Appendix IV: Plots of Analytical Soil Column Response

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Appendix IV: Plots of Analytical Soil Column Response

The target surface ground motions are modified using a deconvolution procedure to produce acceleration histories to be applied to the base of the soil column. The deconvolution procedure is based on the assumption that the soil mass behaves as an idealized one-dimensional soil column. If the soil column used in the finite element models perfectly replicates those assumptions, the ground motion measured at the surface of the soil column without the presence of any structures should closely match the original surface motion.

To assess the ability of the model used in this work to replicate the original surface ground motion, the cask and pad have been removed from the soil column models, and each of the three soil columns (soft soil, stiff soil, and rock) has been subjected to the five deconvolved base ground motion records for each of the three spectral shapes used in this study. The boundary conditions on the soil column model ensure that the ground motion is nearly identical at any two nodes located on the same vertical layer of the column.

The plots provided in this appendix compare the spectral content of the original surface ground motion with the spectral content of the motion of a point at the center of the top surface of the analytical soil column model. Plots are provided for the 1st horizontal and vertical components of ground motion. These plots show the pseudo-spectral acceleration (PSA) with 5% damping, and are plotted in terms of the ratio of the PSA to the peak ground acceleration (PGA) in a given direction. Each plot shows the spectral shape of the original surface motion, as well as the analytical surface motion obtained using the soft soil, stiff soil, and rock profiles.

From these plots, it is evident that in all cases, the spectral shape of the analytical surface motion reasonably matches that of the original surface input motion at periods higher than approximately 0.3 s. The plots are cut off at 1.4 s, and at periods higher than this, there is very close agreement in all cases. At higher frequencies, the deviations between the analytical surface motion and the original surface motion are much larger. In general, the response at the surface of the stiffer soil column models is closer to the original surface motion than is that for the soft soil column model, especially at higher frequencies. Also, the horizontal components of the analytical surface motion are generally closer to the original ground motion.

It is believed that the major source of the discrepancies between the original surface motion and the analytical surface motion is the fact that the representation of damping in the finite element models is different from the damping used in the deconvolution procedure. In the deconvolution procedure, damping is frequency independent. In contrast, with the Rayleigh damping procedure used in the finite element analysis code, the amount of damping in a given mode is dependent on the frequency of that mode and on the values of the mass and stiffness proportional damping coefficients. In this work, only mass-proportional damping was used because of the excessively long run times that result from the use of stiffness-proportional damping with the explicit time integration method.

While there are clearly discrepancies between the original surface motions and the analytical surface motions in the high frequency range in some cases, these are not believed to have a significant effect on the cask response. Once uplift occurs, the cask response appears to be dominated by the seismic input in the range from about 0.5 Hz to 2 Hz, and in this range, the analytical spectral response closely matches the target spectral content.

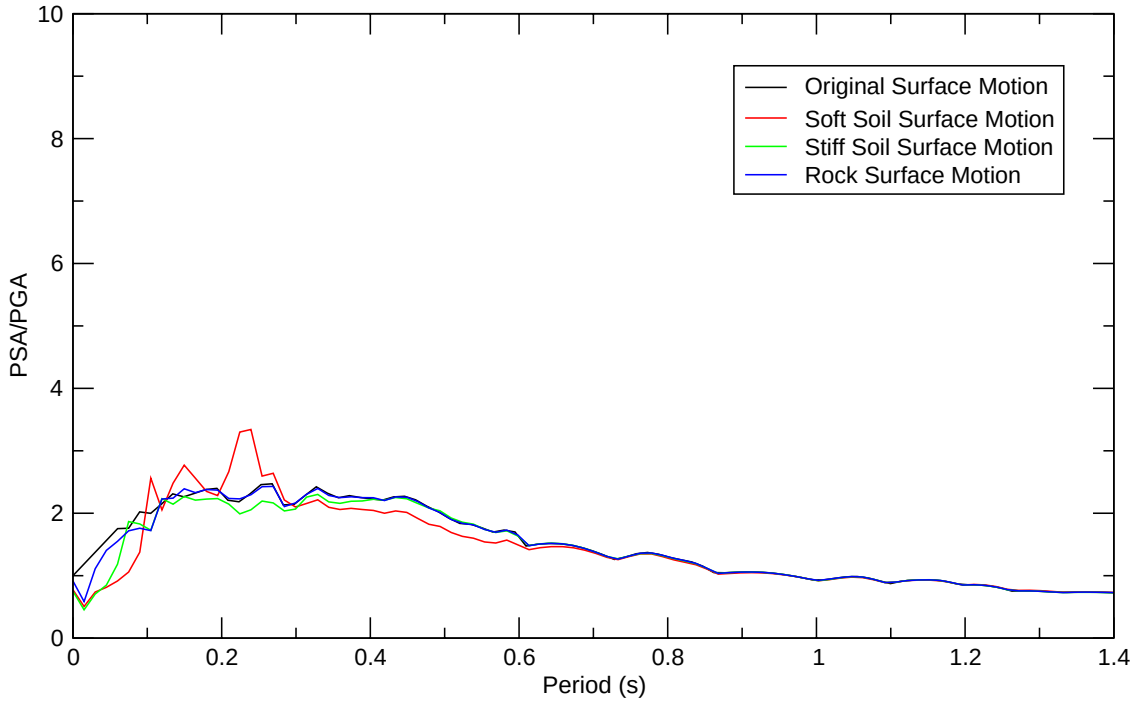

Figure IV.1: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 1 Earthquake, 1st Horizontal Component

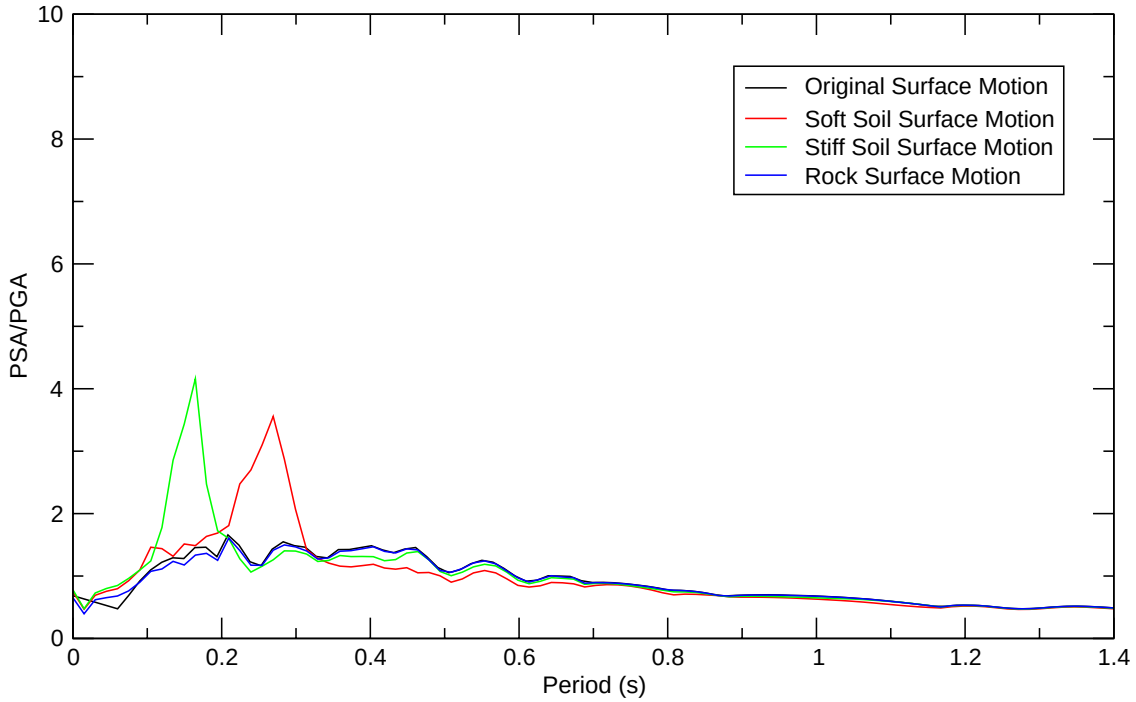

Figure IV.2: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 1 Earthquake, Vertical Component

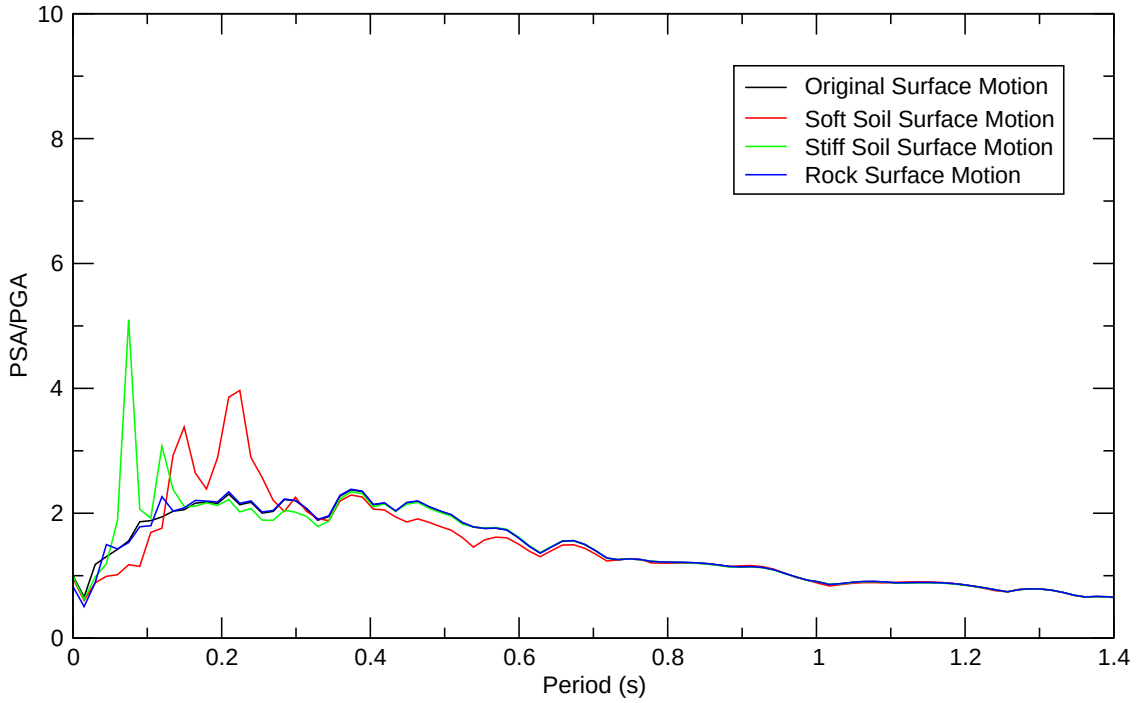

Figure IV.3: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 2 Earthquake, 1st Horizontal Component

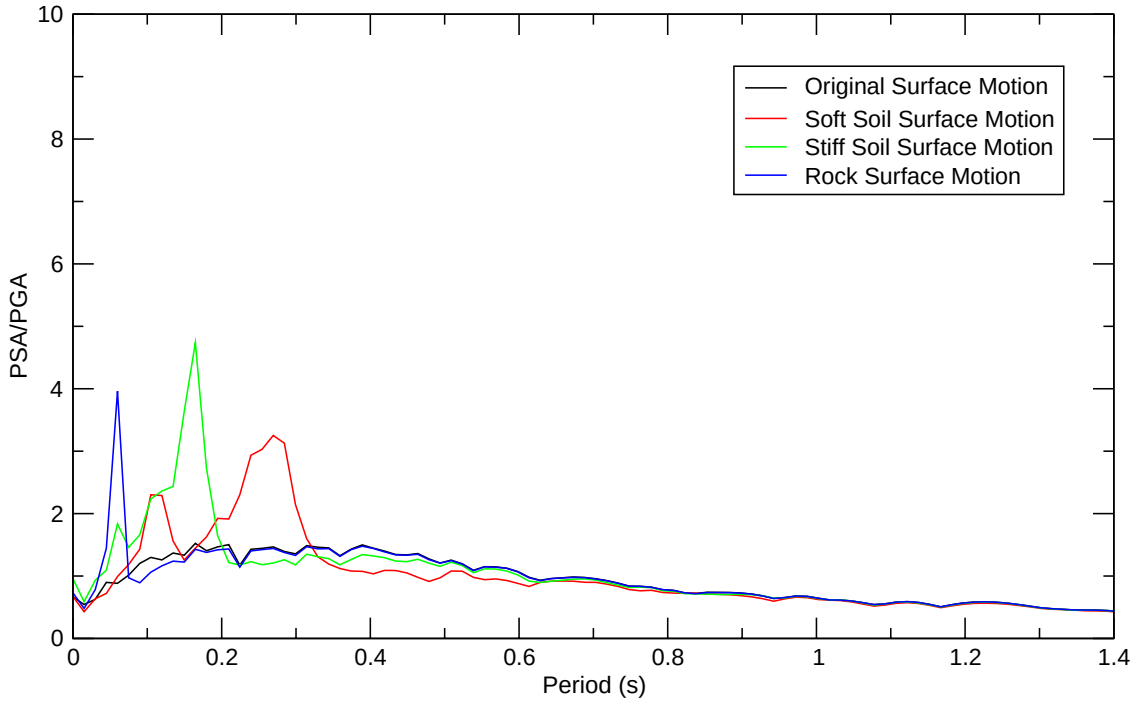

Figure IV.4: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 2 Earthquake, Vertical Component

