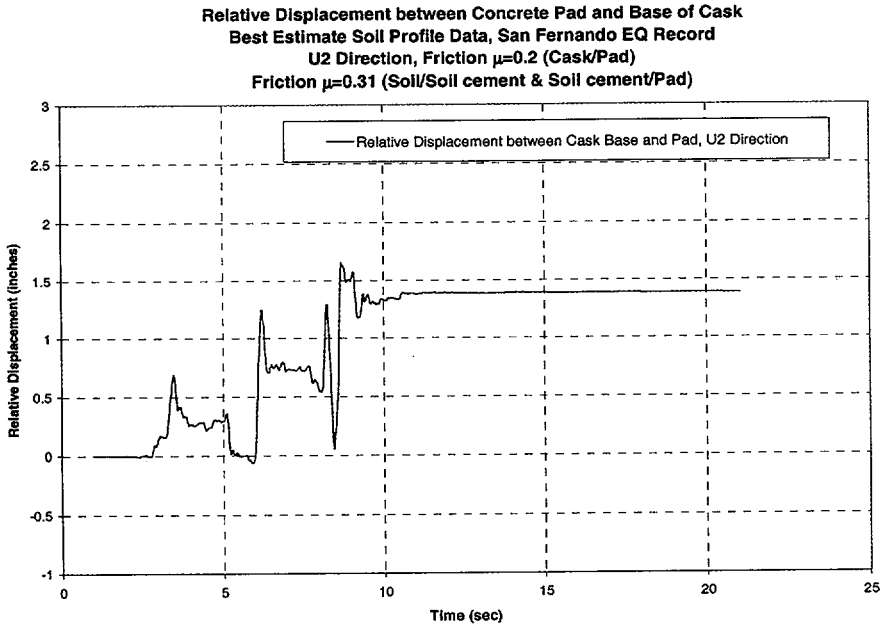

Figure II 1.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

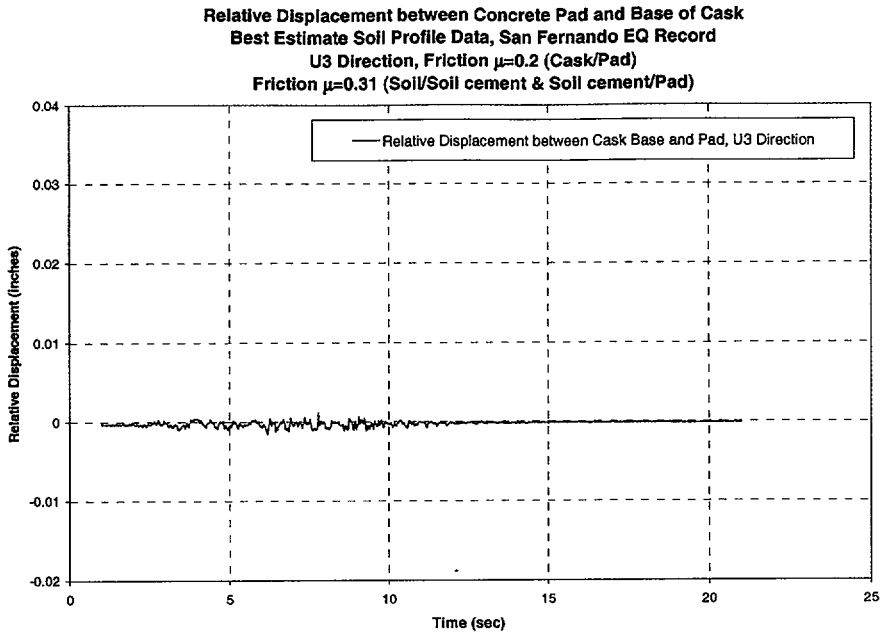

Figure II 1.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

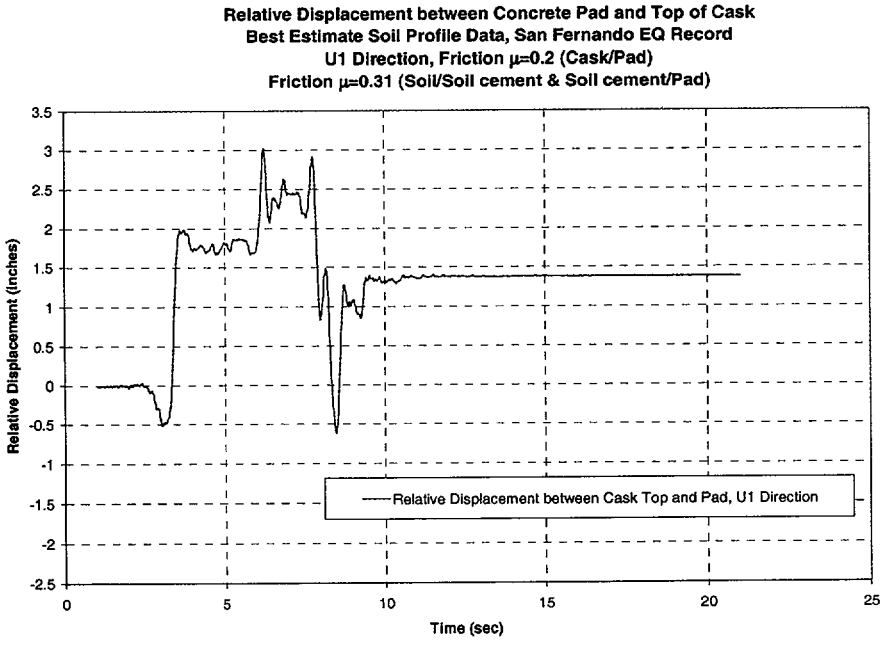

Figure II 1.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

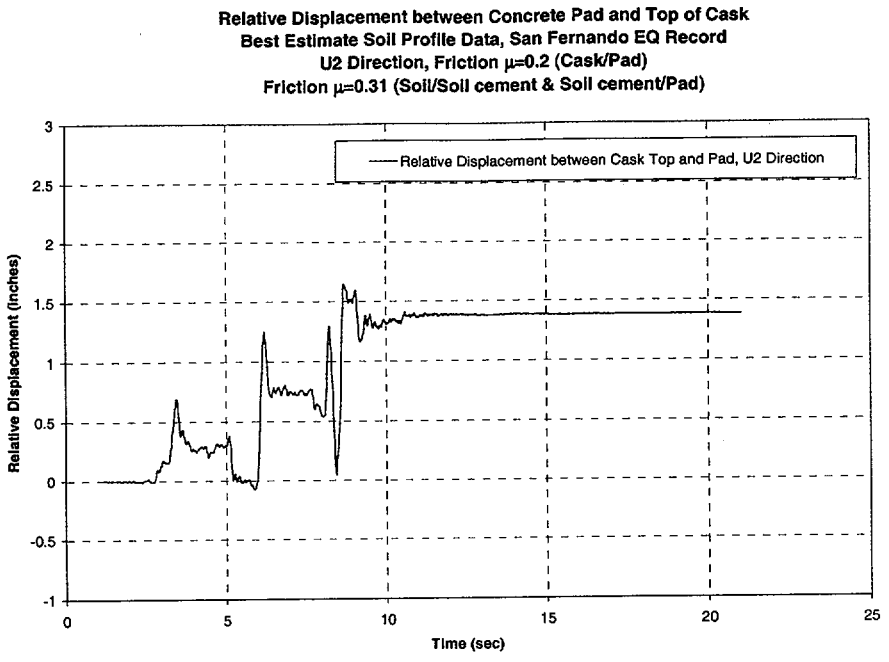

Figure II 1.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

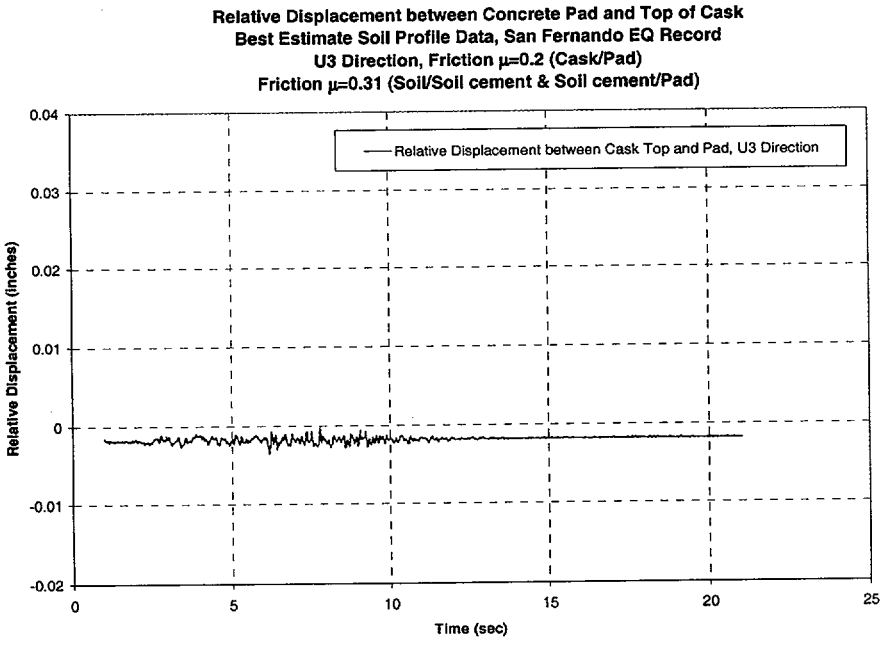

Figure II 1.6. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

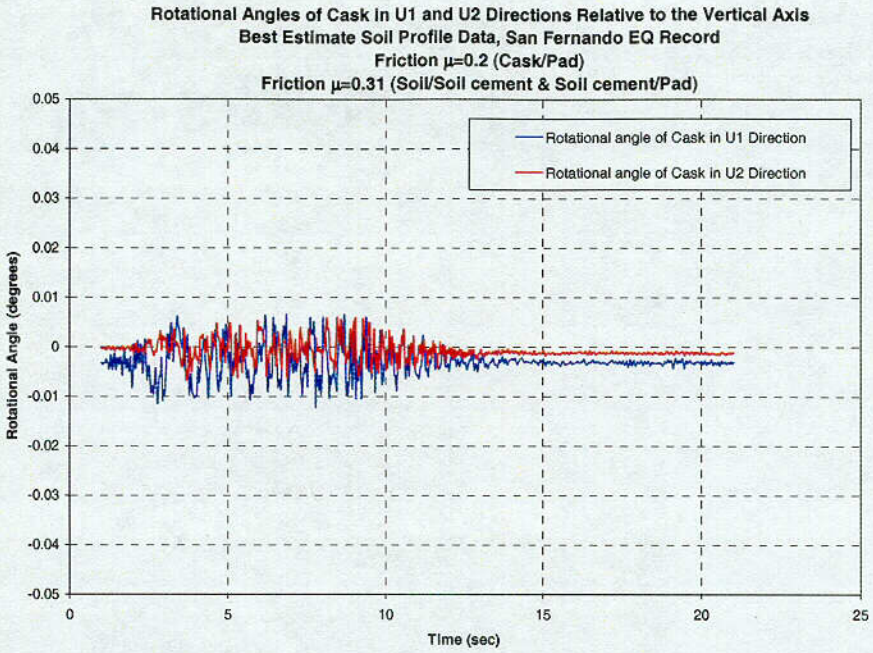

Figure II 1.7. Time History of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Best Estimate Soil Profile Data, San Fernando Earthquake Record, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

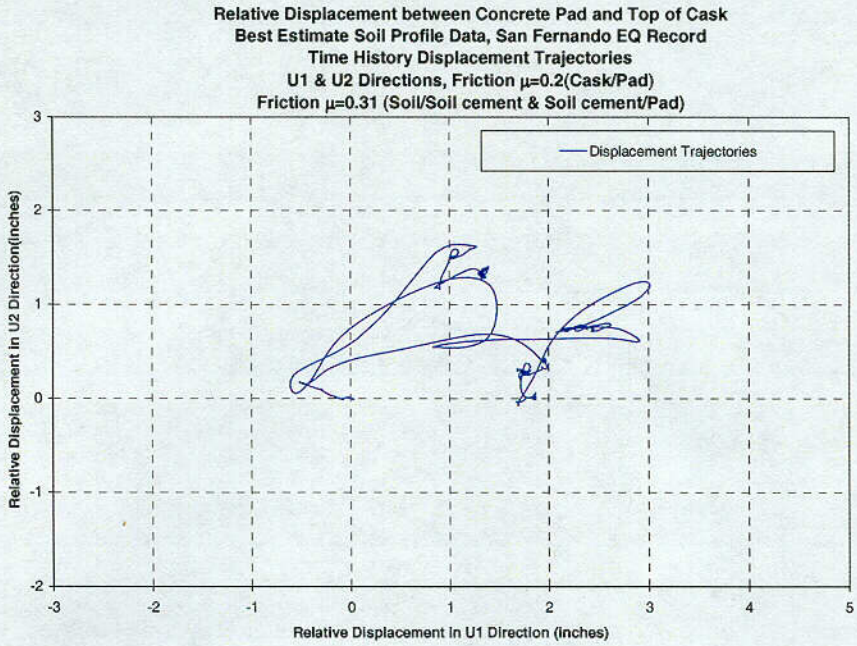

Figure II 1.8. Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

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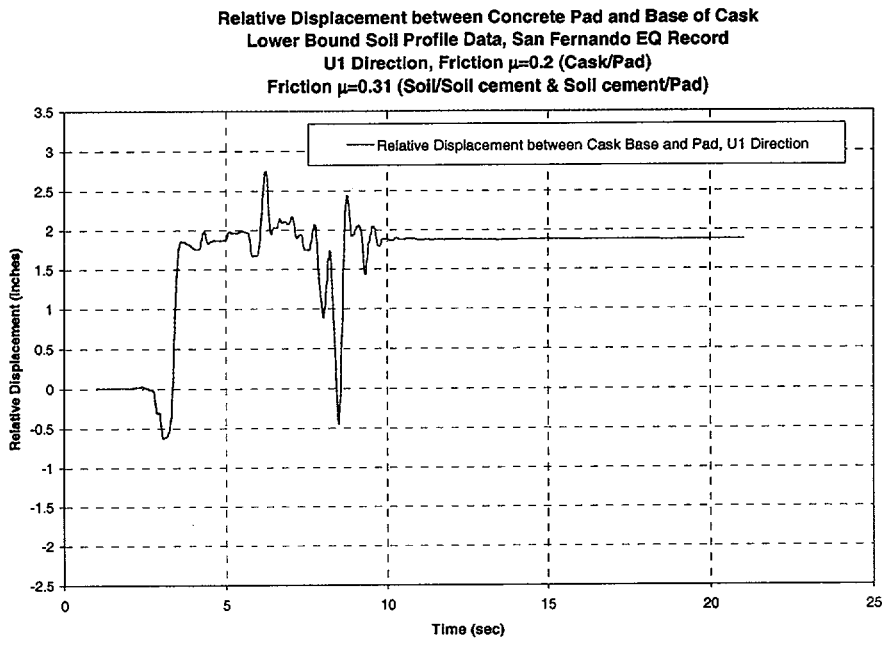