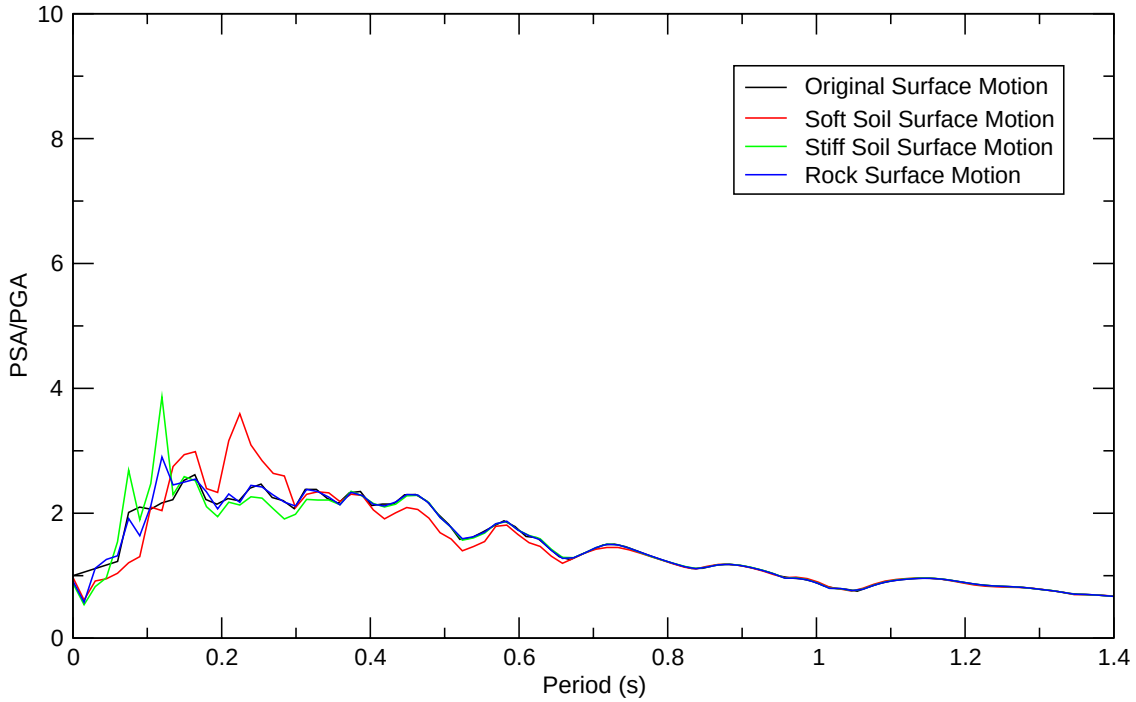

Figure IV.5: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 3 Earthquake, 1st Horizontal Component

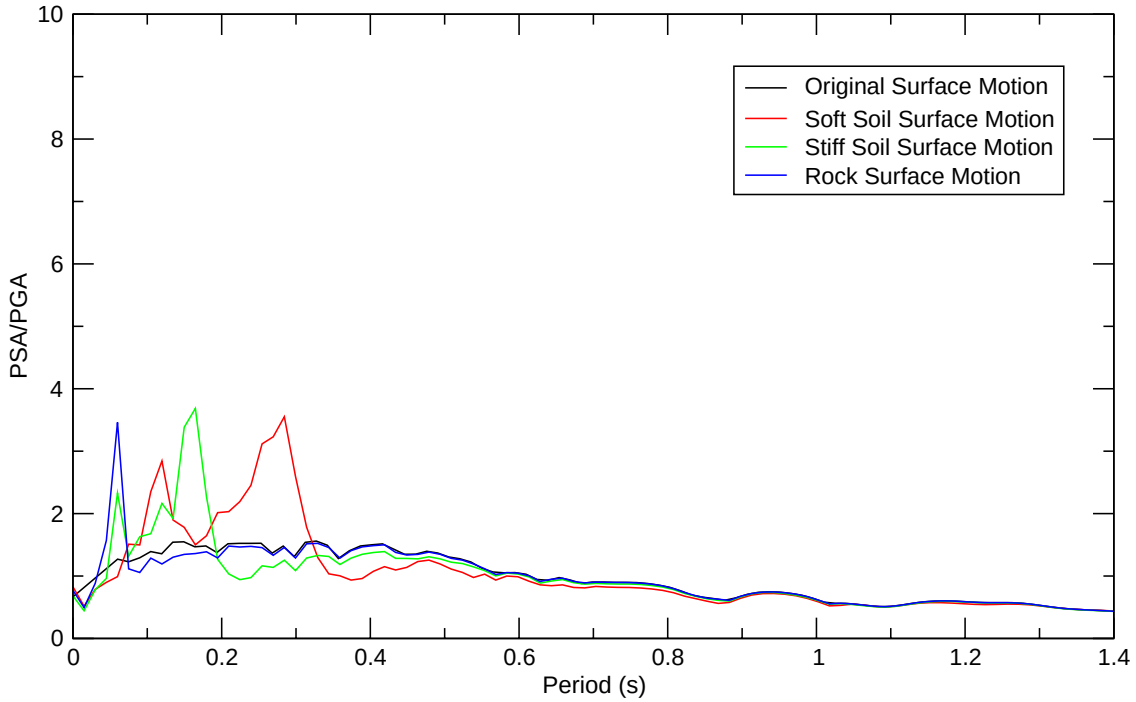

Figure IV.6: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 3 Earthquake, Vertical Component

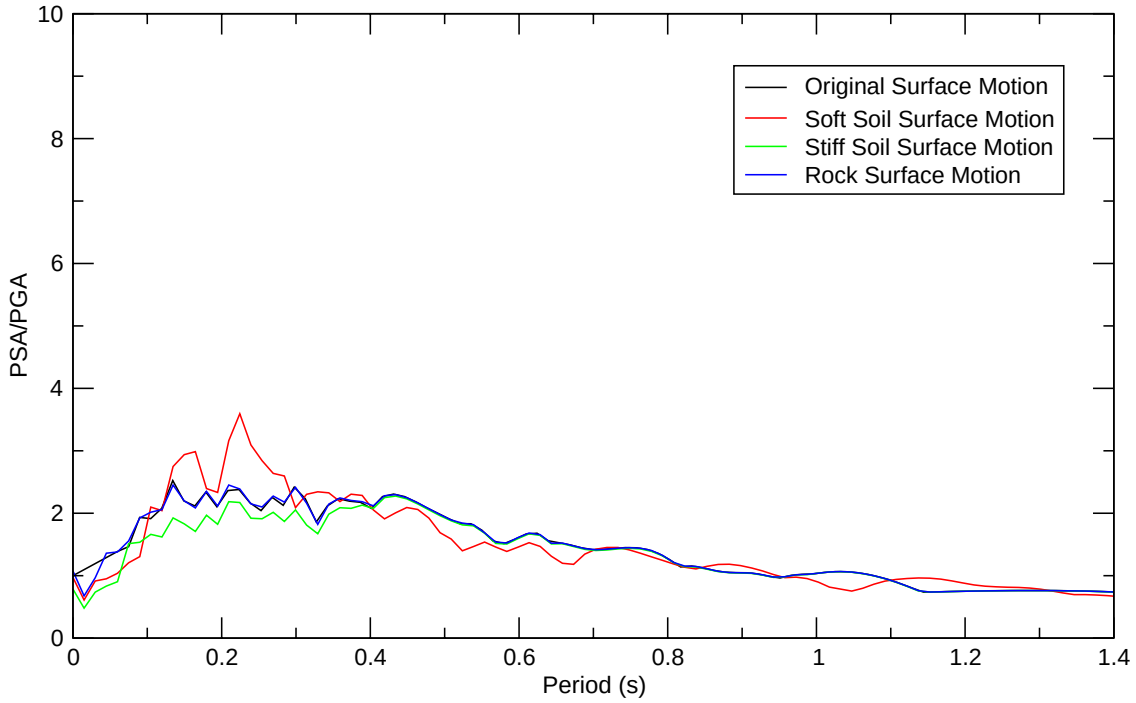

Figure IV.7: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 4 Earthquake, 1st Horizontal Component

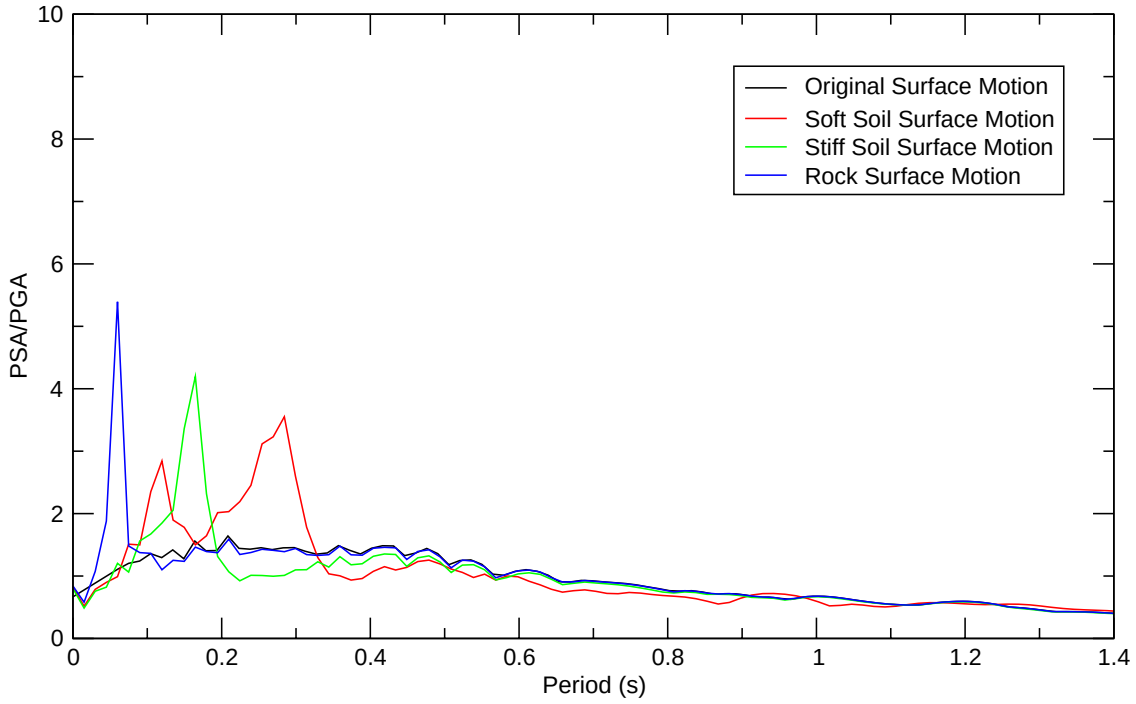

Figure IV.8: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 4 Earthquake, Vertical Component