Figure II 2.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, San Fernando Earthquake Record, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

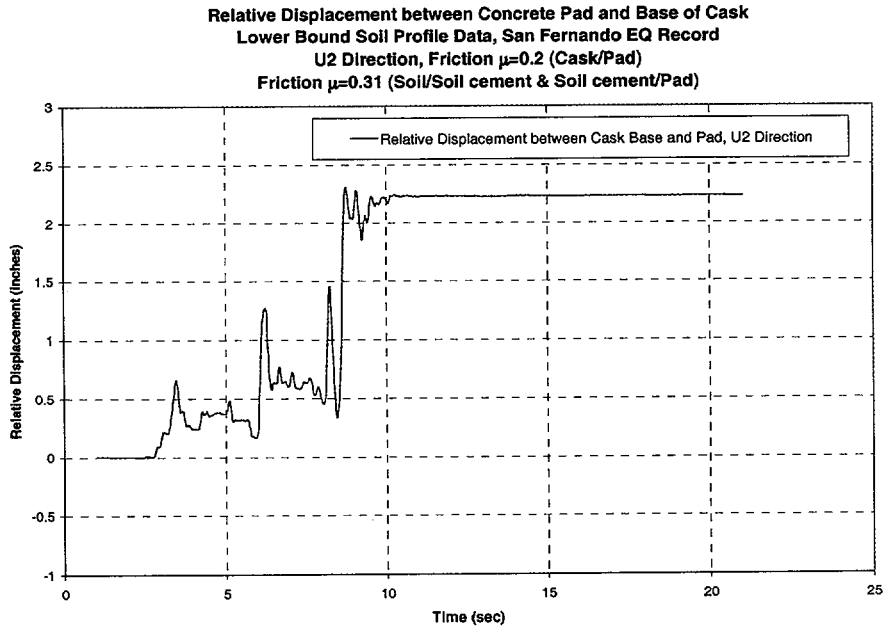

Figure II 2.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, San Fernando Earthquake Record, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

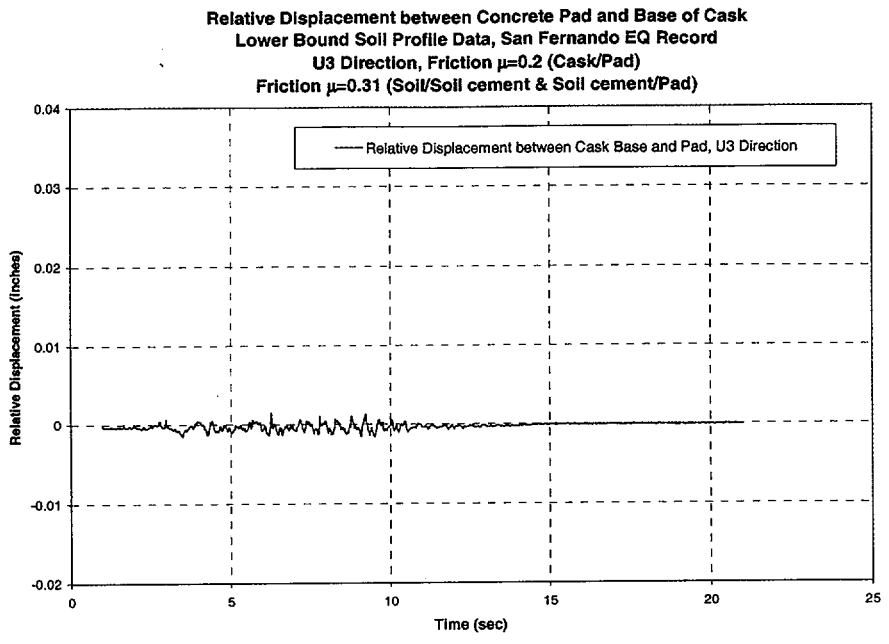

Figure II 2.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, San Fernando Earthquake Record, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

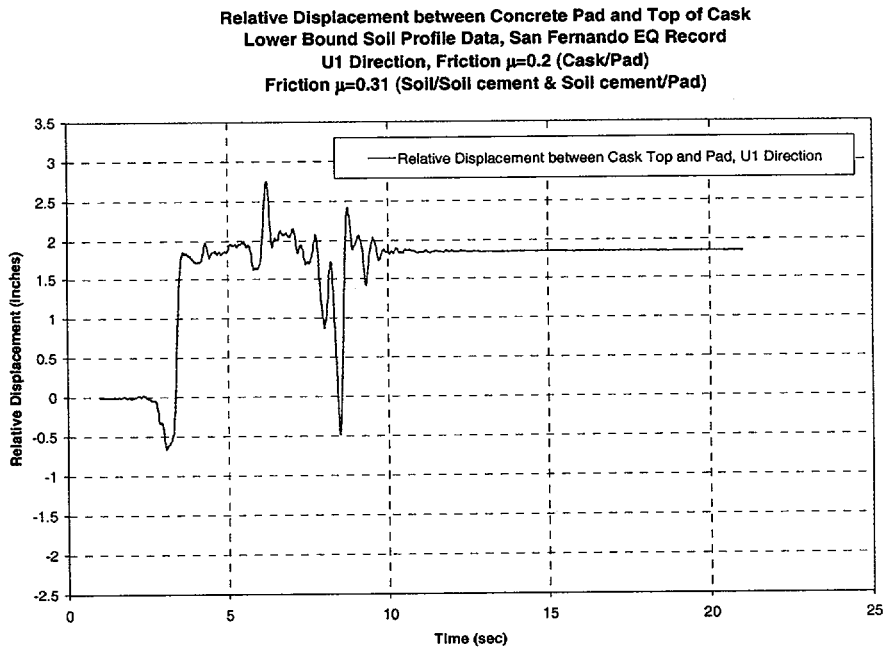

Figure II 2.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, San Fernando Earthquake Record, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

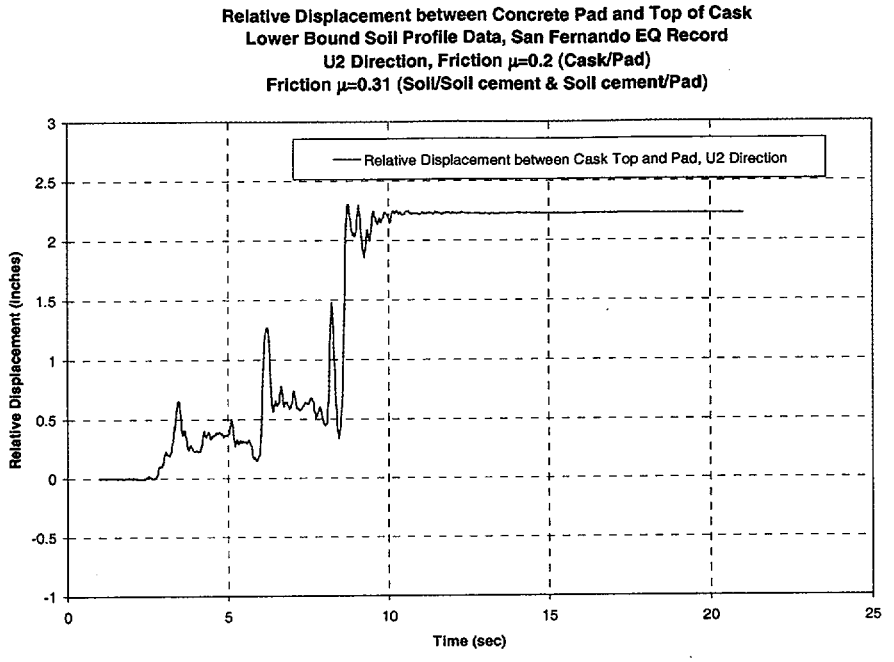

Figure II 2.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, San Fernando Earthquake Record, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

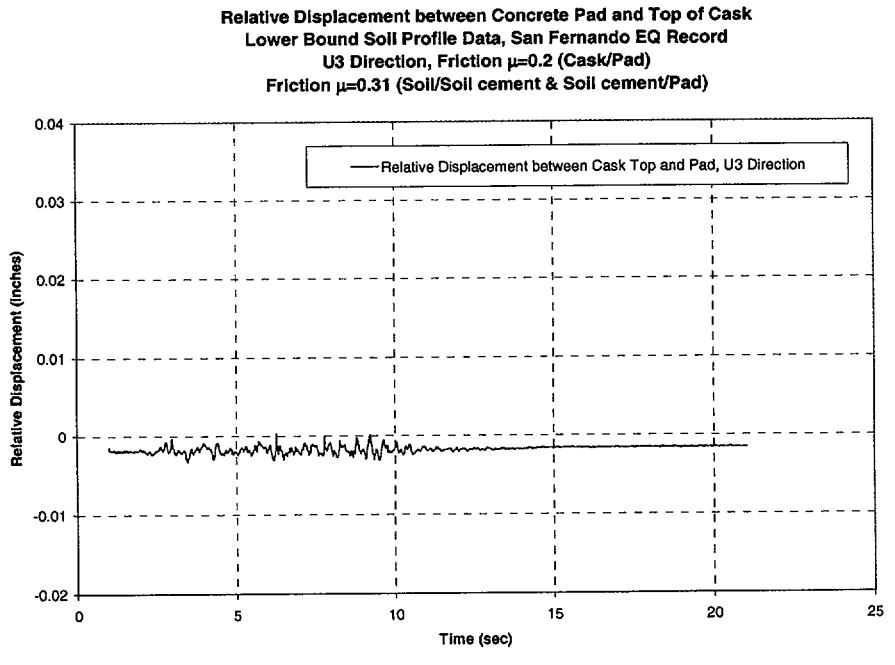

Figure II 2.6. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, San Fernando Earthquake Record, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

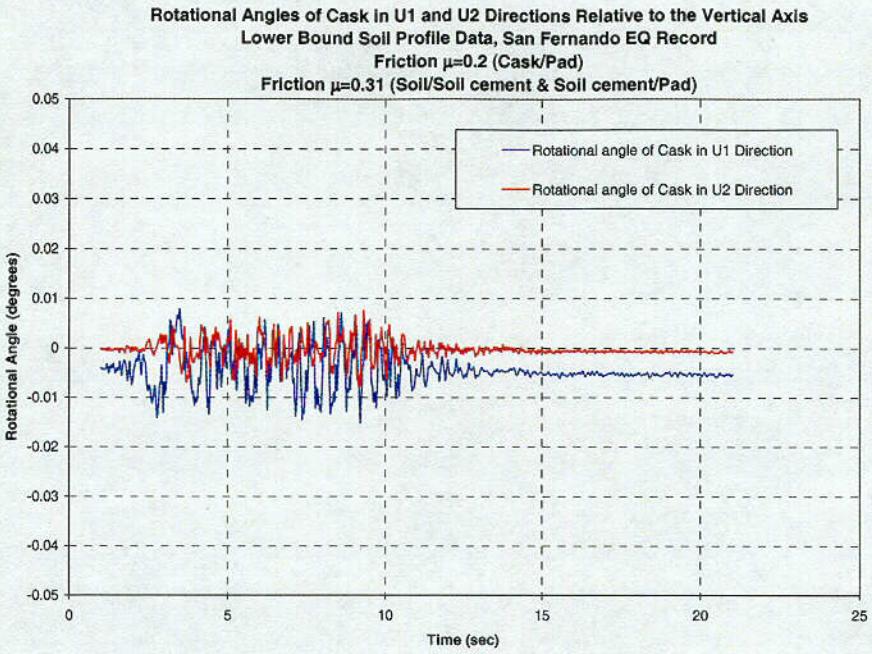

Figure II 2.7. Time History of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Lower Bound Soil Profile Data, San Fernando Earthquake Record, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

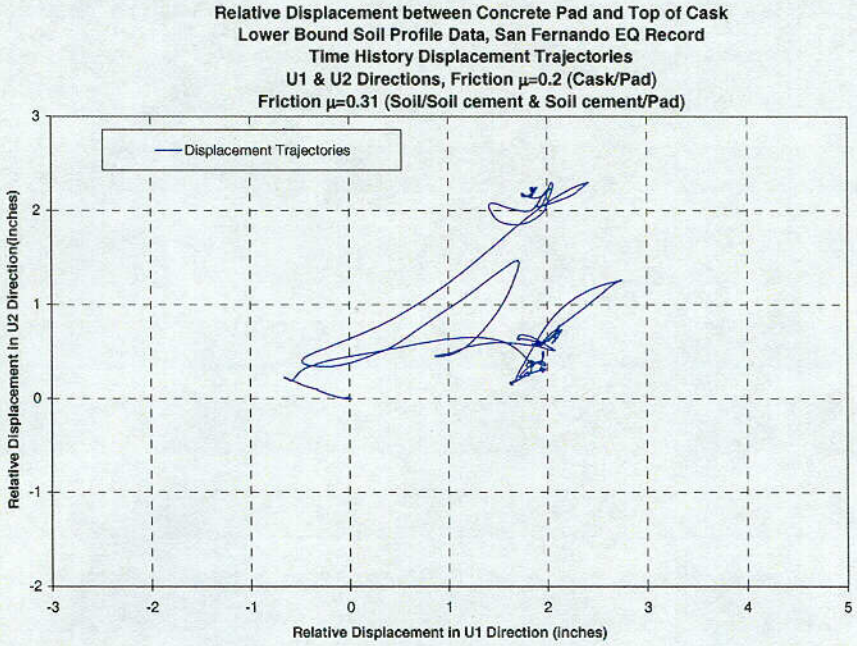

Figure II 2.8. Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, San Fernando Earthquake Record, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

c19

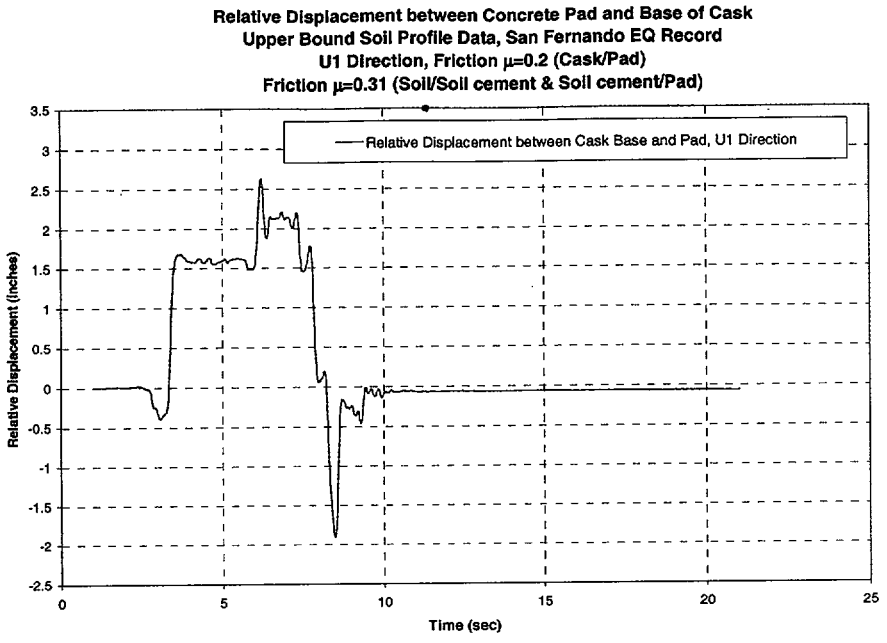

Figure II 3.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Upper Bound Soil Profile Data, San Fernando Earthquake Record, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