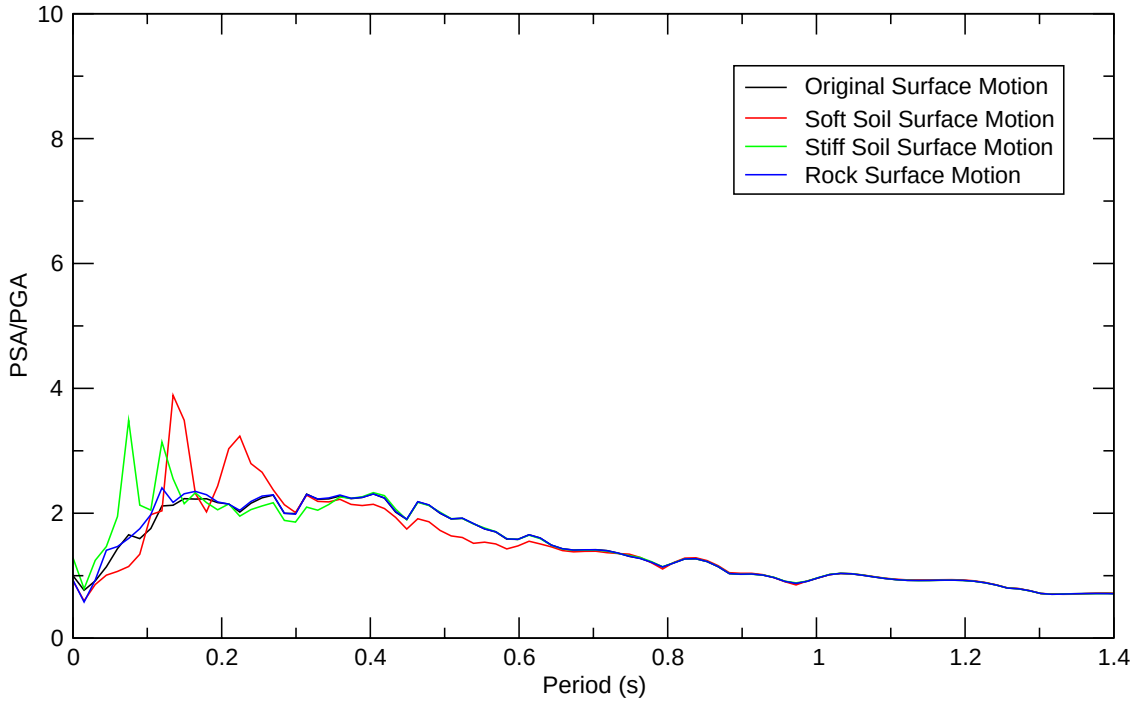

Figure IV.9: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 5 Earthquake, 1st Horizontal Component

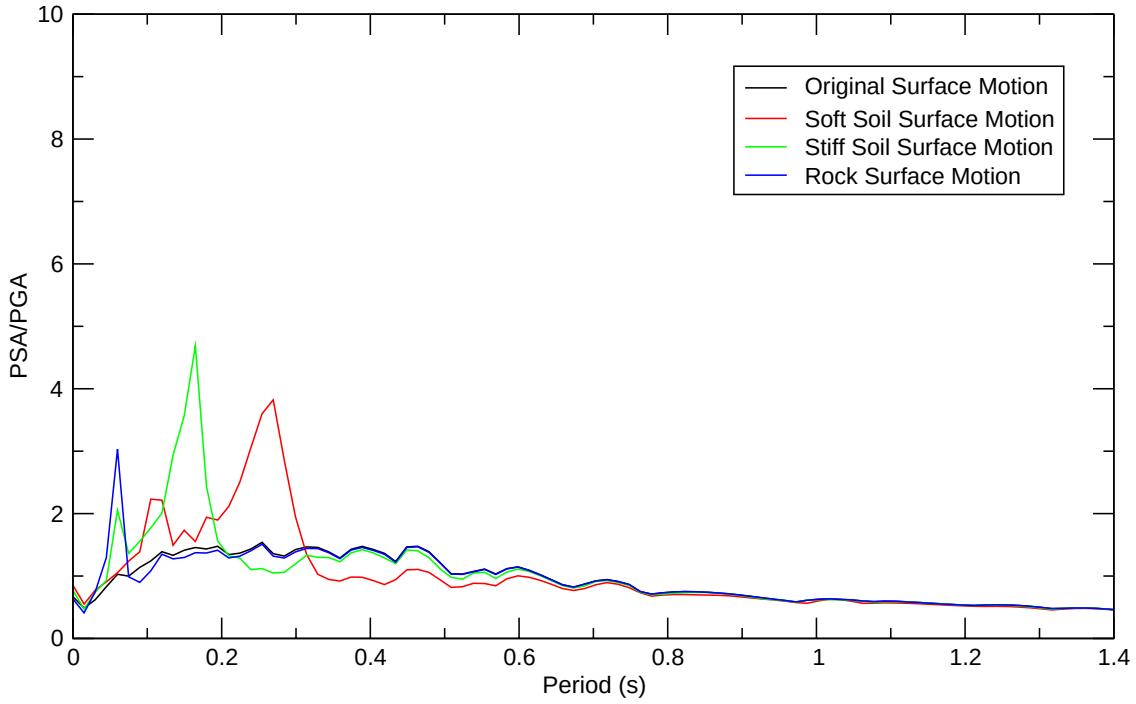

Figure IV.10: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-0098 Spectral Shape, Case 5 Earthquake, Vertical Component

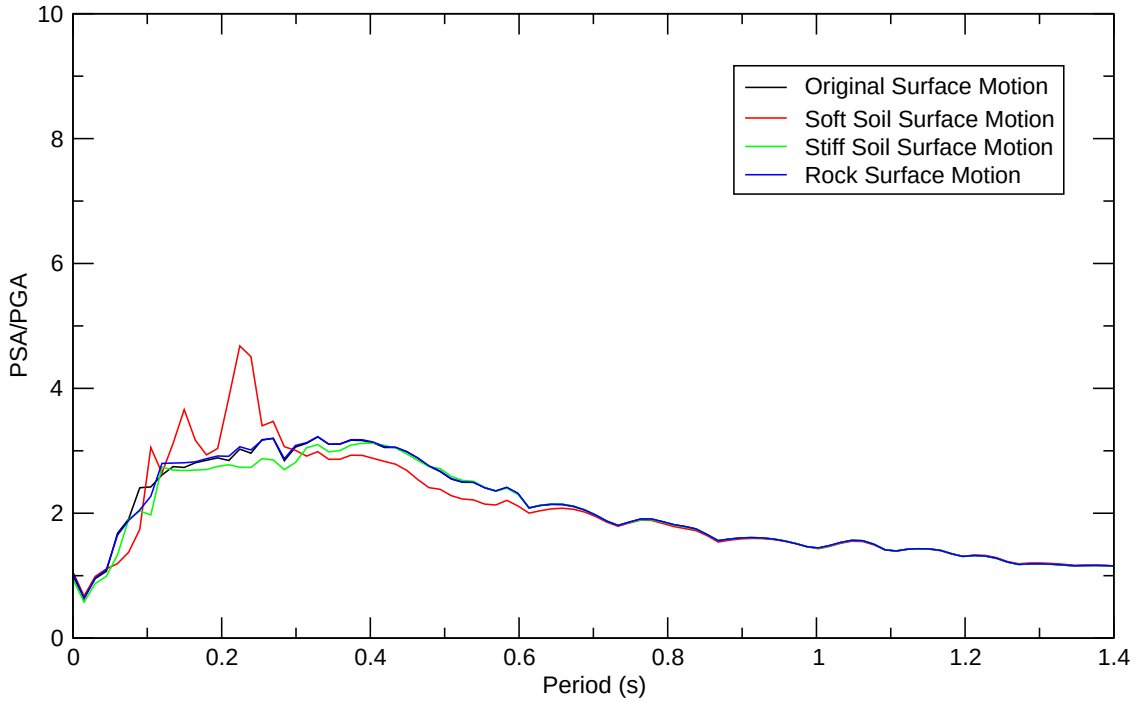

Figure IV.11: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 1 Earthquake, 1st Horizontal Component

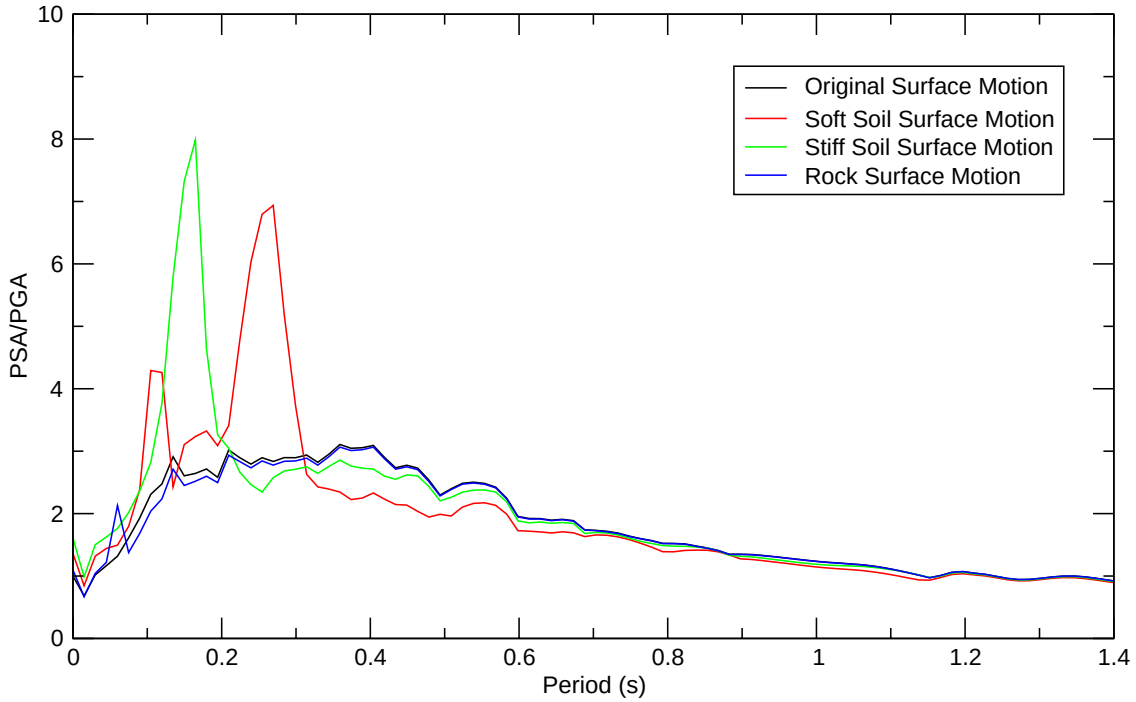

Figure IV.12: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 1 Earthquake, Vertical Component

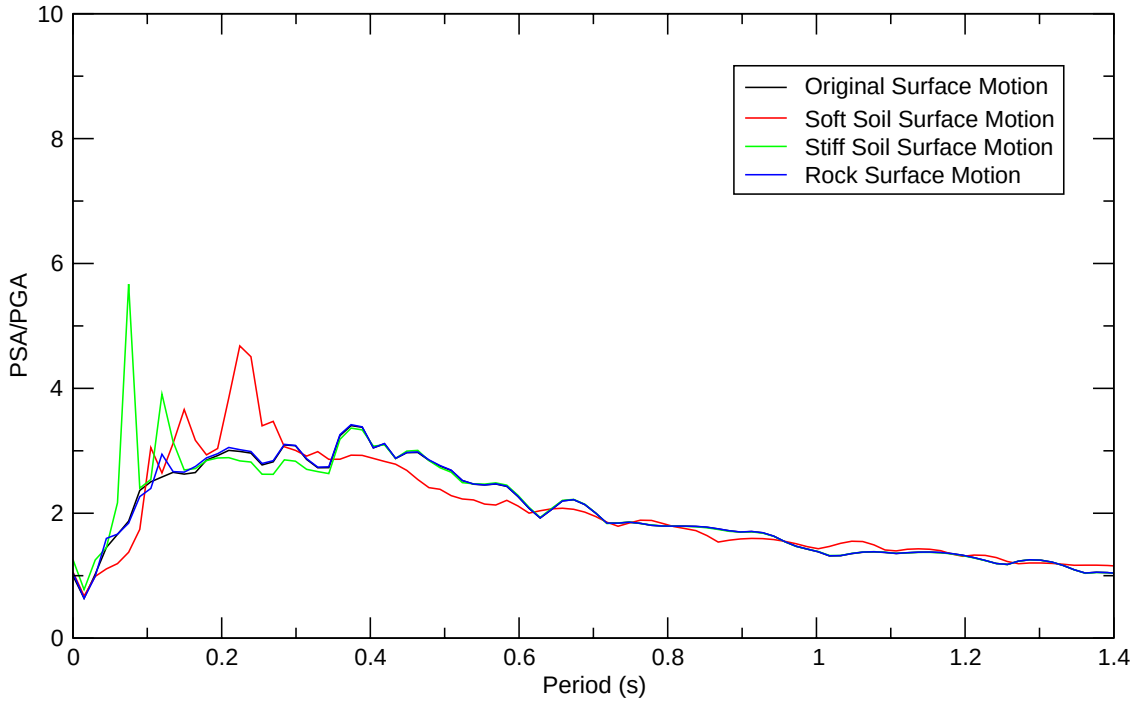

Figure IV.13: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 2 Earthquake, 1st Horizontal Component