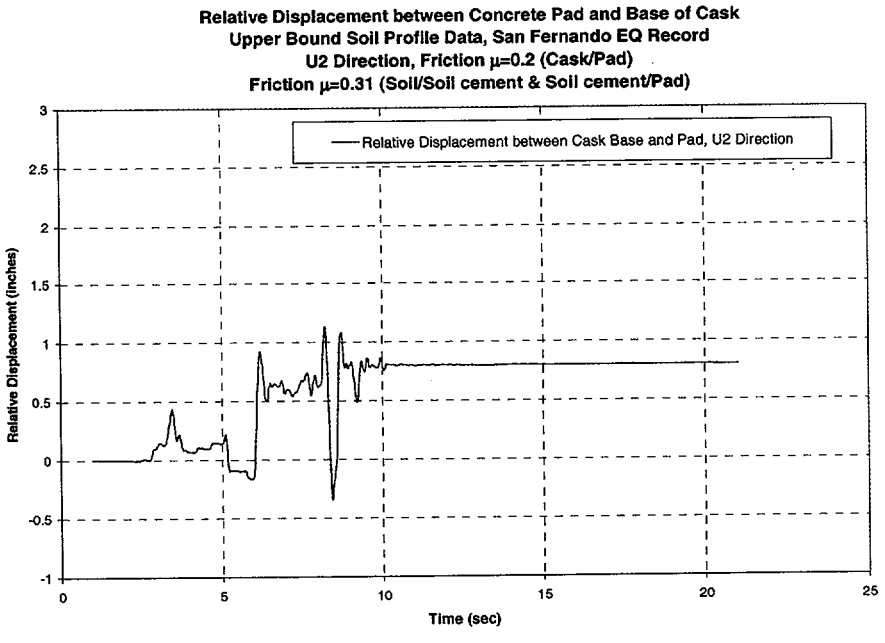

Figure II 3.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Upper Bound Soil Profile Data, San Fernando Earthquake Record, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

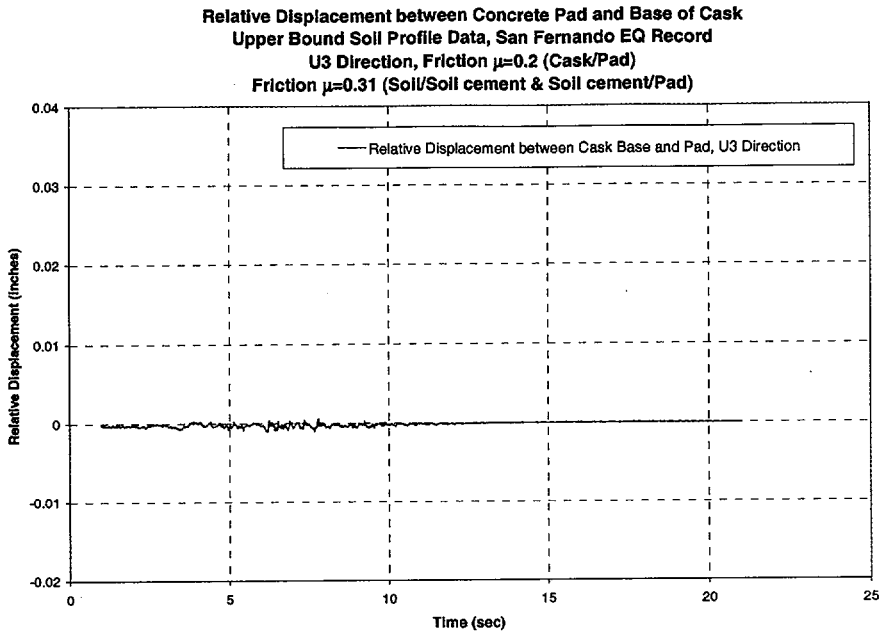

Figure II 3.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Upper Bound Soil Profile Data, San Fernando Earthquake Record, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

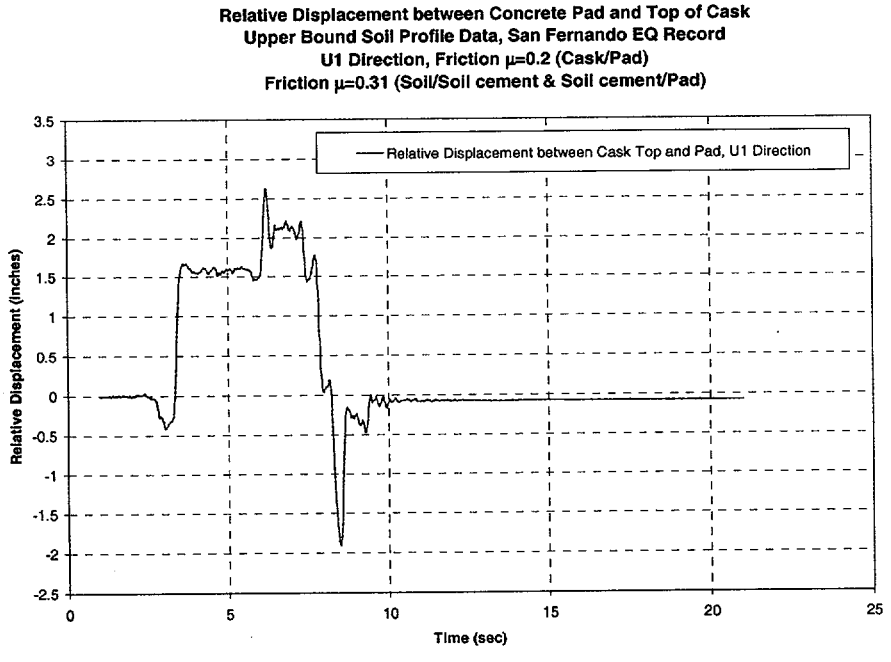

Figure II 3.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, San Fernando Earthquake Record, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

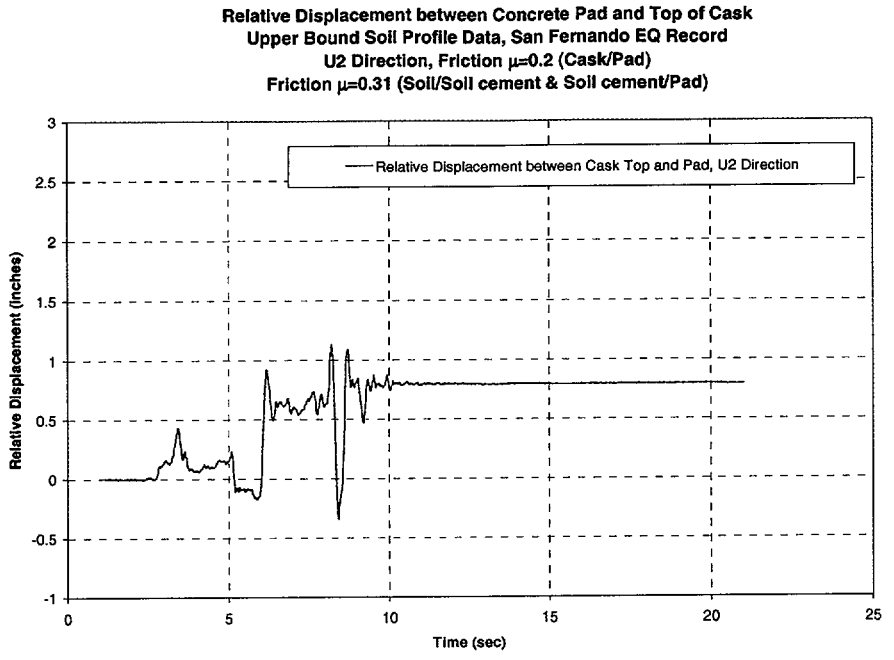

Figure II 3.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, San Fernando Earthquake Record, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

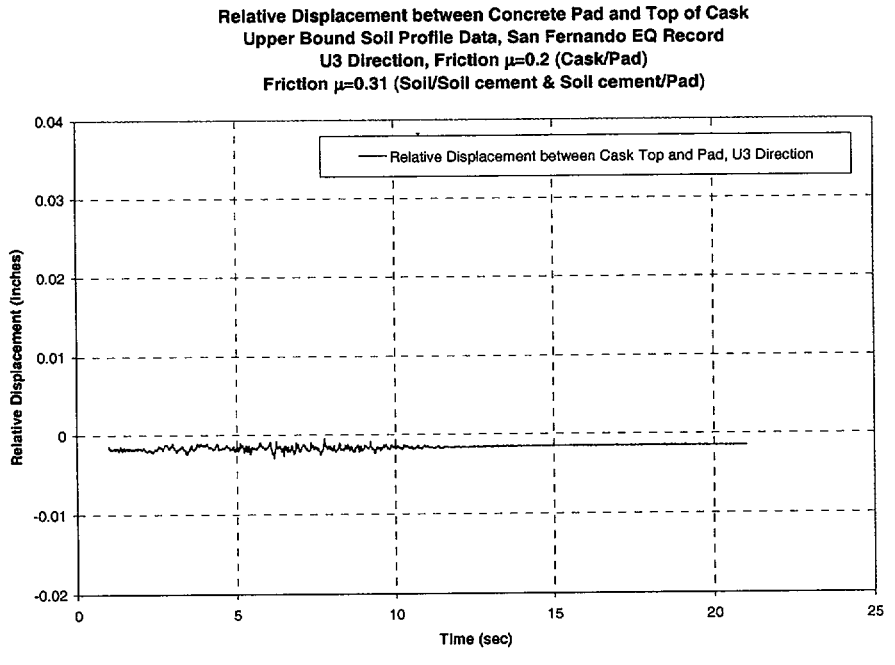

Figure II 3.6. Time history of Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, San Fernando Earthquake Record, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

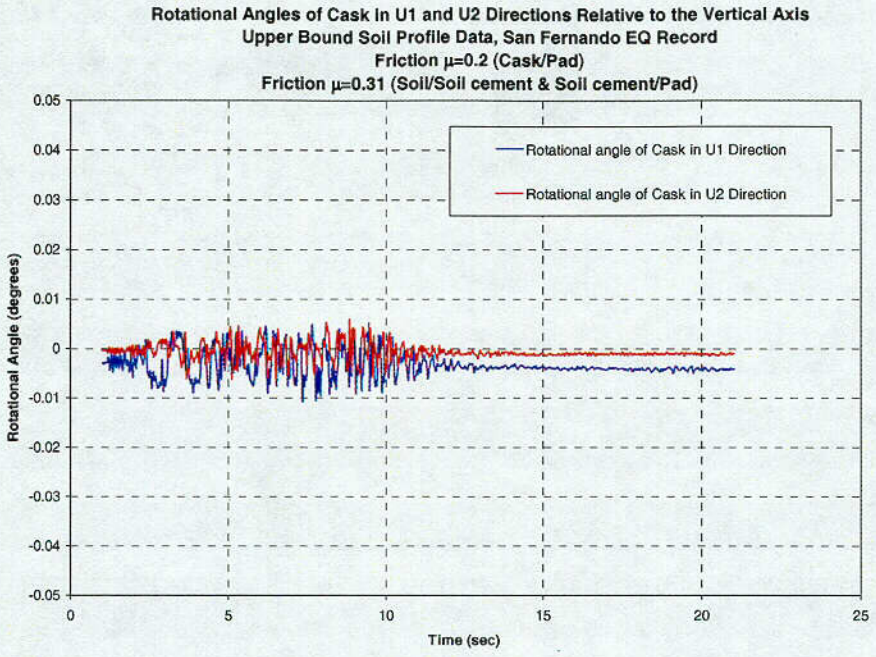

Figure II 3.7. Time History of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Upper Bound Soil Profile Data, San Fernando Earthquake Record, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

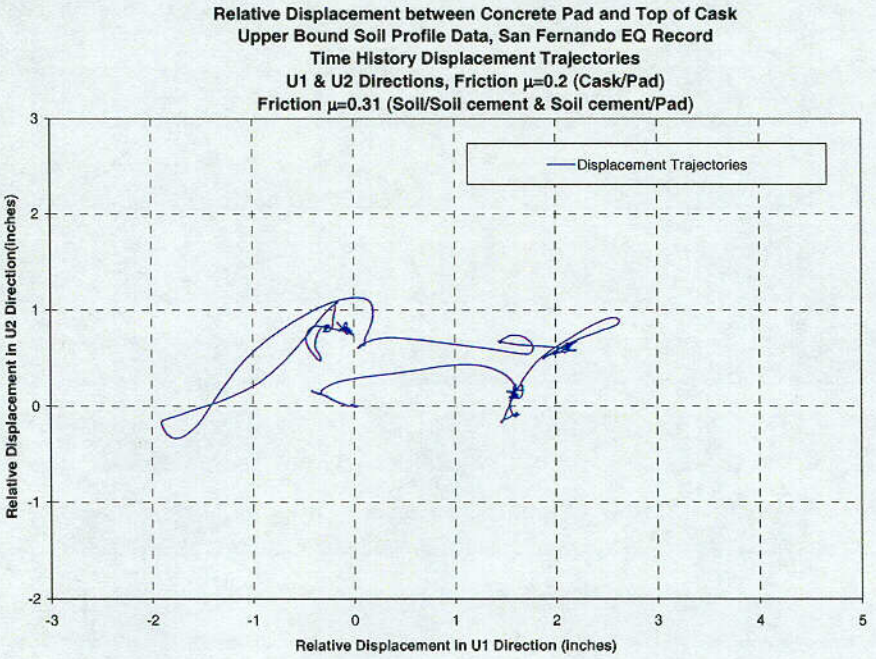

Figure II 3.8. Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, San Fernando Earthquake Record, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