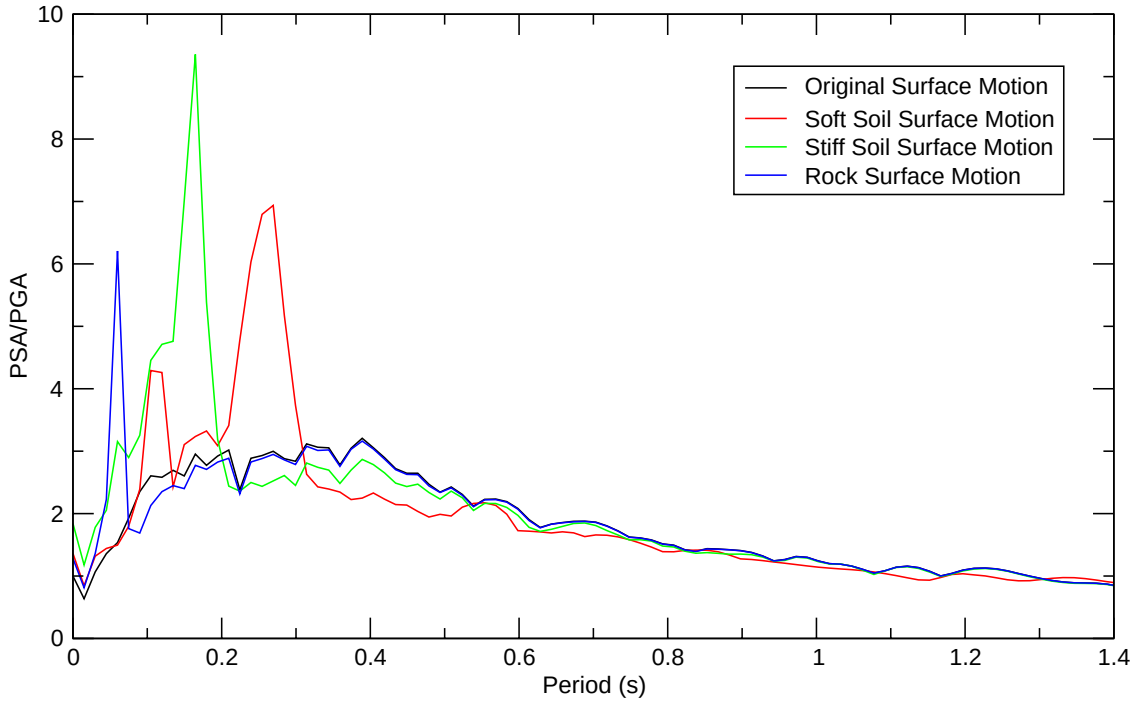

Figure IV.14: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 2 Earthquake, Vertical Component

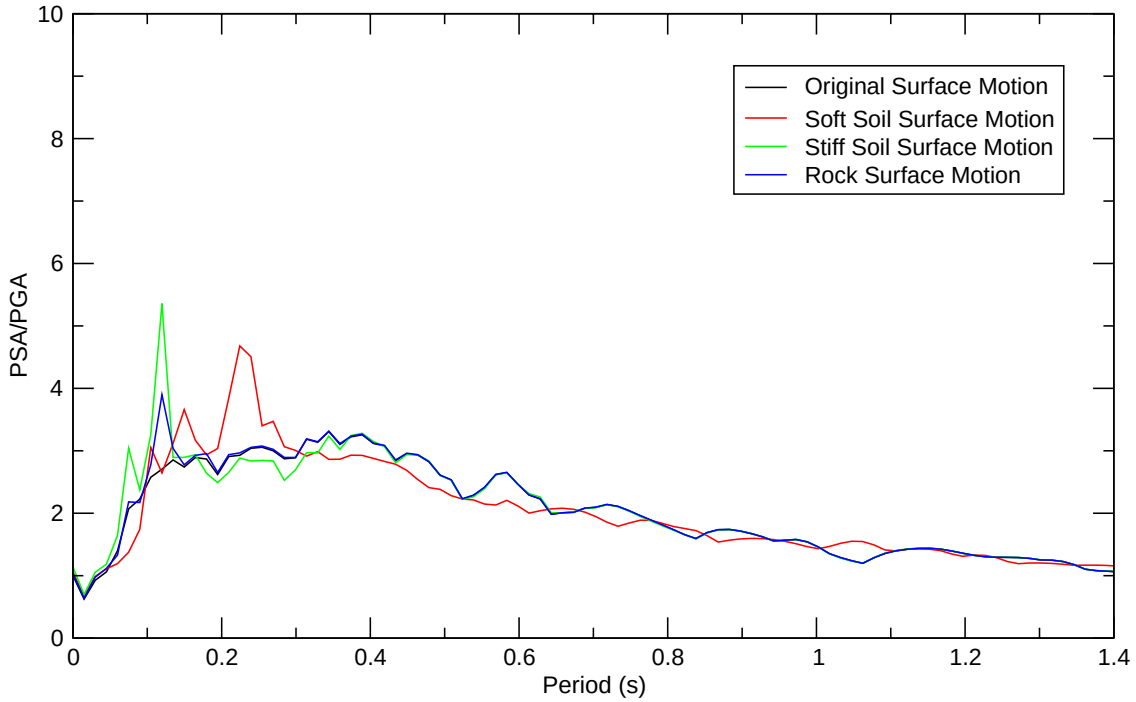

Figure IV.15: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 3 Earthquake, 1st Horizontal Component

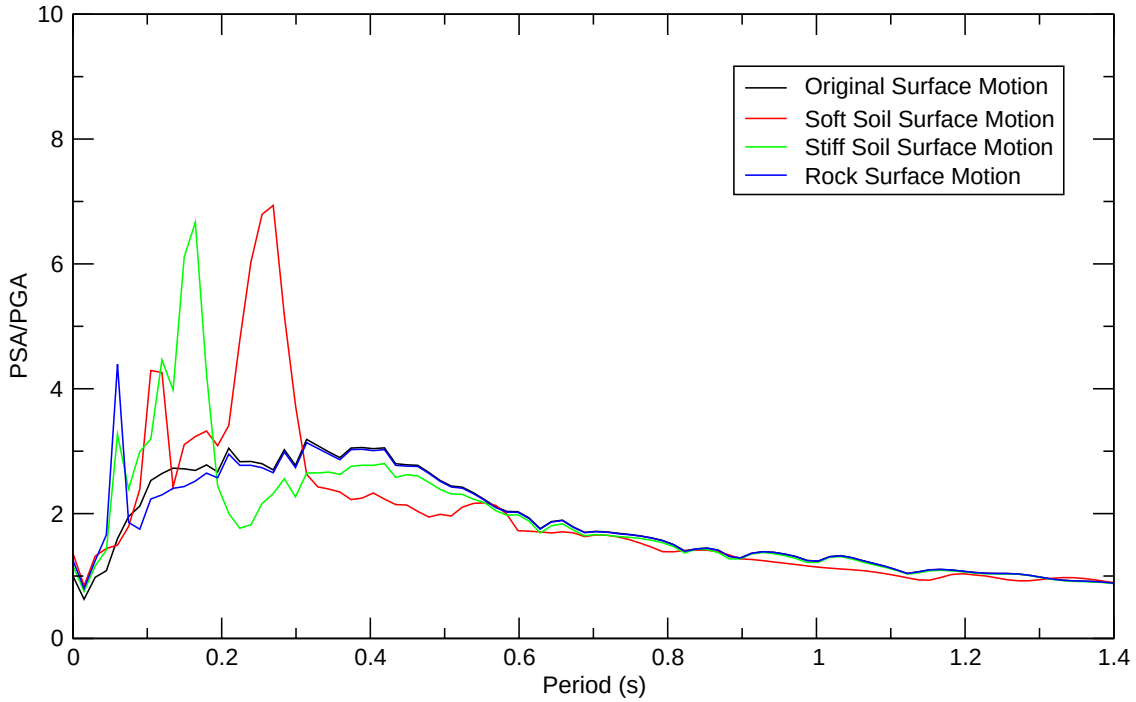

Figure IV.16: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 3 Earthquake, Vertical Component

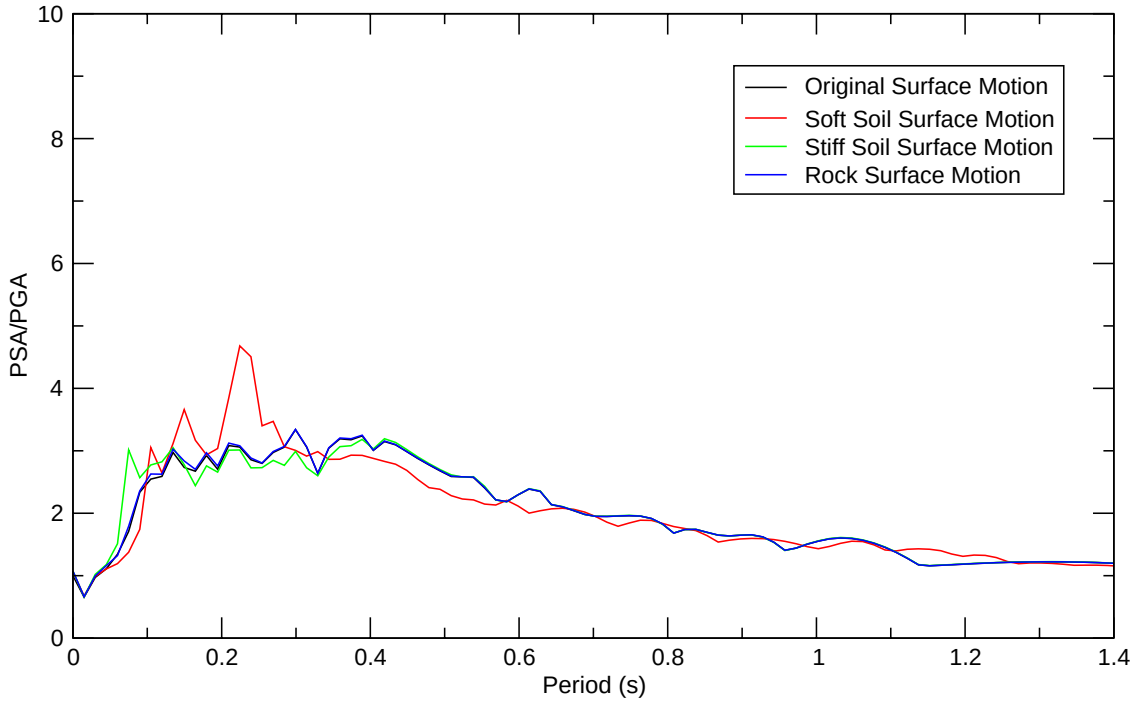

Figure IV.17: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 4 Earthquake, 1st Horizontal Component