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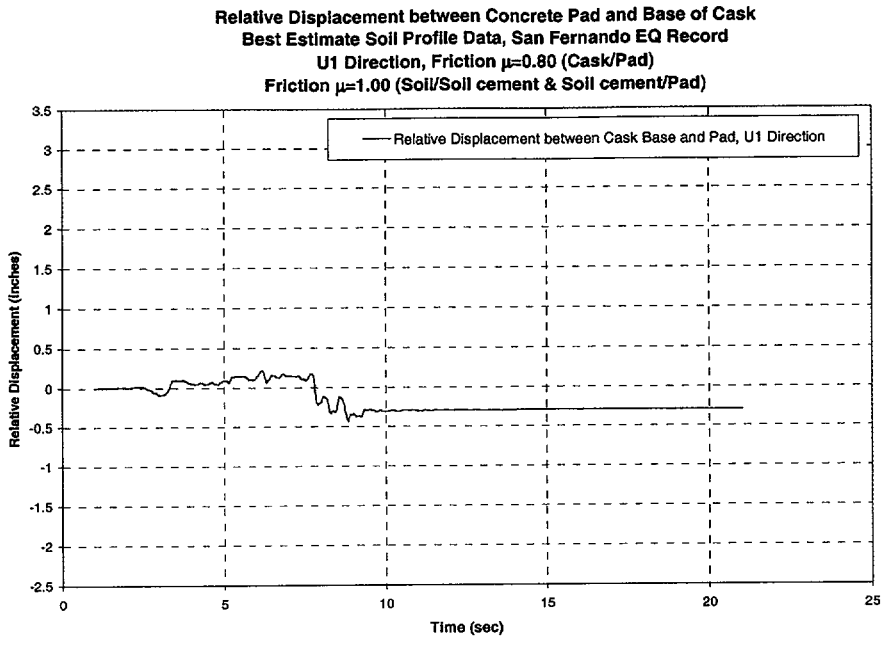

Figure II 4.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U1 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

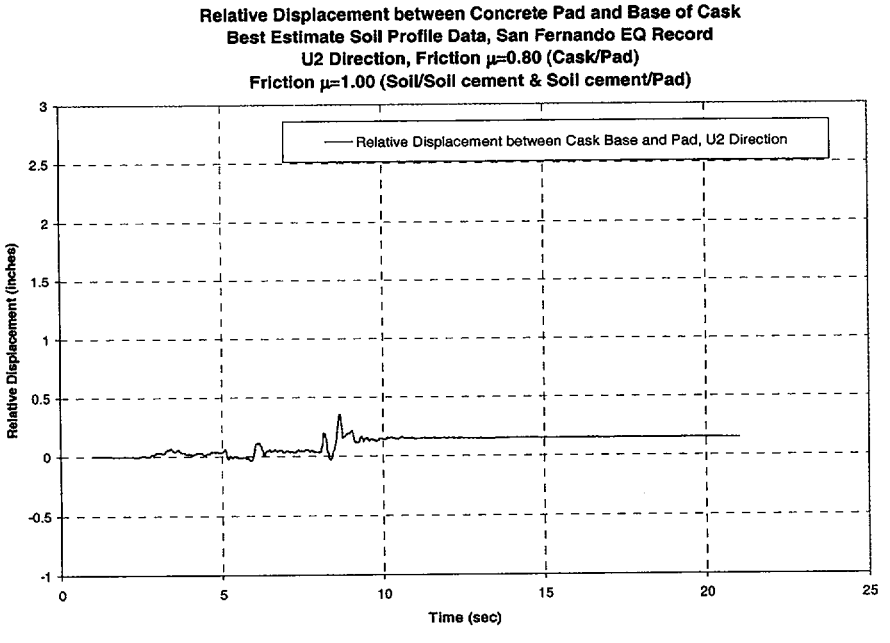

Figure II 4.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U2 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

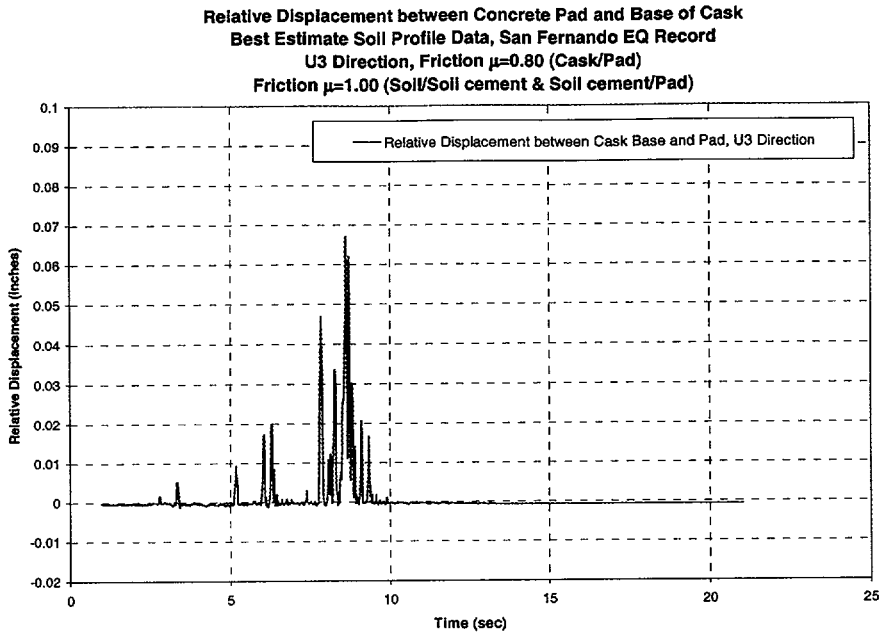

Figure II 4.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U3 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

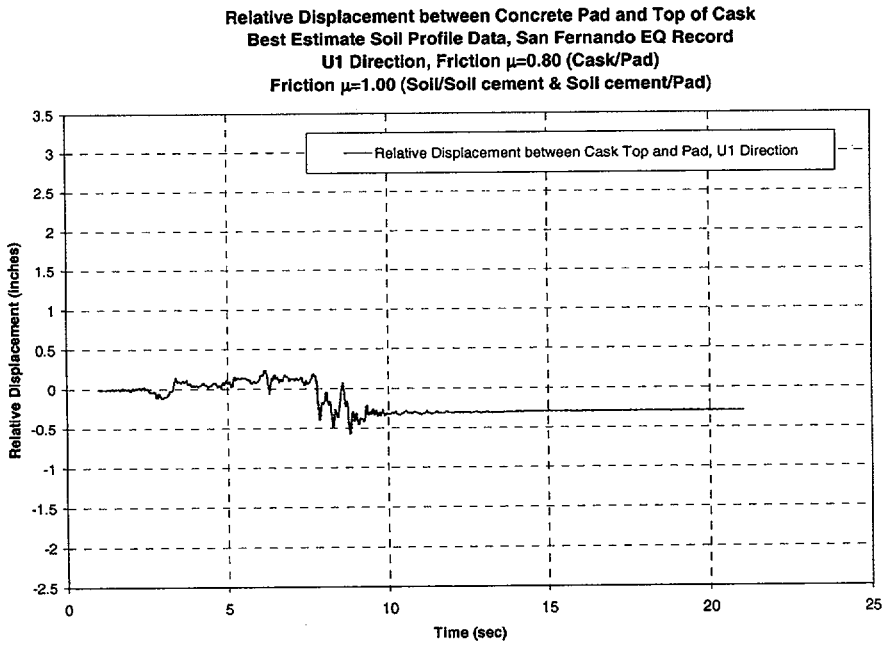

Figure II 4.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U1 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

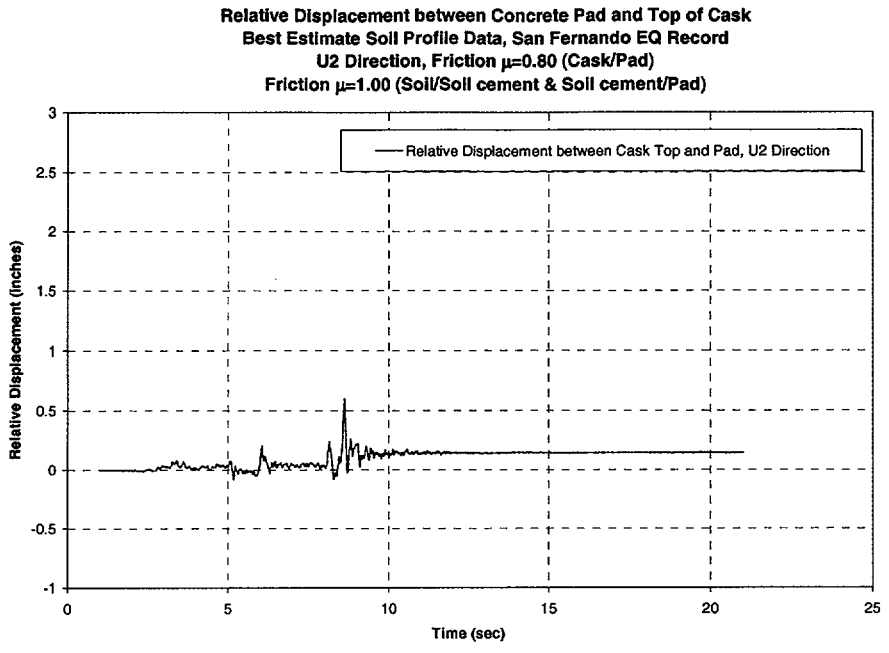

Figure II 4.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U2 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

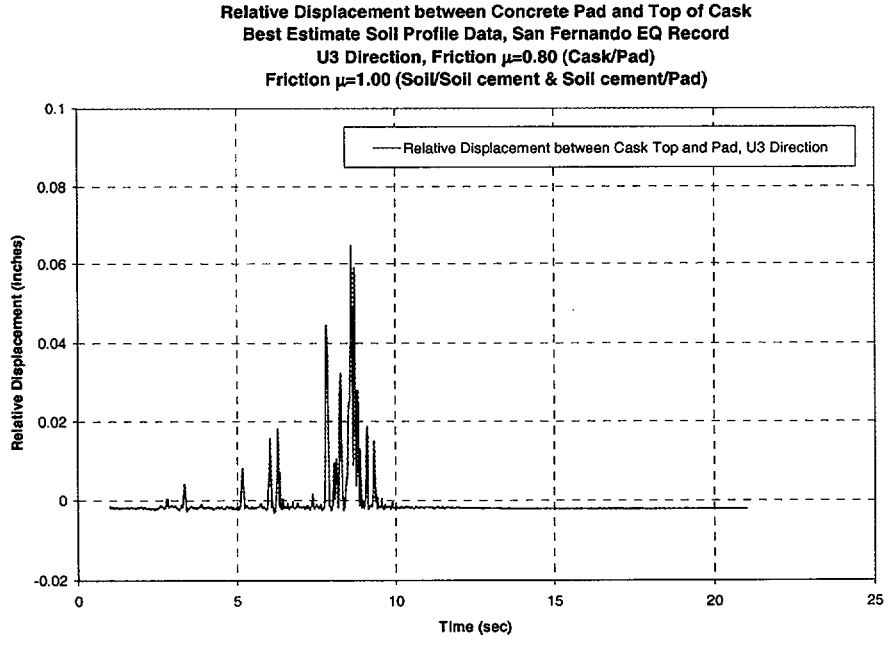

Figure II 4.6. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, U3 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

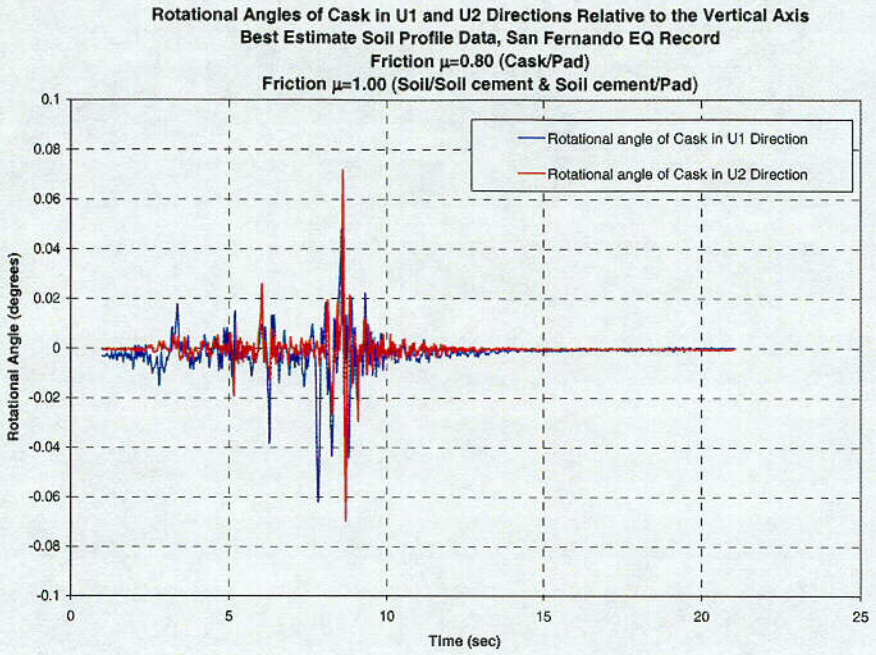

Figure II 4.7. Time History of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Best Estimate Soil Profile Data, San Fernando Earthquake Record, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

Figure II 4.8. Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, San Fernando Earthquake Record, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

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APPENDIX III

ANALYSIS RESULTS FOR THE SEISMIC EVENT WITH A 10,000-YEAR RETURN PERIOD

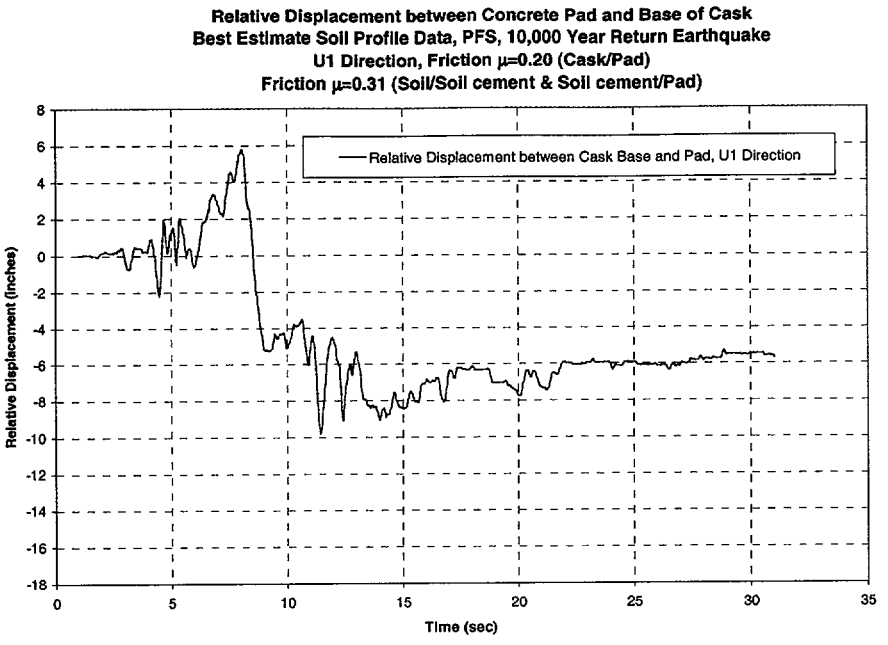

Figure III 1.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 10,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