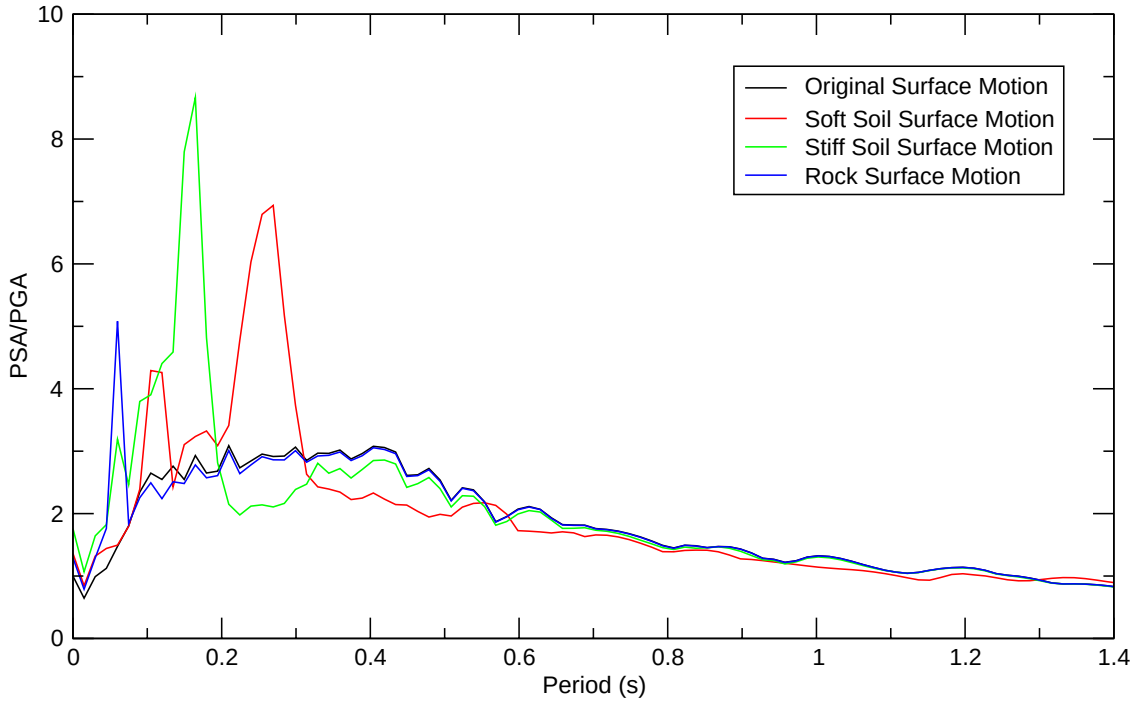

Figure IV.18: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 4 Earthquake, Vertical Component

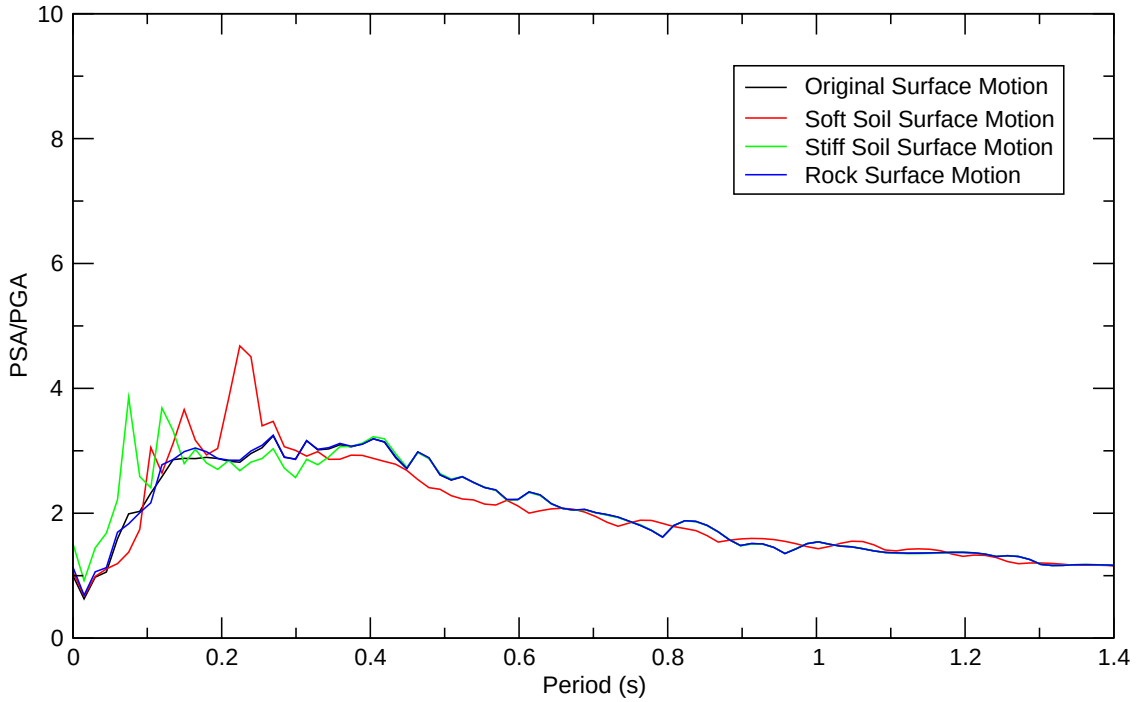

Figure IV.19: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 5 Earthquake, 1st Horizontal Component

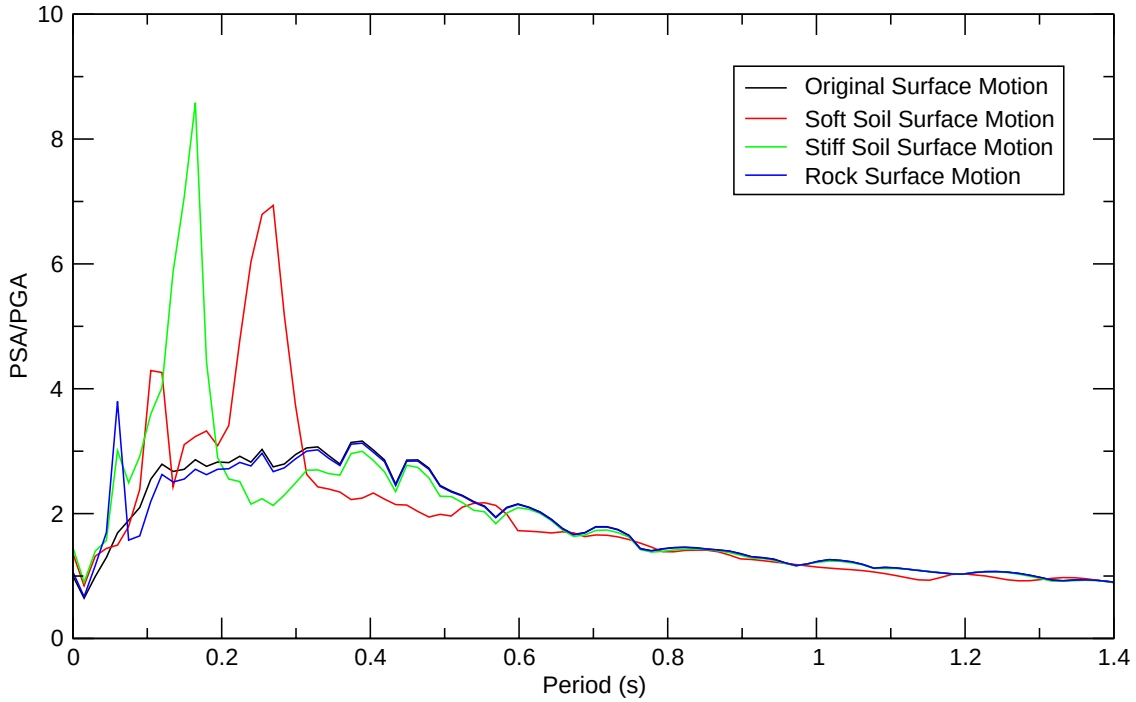

Figure IV.20: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, Regulatory Guide 1.60 Spectral Shape, Case 5 Earthquake, Vertical Component

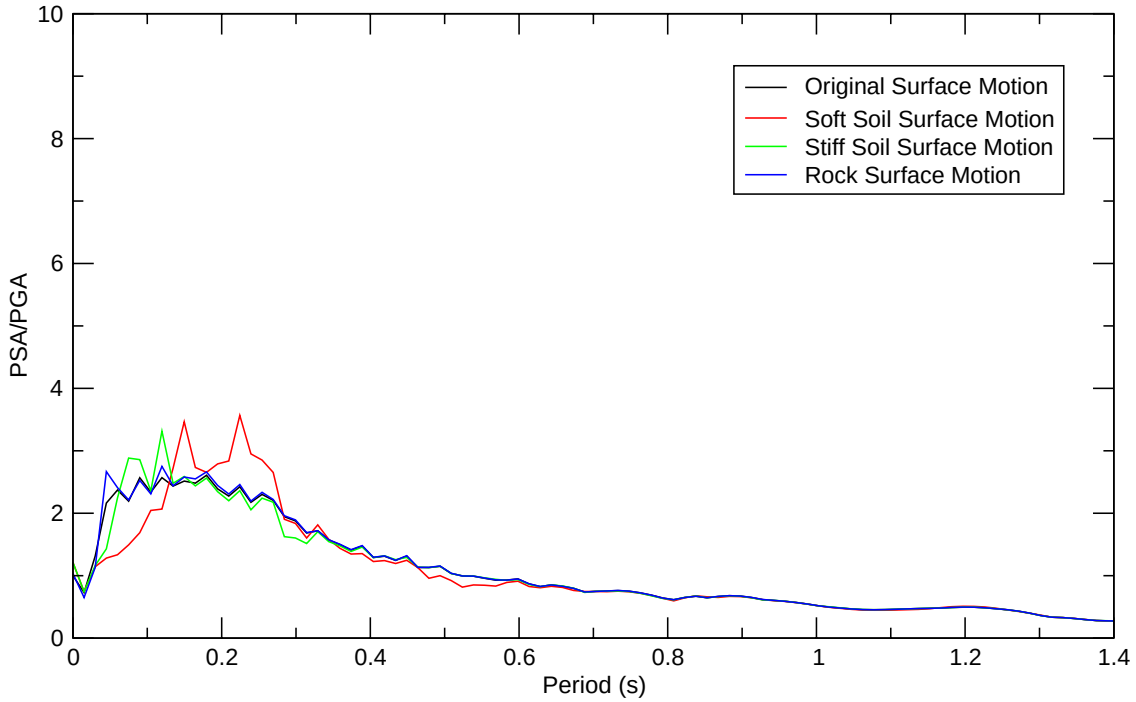

Figure IV.21: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case A Earthquake, 1st Horizontal Component

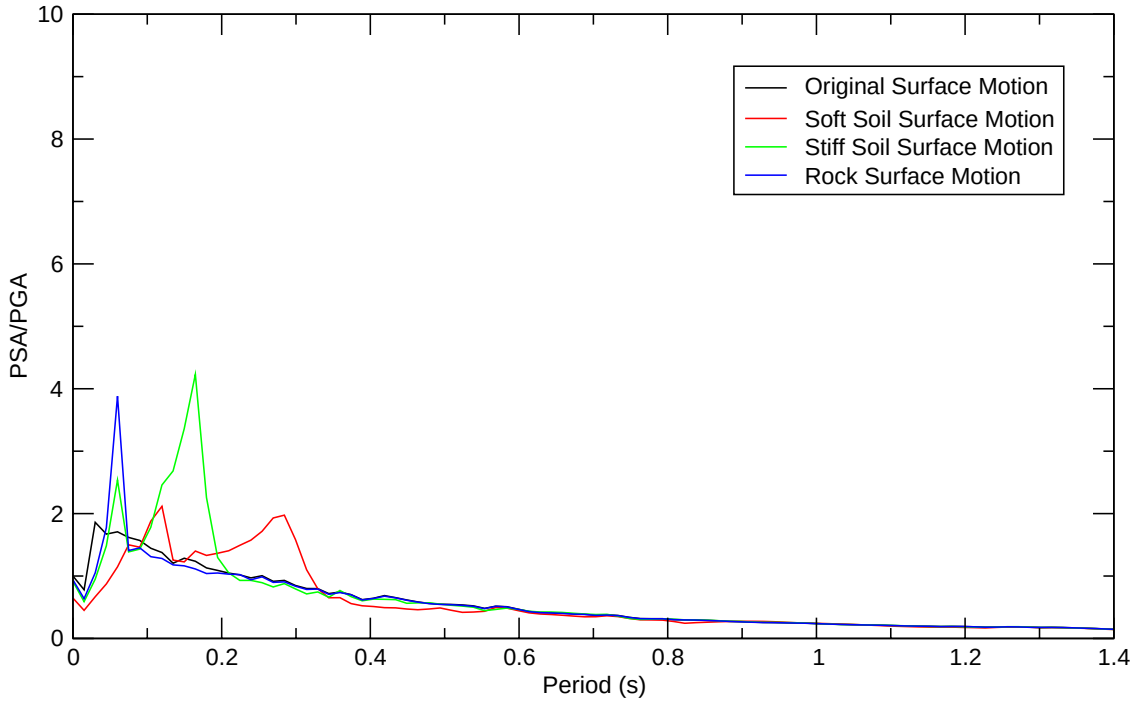

Figure IV.22: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case A Earthquake, Vertical Component