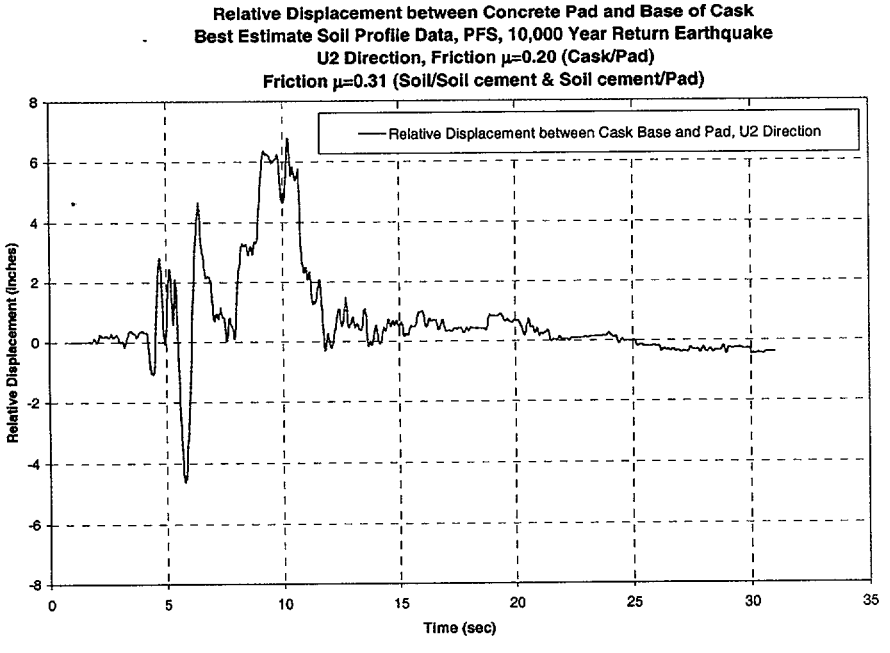

Figure III 1.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 10,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

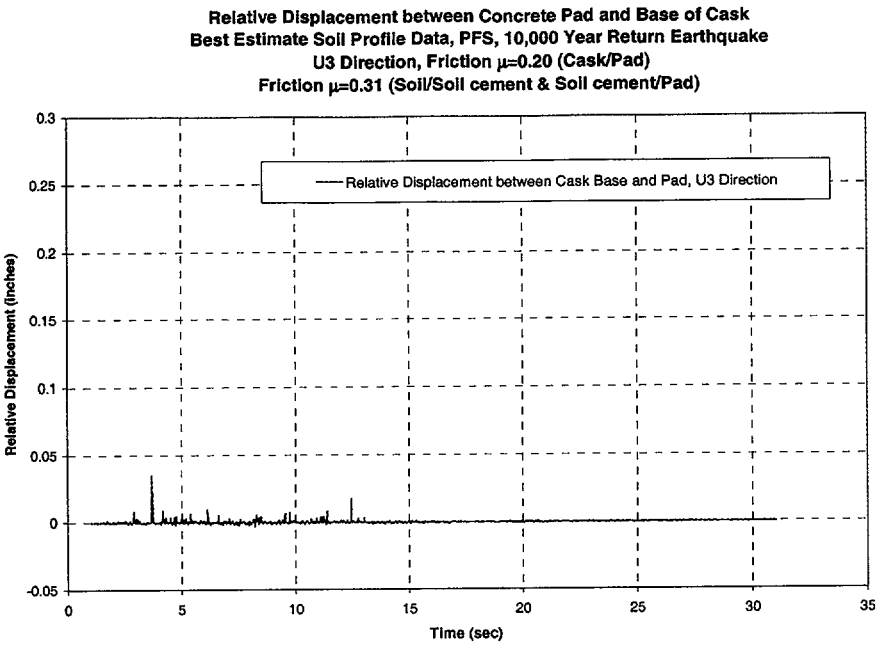

Figure III 1.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Best Estimate Soil Profile Data, PFS, 10,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

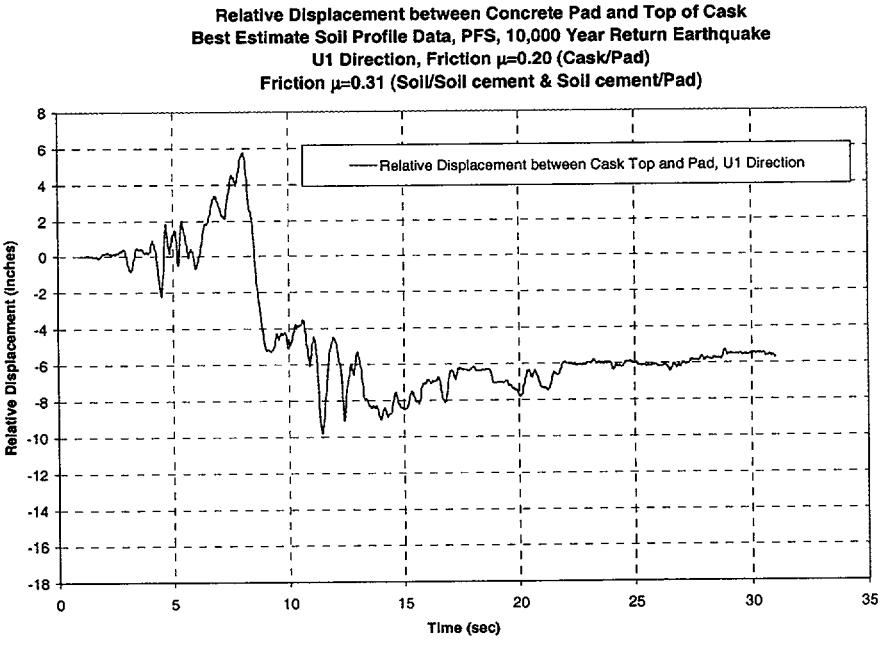

Figure III 1.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 10,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

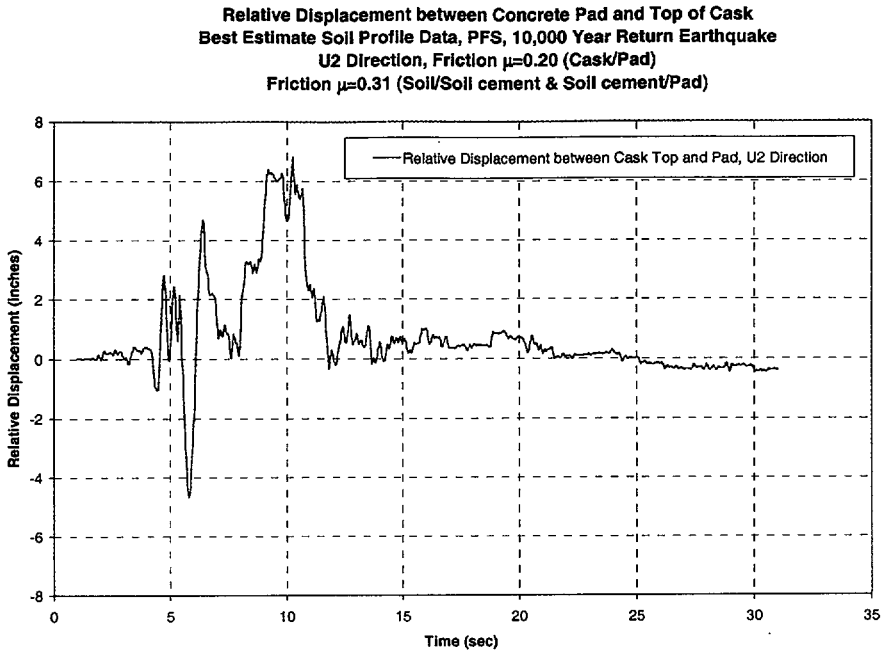

Figure III 1.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 10,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

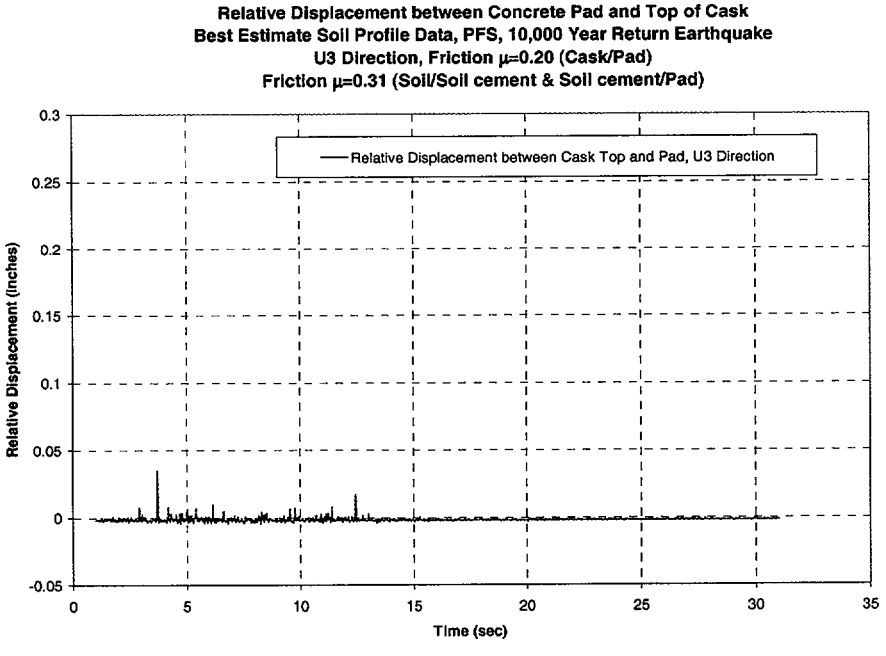

Figure III 1.6. Time history of Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 10,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

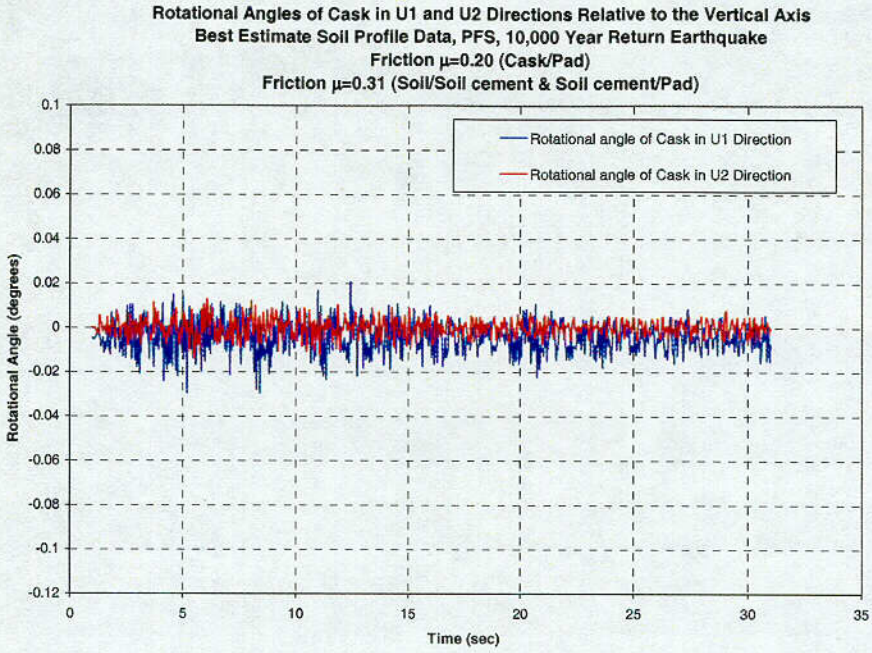

Figure III 1.7. Time History of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Best Estimate Soil Profile Data, PFS, 10,000 Year Return Earthquake, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

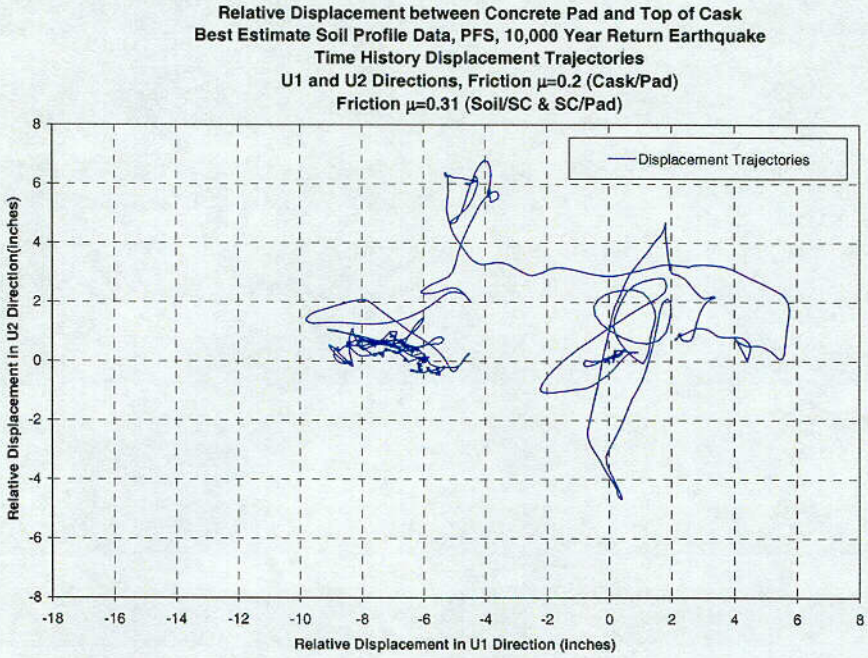

Figure III 1.8. Relative Displacement between Concrete Pad and Top of Cask, Best Estimate Soil Profile Data, PFS, 10,000 Year Return Earthquake, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

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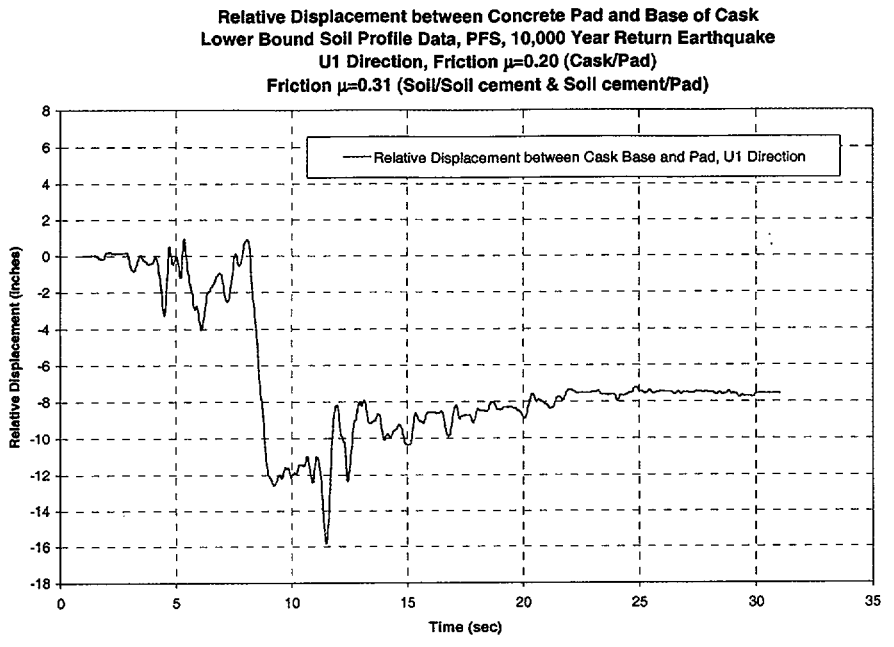

Figure III 2.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

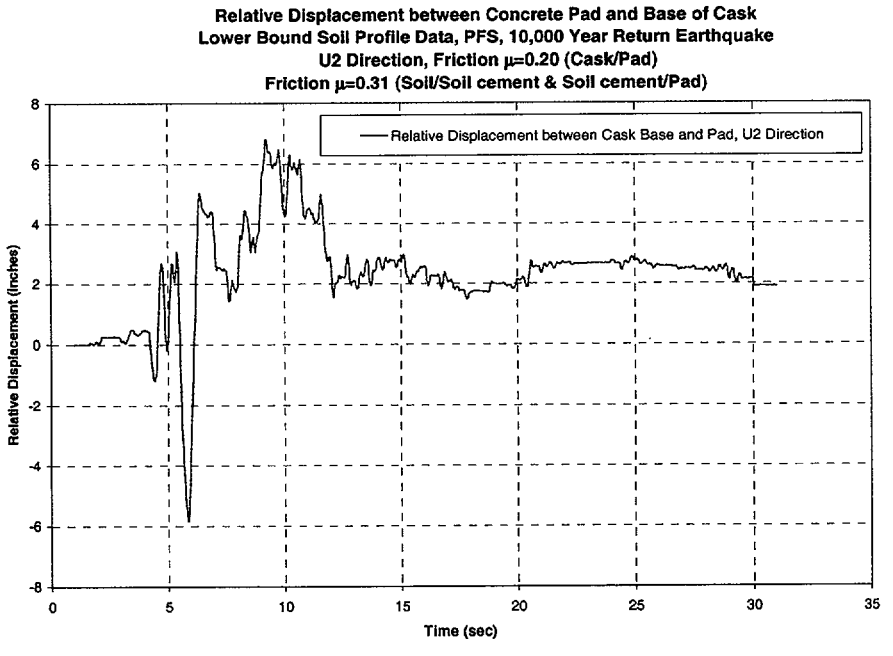

Figure III 2.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

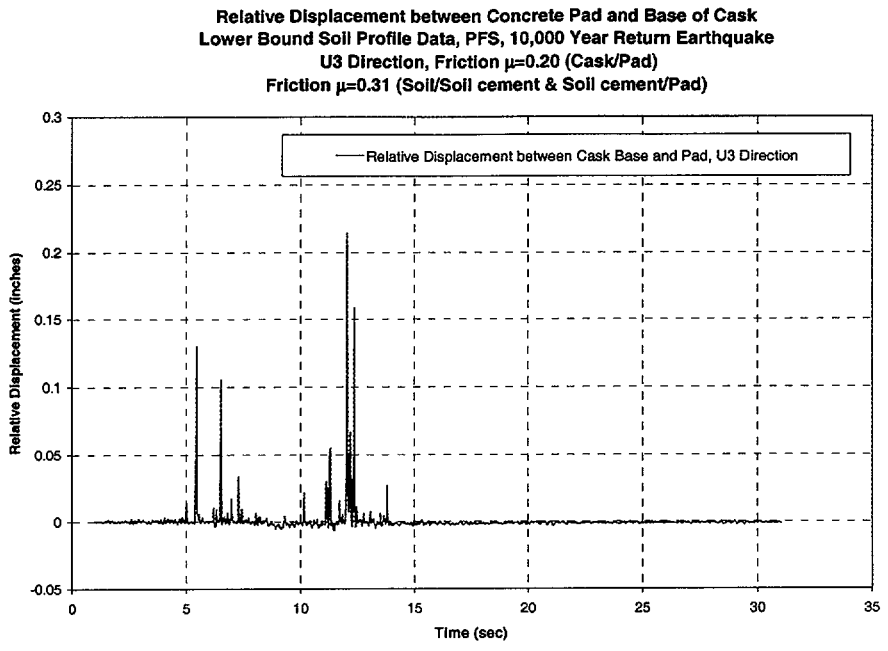

Figure III 2.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

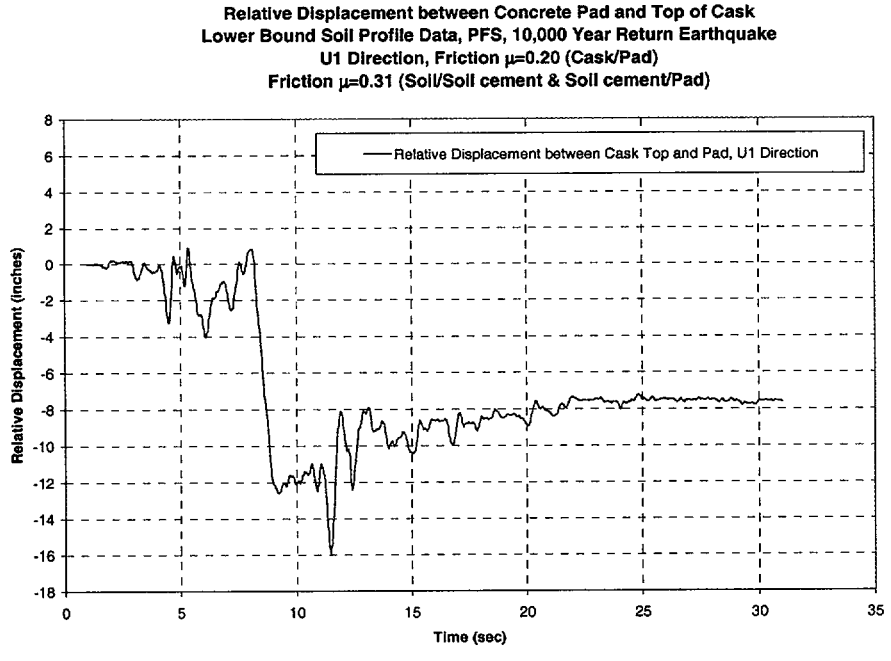

Figure III 2.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

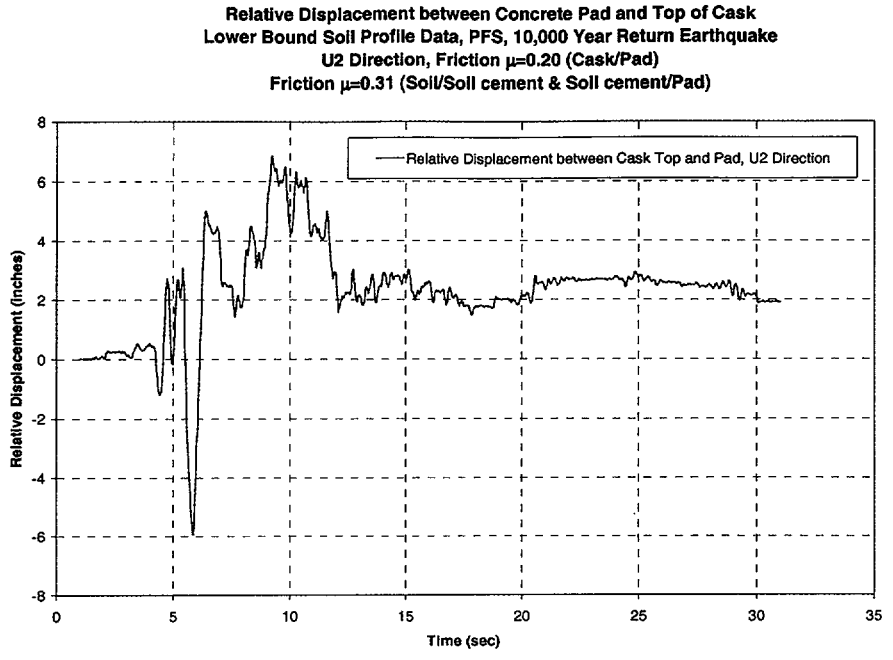

Figure III 2.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

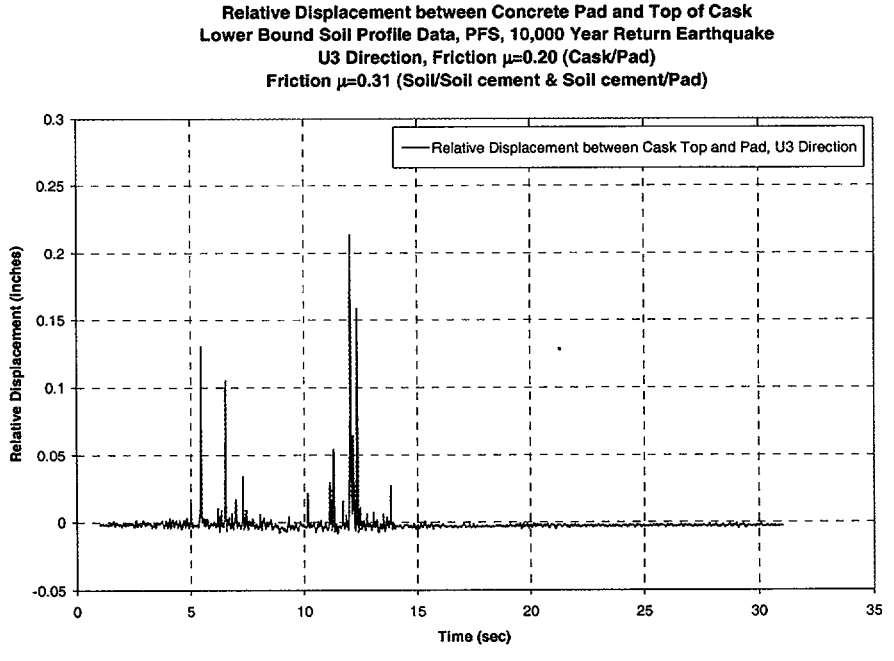

Figure III 2.6. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

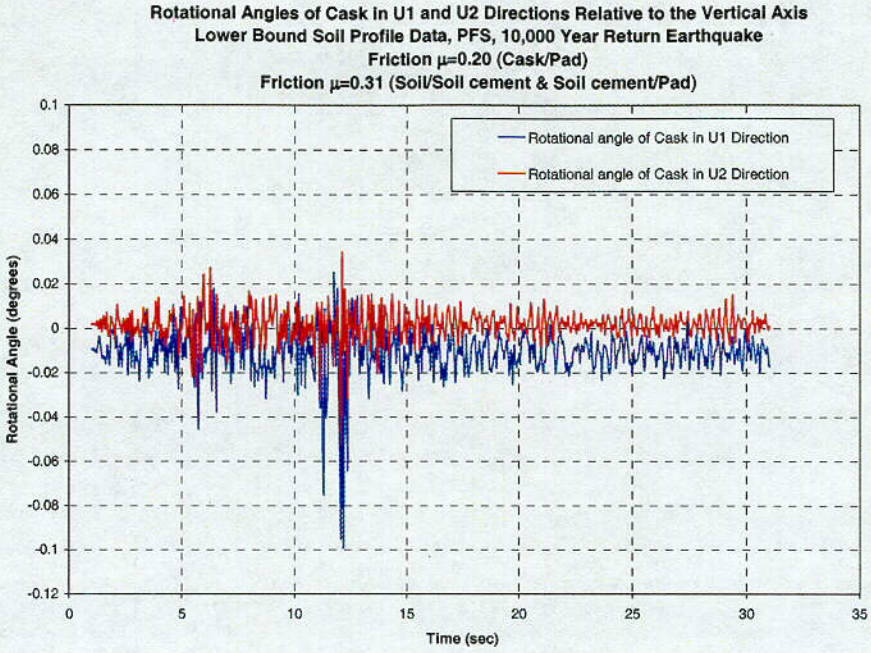

Figure III 2.7. Time History of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

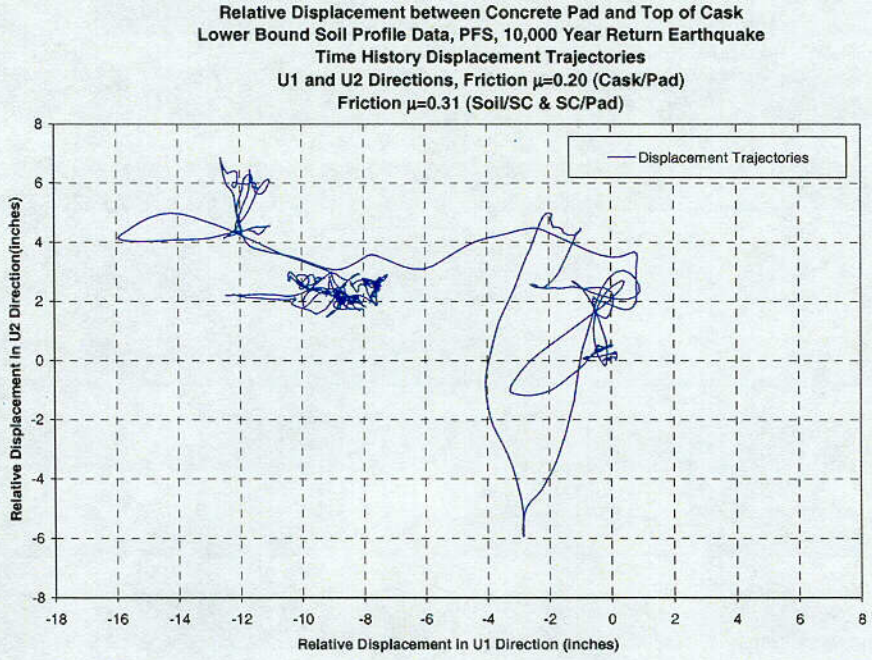

Figure III 2.8. Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

C23

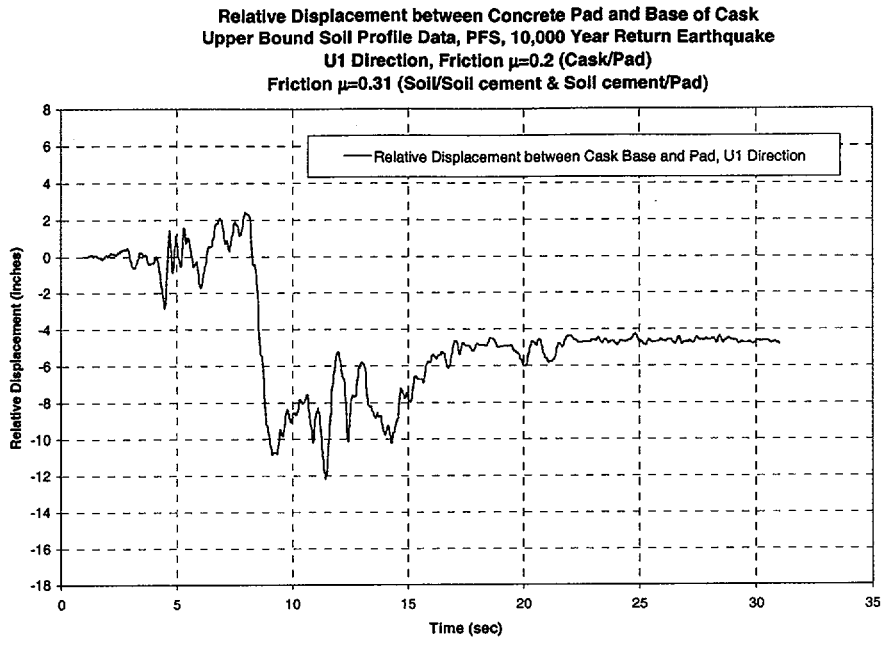

Figure III 3.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Upper Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