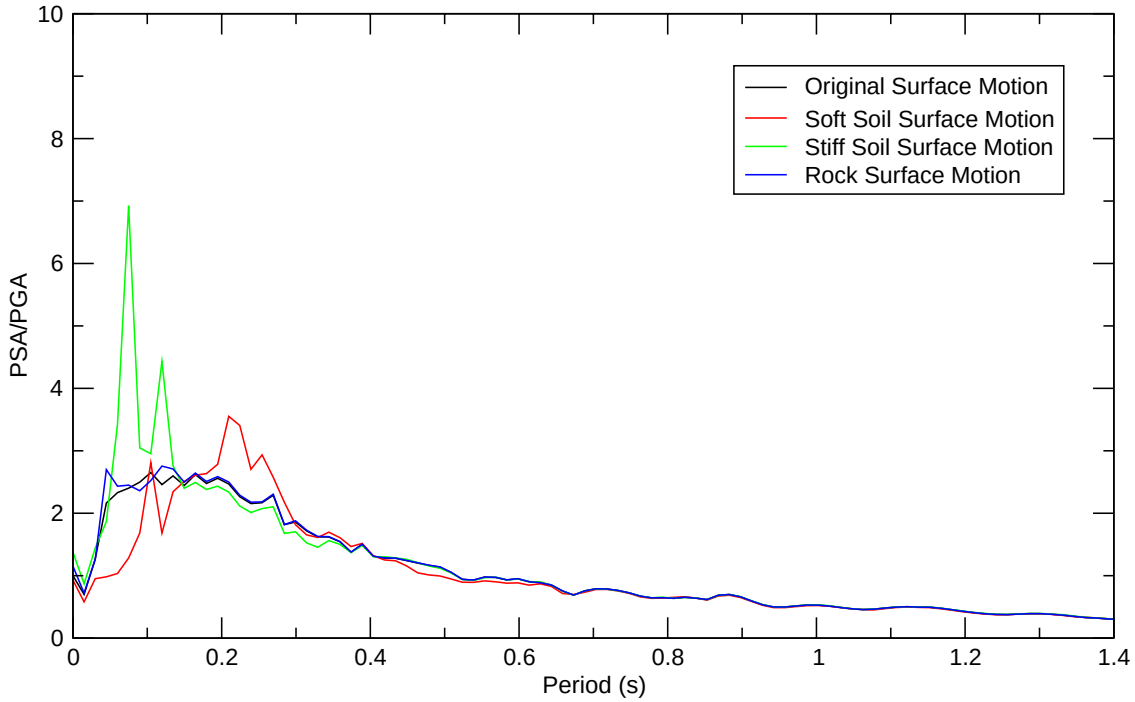

Figure IV.23: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case B Earthquake, 1st Horizontal Component

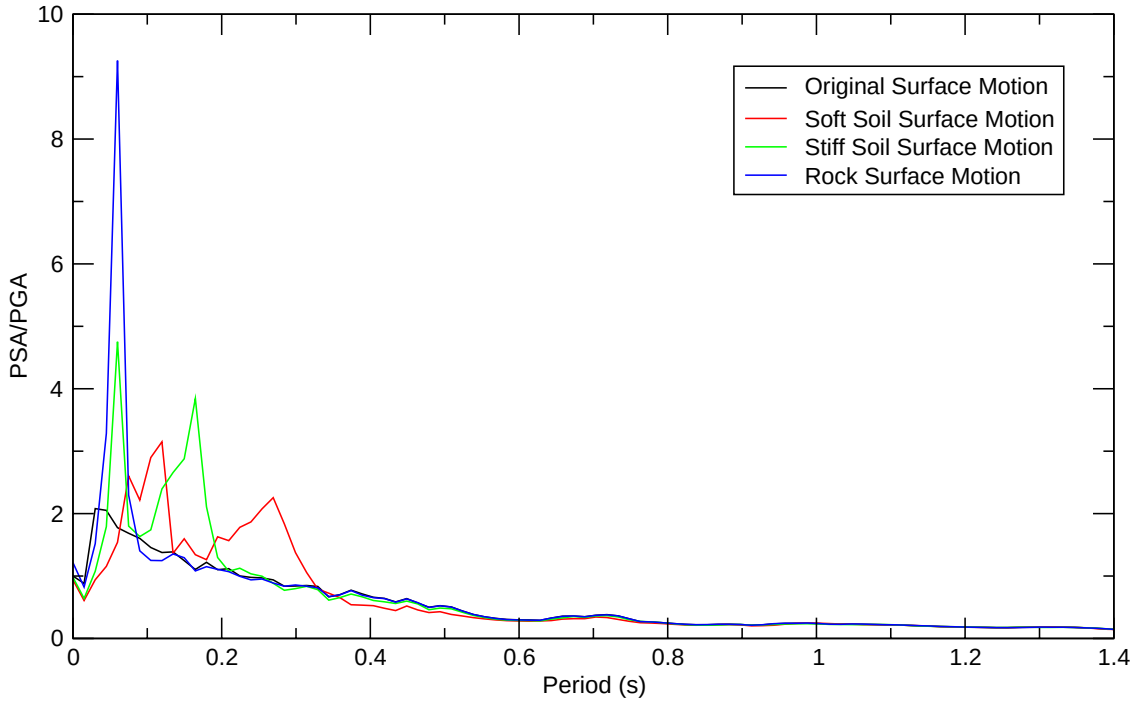

Figure IV.24: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case B Earthquake, Vertical Component

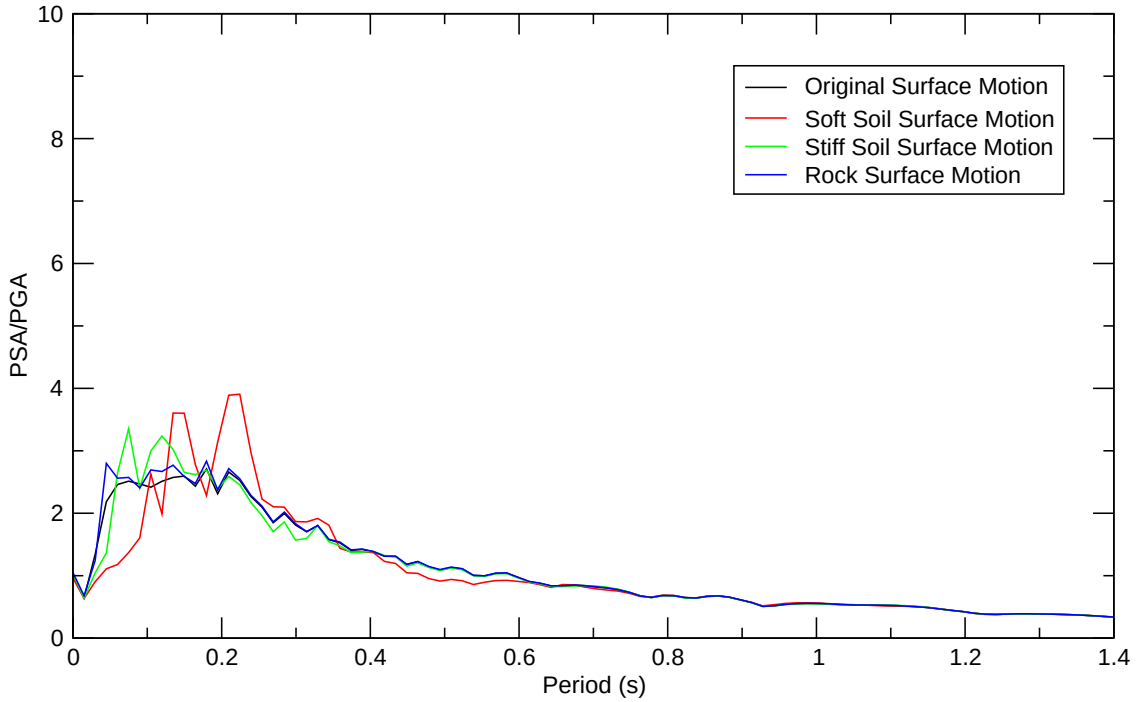

Figure IV.25: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case C Earthquake, 1st Horizontal Component

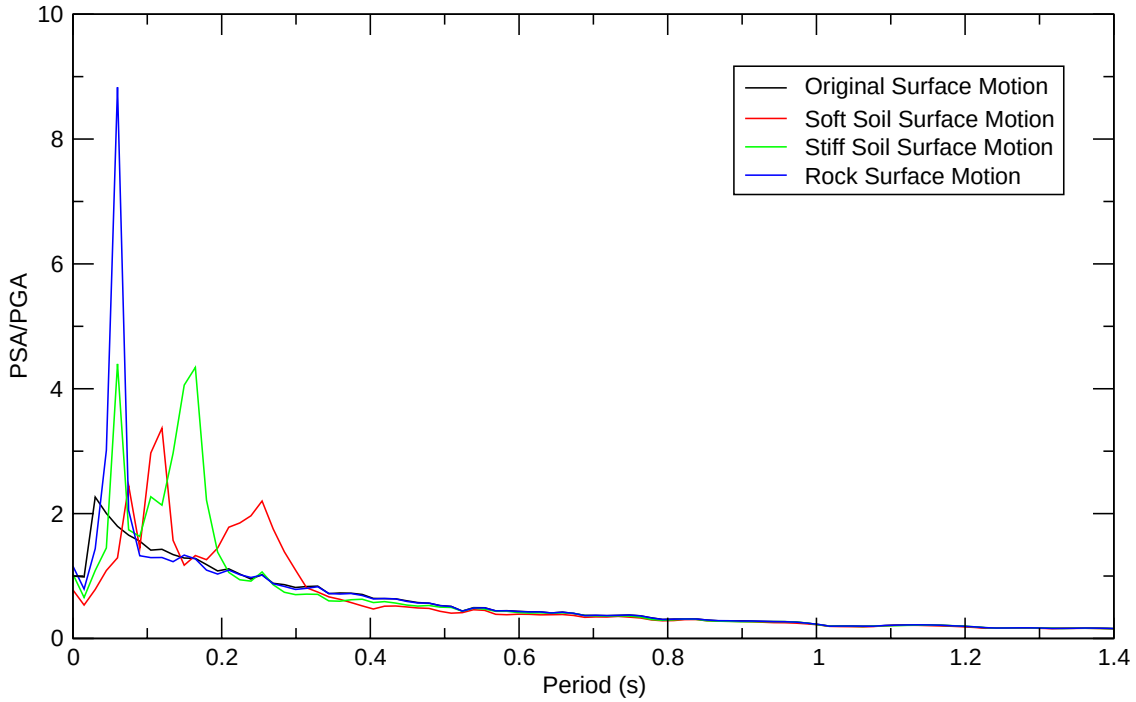

Figure IV.26: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case C Earthquake, Vertical Component

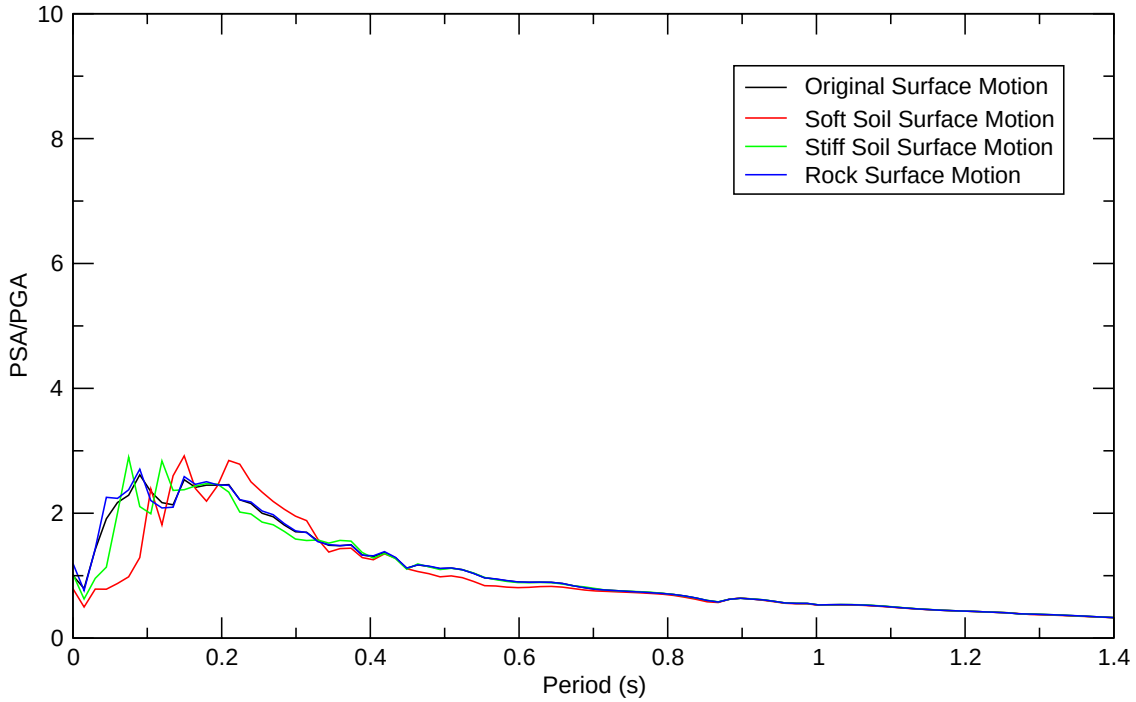

Figure IV.27: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case D Earthquake, 1st Horizontal Component

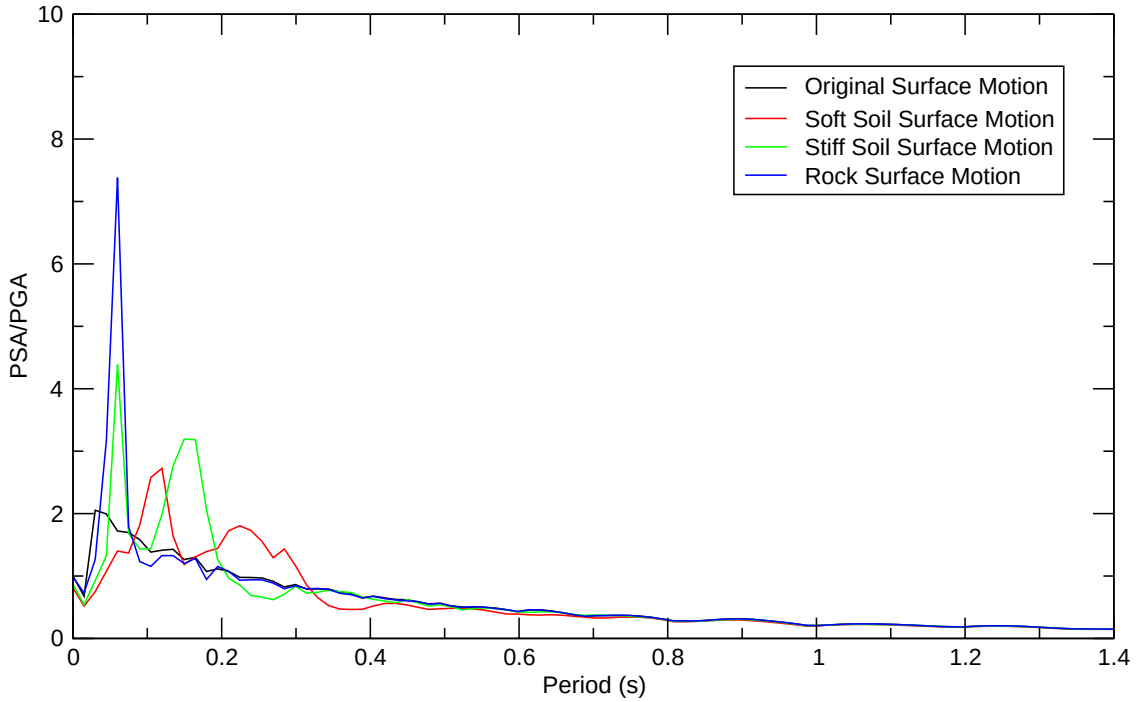

Figure IV.28: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case D Earthquake, Vertical Component

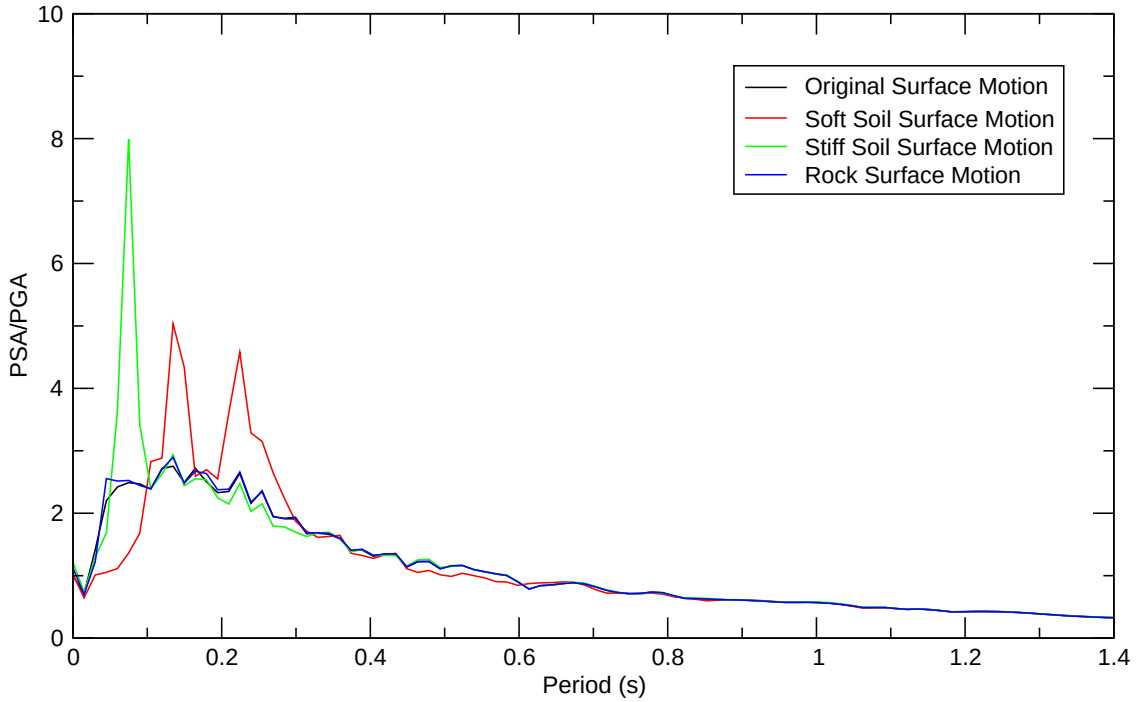

Figure IV.29: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case E Earthquake, 1st Horizontal Component

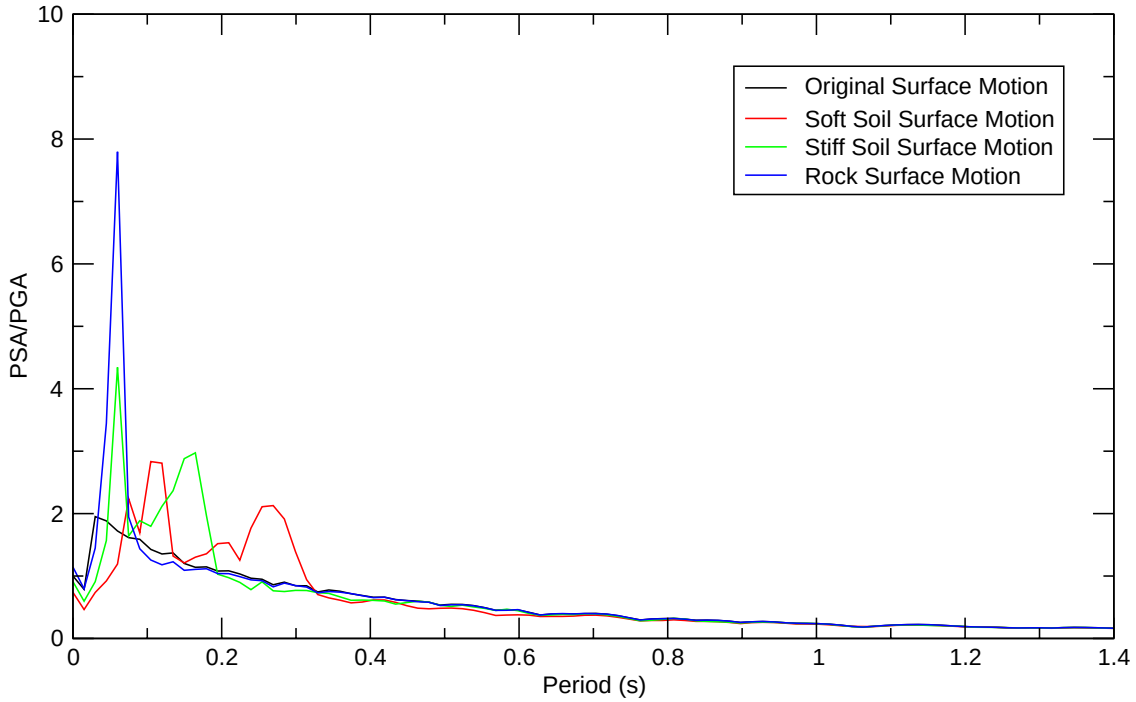

Figure IV.30: Comparison of Original Surface Motion and Motion at Top of Soil Column Model, NUREG/CR-6728 Spectral Shape, Case E Earthquake, Vertical Component

Appendix V: Complete Parametric Cask Analysis Results

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Appendix V: Complete Parametric Cask Analysis Results

A complete summary of the parametric cask analysis results is provided in this appendix. This presentation is split in two parts. In Section V.1, the response of the cylindrical cask and rectangular module under all of the conditions considered in this study is presented in tabular form. A subset of this data is plotted graphically in Section V.2.

V.1 Tabular Presentation of Results

Separate tables are provided in this section to show the cask response in terms of three key parameters: peak horizontal cask top displacement relative to the pad, peak cask rotation, and peak horizontal cask bottom displacement relative to the pad. Initially, all cask analyses were run at a number of pre-determined levels of peak ground acceleration (PGA). In cases where the cask tipped over, additional analyses were performed at more refined increments of PGA to better define the point at which the cask first tips over. This was done only for selected analysis cases, so in the tables there are a number of combinations of parameters for which analyses were not run. These cases are denoted in the tables with "---". In the cases when the cask overturns, the peak cask displacements and rotations are no longer meaningful. Thus, these cases are denoted as "Tips", and the cells are black to highlight these cases.

Because of the nonlinear nature of the cask behavior, the peak cask response does not always increase monotonically with increasing ground motion. In a few cases, the cask overturned at a given level of ground motion, but did not overturn at a higher level of ground motion. The results for these cases are reported, but there is an asterisk "*" to the right of the result in the tables to denote these special cases.