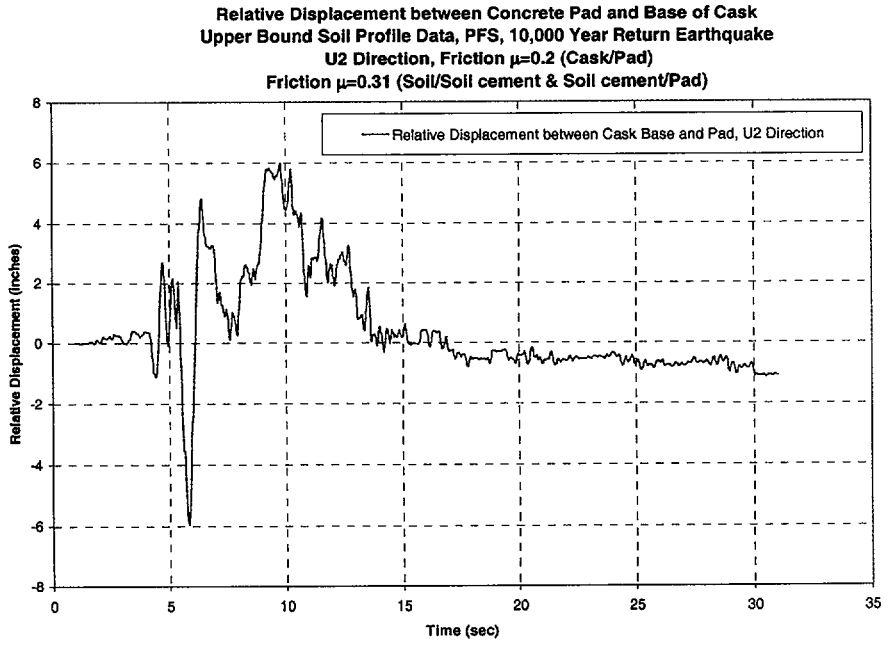

Figure III 3.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Upper Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

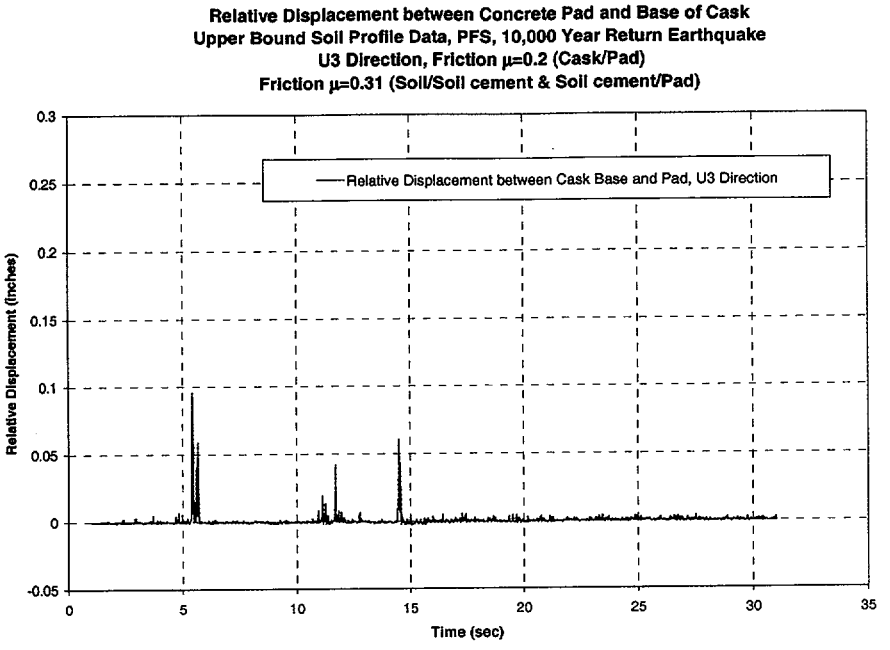

Figure III 3.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Upper Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

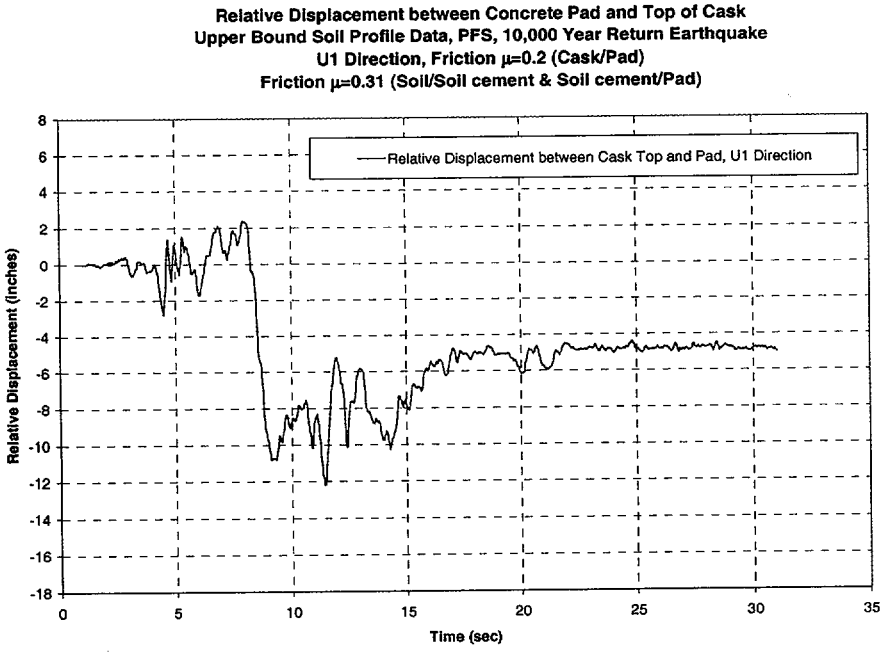

Figure III 3.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U1 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

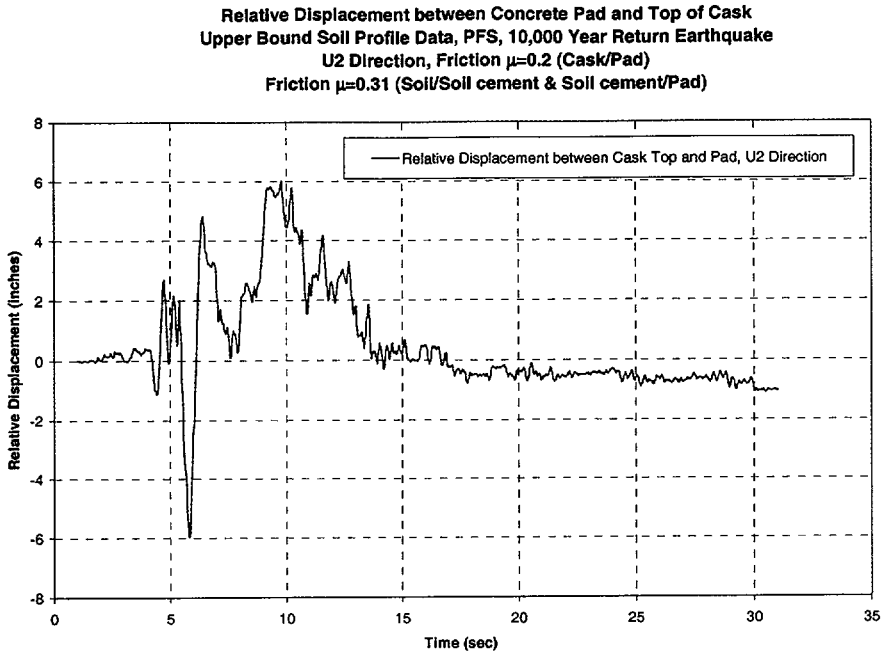

Figure III 3.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U2 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

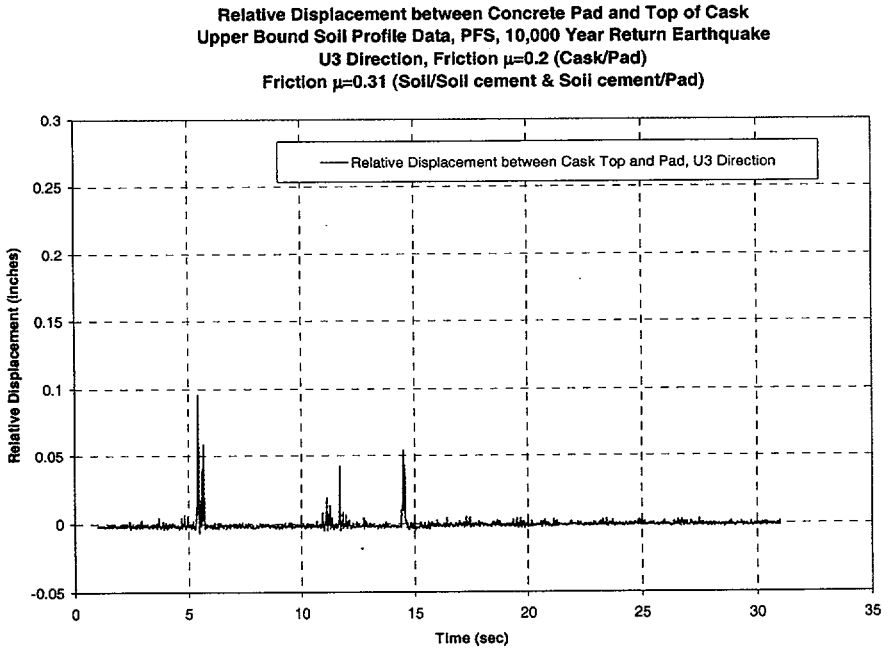

Figure III 3.6. Time history of Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U3 Direction, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement and Soil Cement/Pad)

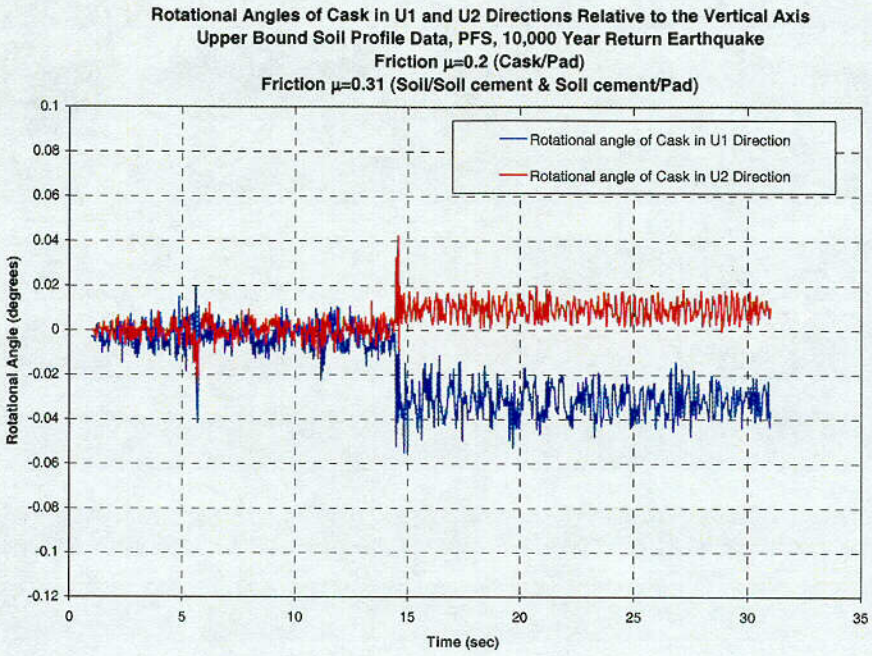

Figure III 3.7. Time History of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Upper Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

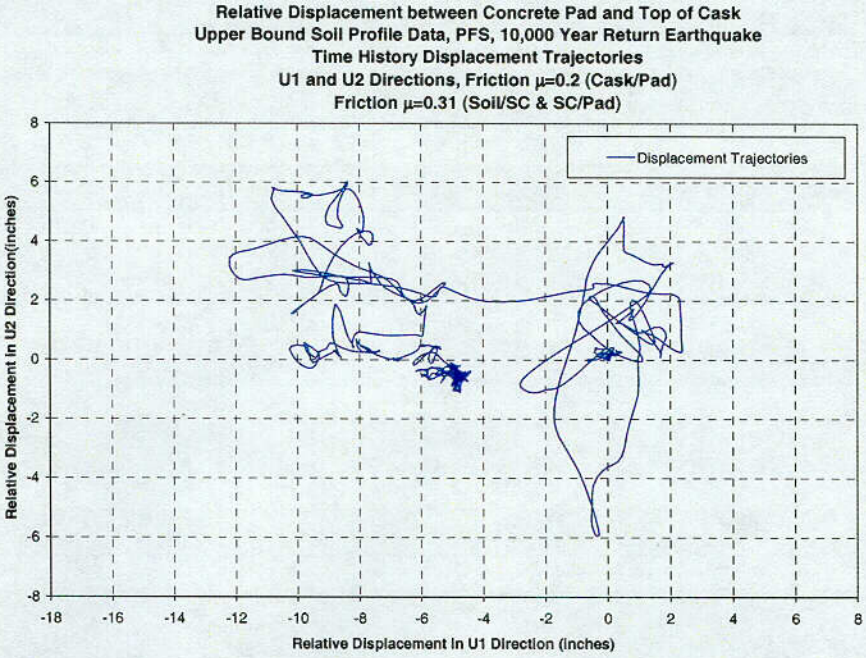

Figure III 3.8. Relative Displacement between Concrete Pad and Top of Cask, Upper Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.20 (Cask/Pad), Friction μ=0.31 (Soil/Soil Cement & Soil Cement/Pad)

C24

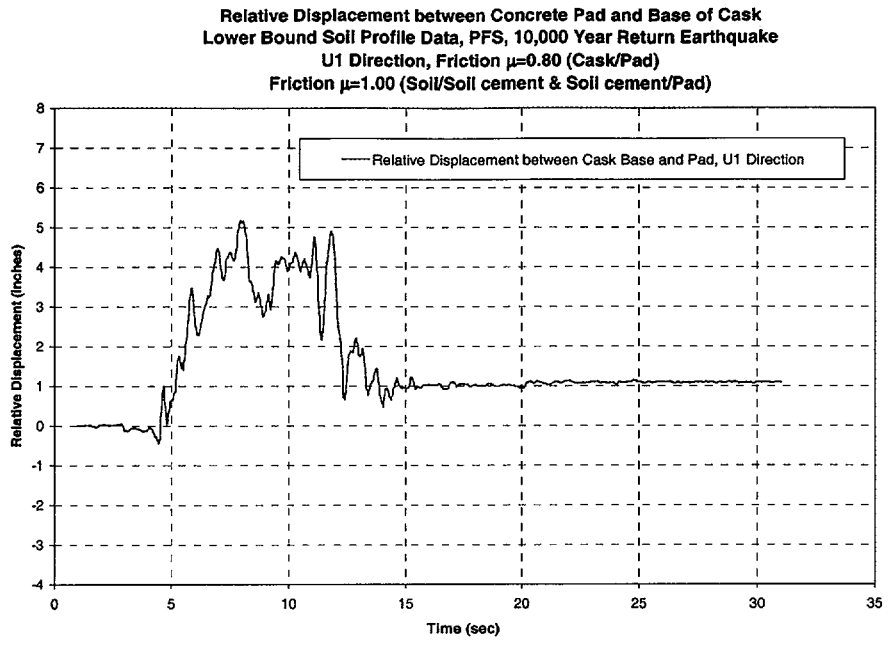

Figure III 4.1. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U1 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

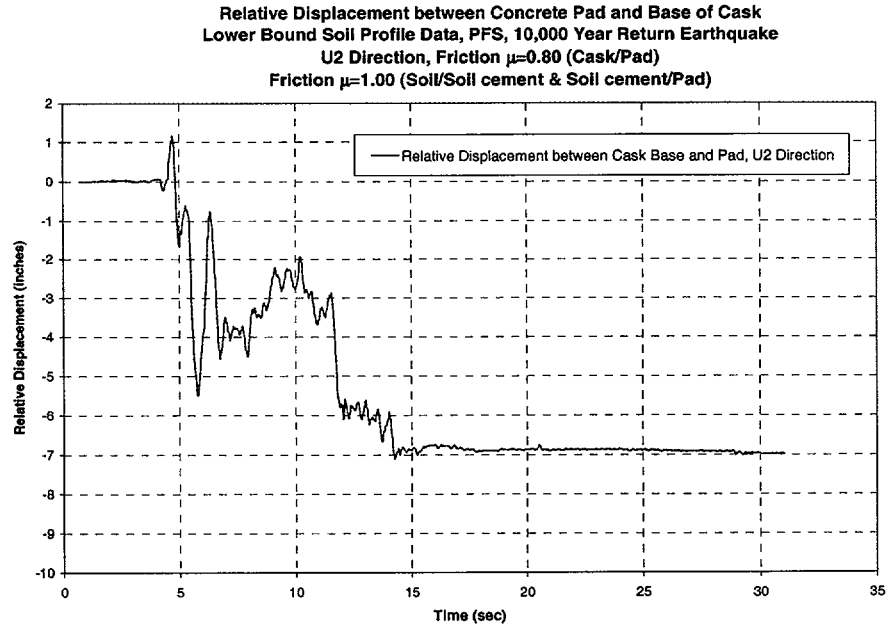

Figure III 4.2. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U2 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

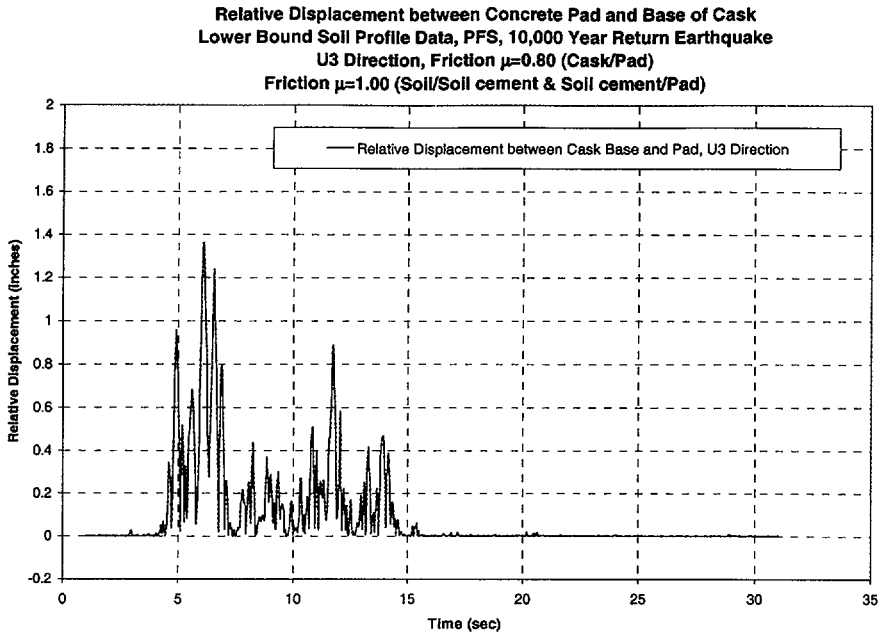

Figure III 4.3. Time history of Relative Displacement between Concrete Pad and Base of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U3 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

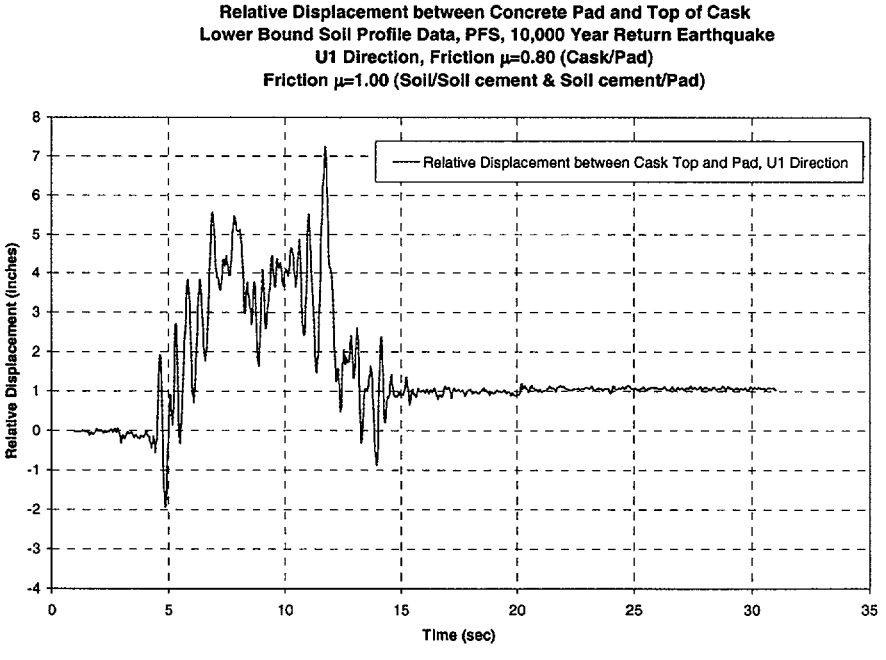

Figure III 4.4. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U1 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

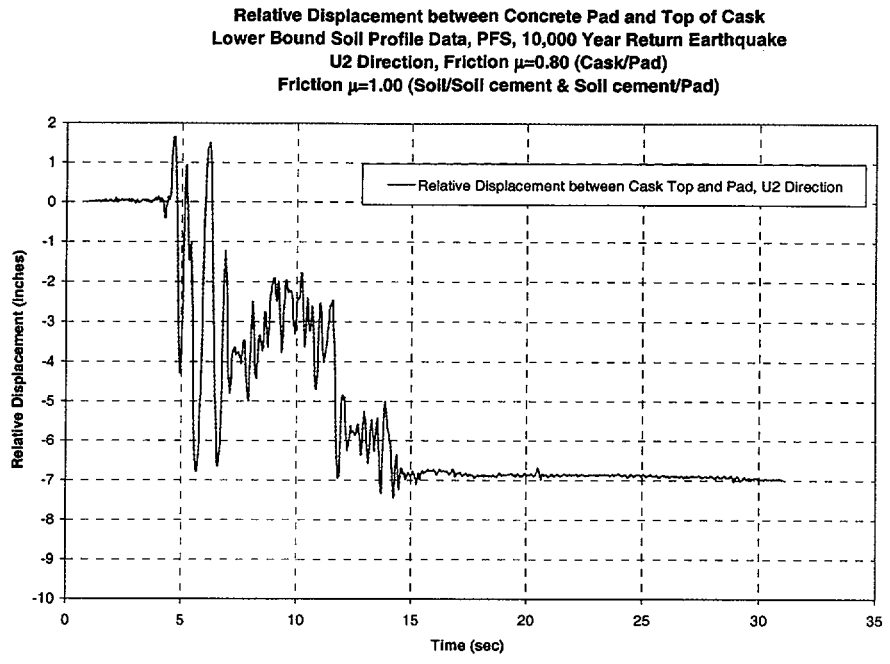

Figure III 4.5. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U2 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

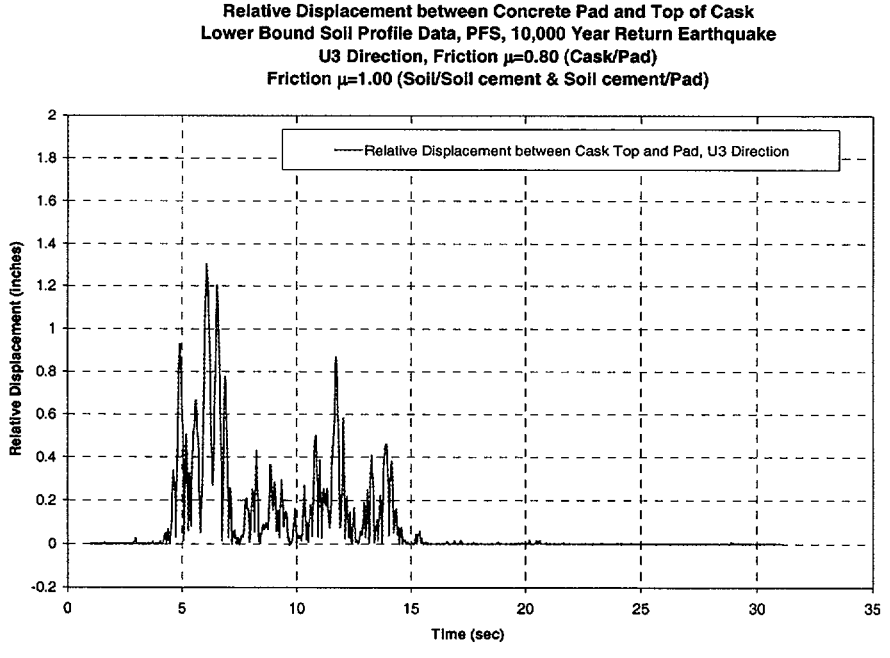

Figure III 4.6. Time history of Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, U3 Direction, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement and Soil Cement/Pad)

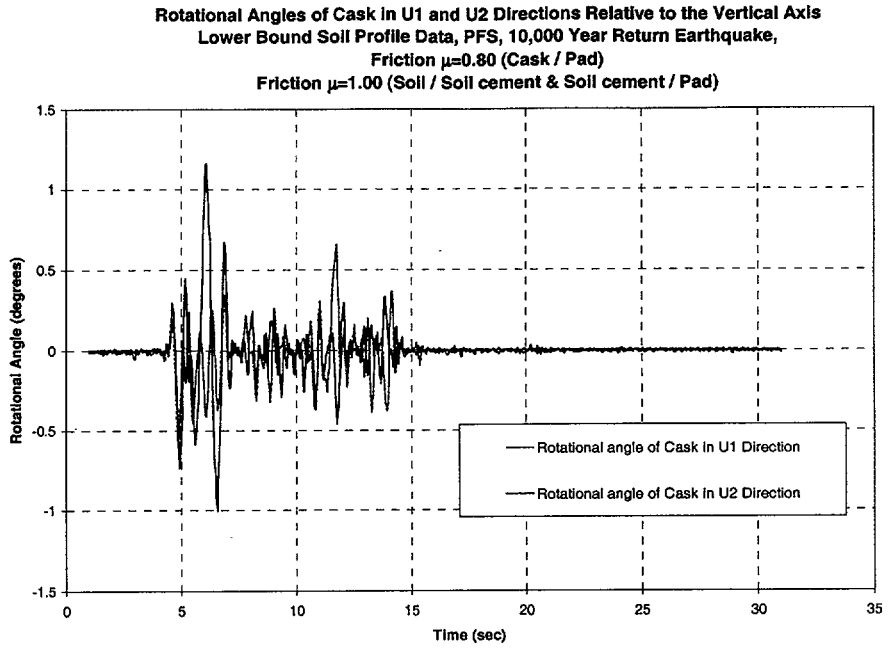

Figure III 4.7. Time History of Rotational Angle of Cask in U1 and U2 Directions Relative to the Vertical Axis, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)

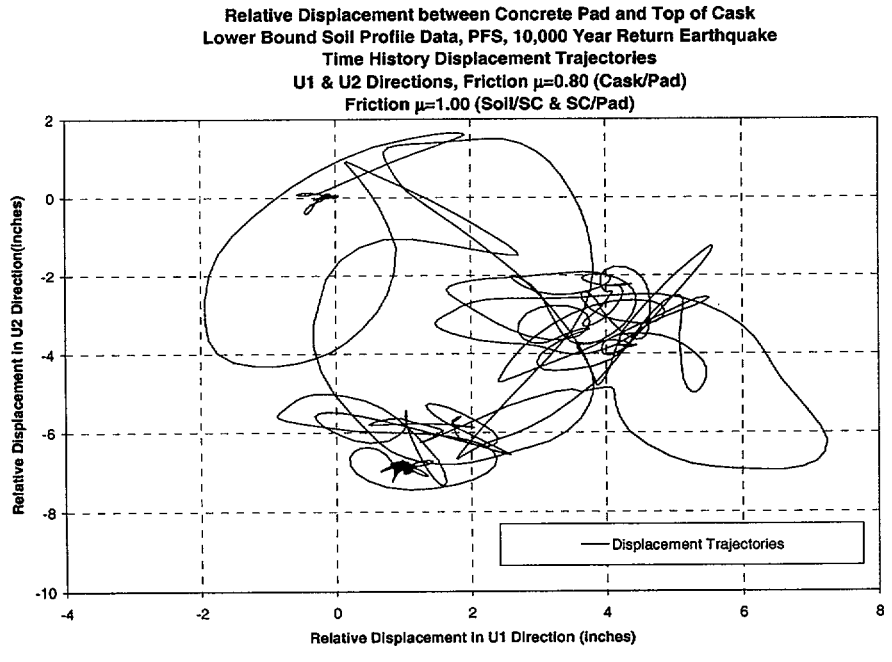

Figure III 4.8. Relative Displacement between Concrete Pad and Top of Cask, Lower Bound Soil Profile Data, PFS, 10,000 Year Return Earthquake, Time History Displacement Trajectories, U1 & U2 Directions, Friction μ=0.80 (Cask/Pad), Friction μ=1.00 (Soil/Soil Cement & Soil Cement/Pad)