Table V.1: Peak Cask Top Displacements (m), Cylindrical Cask, NUREG/CR-0098 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.008	0.003	0.003	0.003	0.002	0.002	0.005	0.002	0.002
	0.60g	0.106	0.399	0.377	0.091	0.291	1.087	0.103	1.627	0.193
	1.00g	0.288	2.312	2.451	0.357	1.901	2.281	0.363	1.250	1.347
	1.10g	---	2.269	---	---	---	---	---	---	1.400
	1.25g	0.460	Tips	2.459	0.515	1.257	1.079	0.530	2.577	Tips
Case 2	0.25g	0.008	0.004	0.004	0.004	0.002	0.002	0.005	0.003	0.004
	0.60g	0.085	0.104	0.091	0.101	0.120	0.137	0.101	0.301	0.721
	0.80g	---	---	1.431	---	---	1.327	---	---	---
	0.90g	---	---	1.175	---	---	0.367	---	---	---
	1.00g	0.175	0.439	Tips	0.289	0.689	Tips	0.313	1.603	1.162
	1.10g	---	---	Tips	---	---	1.290*	---	---	1.852
	1.25g	0.267	2.718	Tips	0.415	0.642	2.458*	0.512	1.381	Tips
Case 3	0.25g	0.012	0.004	0.004	0.004	0.002	0.002	0.005	0.005	0.006
	0.60g	0.085	0.286	0.126	0.037	0.241	0.431	0.057	0.343	0.459
	1.00g	0.162	0.492	0.445	0.165	0.565	1.006	0.160	0.901	1.071
	1.10g	---	---	2.523	---	---	---	---	---	---
	1.25g	0.273	3.204	Tips	0.299	2.279	1.752	0.273	2.803	2.276
Case 4	0.25g	0.009	0.003	0.003	0.002	0.001	0.001	0.003	0.002	0.002
	0.60g	0.073	0.079	0.074	0.048	0.025	0.250	0.054	0.154	0.191
	1.00g	0.228	1.084	0.881	0.204	0.304	0.849	0.196	0.945	0.577
	1.25g	0.304	1.227	0.908	0.300	0.672	0.986	0.316	2.029	0.818
Case 5	0.25g	0.013	0.004	0.004	0.005	0.002	0.002	0.005	0.003	0.003
	0.60g	0.065	0.165	0.298	0.064	0.113	0.335	0.101	0.972	0.528
	1.00g	0.178	0.734	0.332	0.162	0.562	2.591	0.162	2.712	0.442
	1.10g	---	---	---	---	---	Tips	---	---	---
	1.25g	0.291	0.726	2.730	0.237	2.530	Tips	0.241	0.704	3.260

Table V.2: Peak Cask Top Displacements (m), Cylindrical Cask, Regulatory Guide 1.60 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.034	0.007	0.006	0.009	0.001	0.001	0.012	0.003	0.008
	0.40g	0.116	0.351	0.426	0.100	0.206	0.345	0.109	0.456	1.116
	0.50g	0.211	1.134	1.114	0.225	1.362	1.217	0.239	0.856	2.417
	0.55g	---	---	2.082	---	---	2.221	---	---	---
	0.60g	0.356	2.464	Tips	0.397	1.905	Tips	0.409	2.099	2.433
	0.80g	---	Tips	2.425*	---	1.052	2.069*	---	1.591	2.057
	1.00g	1.105	Tips	Tips	1.162	Tips	Tips	1.150	Tips	Tips
Case 2	0.25g	0.040	0.026	0.029	0.026	0.003	0.003	0.027	0.008	0.021
	0.40g	0.103	0.077	0.304	0.112	0.096	0.355	0.113	0.084	0.076
	0.50g	0.120	0.356	0.145	0.187	0.615	0.194	0.199	0.234	0.262
	0.60g	0.162	0.331	2.009	0.269	0.777	1.374	0.264	1.396	1.736
	0.80g	---	Tips	0.946	---	1.933	Tips	---	Tips	---
	1.00g	0.406	Tips	Tips	0.488	Tips	Tips	0.568	Tips	2.758
Case 3	0.25g	0.041	0.010	0.009	0.012	0.002	0.002	0.012	0.008	0.008
	0.40g	0.092	0.065	0.067	0.031	0.338	0.393	0.059	0.125	0.672
	0.50g	0.129	0.837	0.732	0.065	1.422	0.716	0.114	0.180	0.667
	0.60g	0.166	0.873	3.097	0.144	1.560	1.007	0.185	0.897	1.918
	0.80g	---	1.410	Tips	---	1.526	1.437	---	Tips	2.882
	1.00g	0.757	Tips	Tips	0.712	Tips	Tips	0.728	Tips	Tips
Case 4	0.25g	0.118	0.259	0.299	0.013	0.002	0.002	0.016	0.006	0.008
	0.40g	0.264	0.497	0.889	0.076	0.141	0.473	0.092	0.036	0.858
	0.50g	0.349	0.542	0.671	0.164	0.386	0.178	0.186	0.405	0.651
	0.60g	0.427	0.587	1.062	0.291	0.270	0.809	0.319	0.415	0.850
	0.80g	---	---	3.484	---	1.405	Tips	---	---	0.818
	1.00g	1.169	2.081	Tips	0.716	Tips	Tips	0.802	1.114	Tips
Case 5	0.25g	0.031	0.006	0.006	0.018	0.002	0.002	0.019	0.004	0.004
	0.40g	0.085	0.397	0.479	0.073	0.473	0.432	0.100	0.510	0.444
	0.50g	0.138	0.610	0.194	0.119	0.681	1.377	0.138	0.446	0.484
	0.60g	0.198	0.582	0.395	0.177	0.686	0.506	0.190	0.461	1.200
	0.80g	---	Tips	Tips	---	Tips	Tips	---	1.861	Tips
	1.00g	0.765	Tips	Tips	0.558	Tips	Tips	0.588	Tips	Tips

Table V.3: Peak Cask Top Displacements (m), Cylindrical Cask, NUREG/CR-6728 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case A	0.25g	0.018	0.006	0.006	0.005	0.003	0.003	0.006	0.008	0.008
	0.60g	0.037	0.052	0.055	0.038	0.074	0.060	0.036	0.097	0.222
	1.00g	0.111	0.310	0.229	0.122	0.598	0.568	0.124	0.323	0.303
	1.25g	0.189	0.223	0.239	0.177	0.254	0.333	0.182	0.279	0.316
Case B	0.25g	0.008	0.006	0.006	0.004	0.004	0.004	0.004	0.009	0.006
	0.60g	0.049	0.082	0.157	0.029	0.050	0.348	0.027	0.069	0.053
	1.00g	0.095	0.314	0.546	0.072	0.358	0.381	0.075	0.142	0.352
	1.25g	0.141	0.210	0.473	0.096	0.348	0.530	0.097	0.310	0.279
Case C	0.25g	0.013	0.005	0.005	0.005	0.004	0.004	0.007	0.007	0.016
	0.60g	0.073	0.130	0.037	0.026	0.088	0.051	0.025	0.084	0.128
	1.00g	0.114	0.360	0.342	0.087	0.518	0.227	0.078	0.383	0.649
	1.25g	0.144	0.216	0.555	0.127	0.830	0.759	0.113	0.739	0.510
Case D	0.25g	0.012	0.004	0.004	0.004	0.002	0.002	0.003	0.005	0.005
	0.60g	0.027	0.040	0.046	0.034	0.045	0.073	0.025	0.050	0.061
	1.00g	0.072	0.134	0.107	0.095	0.221	0.622	0.049	0.216	0.175
	1.25g	0.101	0.117	0.139	0.156	0.258	0.307	0.066	0.228	0.320
Case E	0.25g	0.016	0.006	0.006	0.005	0.003	0.003	0.005	0.008	0.009
	0.60g	0.061	0.073	0.081	0.032	0.207	0.076	0.034	0.107	0.212
	1.00g	0.141	0.122	0.140	0.088	0.174	0.200	0.101	0.531	0.098
	1.25g	0.174	0.149	0.096	0.148	0.421	0.545	0.151	0.192	0.801

Table V.4: Peak Cask Top Displacements (m), Rectangular Module, NUREG/CR-0098 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.004	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.001
	0.60g	0.113	0.011	0.004	0.094	0.001	0.001	0.108	0.004	0.002
	1.00g	0.299	0.086	0.084	0.362	0.034	0.037	0.355	0.079	0.027
	1.25g	0.474	0.166	0.128	0.513	0.116	0.135	0.524	0.169	0.096
Case 2	0.25g	0.008	0.001	0.001	0.002	0.000	0.000	0.002	0.000	0.000
	0.60g	0.086	0.015	0.005	0.103	0.007	0.005	0.102	0.006	0.002
	1.00g	0.187	0.133	0.086	0.274	0.094	0.078	0.300	0.073	0.042
	1.25g	0.295	0.218	0.136	0.414	0.186	0.111	0.467	0.136	0.139
Case 3	0.25g	0.004	0.001	0.001	0.002	0.000	0.000	0.003	0.000	0.000
	0.60g	0.092	0.011	0.015	0.031	0.003	0.002	0.061	0.007	0.002
	1.00g	0.176	0.130	0.067	0.146	0.025	0.033	0.178	0.042	0.056
	1.25g	0.251	0.217	0.109	0.278	0.057	0.101	0.281	0.089	0.095
Case 4	0.25g	0.004	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000
	0.60g	0.067	0.009	0.002	0.046	0.001	0.001	0.056	0.006	0.001
	1.00g	0.236	0.083	0.065	0.211	0.045	0.054	0.215	0.069	0.057
	1.25g	0.319	0.117	0.096	0.314	0.109	0.102	0.314	0.154	0.104
Case 5	0.25g	0.007	0.001	0.001	0.003	0.000	0.000	0.004	0.000	0.000
	0.60g	0.060	0.017	0.005	0.062	0.006	0.003	0.095	0.006	0.003
	1.00g	0.163	0.085	0.091	0.160	0.080	0.041	0.164	0.078	0.043
	1.25g	0.270	0.113	0.236	0.234	0.142	0.123	0.243	0.177	0.082

Table V.5: Peak Cask Top Displacements (m), Rectangular Module, Regulatory Guide 1.60 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.032	0.001	0.001	0.006	0.000	0.000	0.009	0.000	0.000
	0.60g	0.359	0.074	0.070	0.393	0.031	0.010	0.411	0.048	0.010
	1.00g	1.124	0.225	0.211	1.114	0.226	0.130	1.134	0.202	0.147
	1.25g	1.706	0.425	0.189	1.696	0.457	0.345	1.679	0.389	0.384
Case 2	0.25g	0.038	0.001	0.001	0.023	0.000	0.000	0.020	0.000	0.000
	0.60g	0.167	0.093	0.041	0.249	0.052	0.031	0.261	0.043	0.029
	1.00g	0.470	0.293	0.151	0.541	0.307	0.258	0.523	0.245	0.112
	1.25g	0.712	0.362	0.273	0.615	0.441	0.211	0.576	0.404	0.299
Case 3	0.25g	0.021	0.001	0.001	0.006	0.000	0.000	0.009	0.000	0.000
	0.60g	0.169	0.081	0.023	0.141	0.013	0.040	0.194	0.019	0.007
	1.00g	0.702	0.243	0.145	0.749	0.125	0.162	0.816	0.160	0.128
	1.25g	1.105	0.373	0.361	1.091	0.287	0.250	1.169	0.319	0.226
Case 4	0.25g	0.130	0.070	0.119	0.009	0.000	0.000	0.011	0.000	0.000
	0.60g	0.411	0.290	0.383	0.291	0.038	0.016	0.312	0.050	0.018
	1.00g	0.978	0.572	0.627	0.767	0.295	0.231	0.832	0.230	0.123
	1.25g	1.462	0.703	0.830	0.835	0.416	0.452	1.142	0.566	0.323
Case 5	0.25g	0.024	0.001	0.001	0.016	0.000	0.000	0.014	0.000	0.000
	0.60g	0.182	0.060	0.084	0.170	0.048	0.022	0.184	0.040	0.012
	1.00g	0.729	0.187	0.289	0.554	0.171	0.317	0.595	0.259	0.185
	1.25g	1.245	0.310	0.641	1.428	0.302	0.473	1.093	0.322	0.307

Table V.6: Peak Cask Top Displacements (m), Rectangular Module, NUREG/CR-6728 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case A	0.25g	0.006	0.001	0.001	0.002	0.000	0.000	0.004	0.001	0.001
	0.60g	0.030	0.014	0.009	0.039	0.004	0.004	0.046	0.010	0.009
	1.00g	0.099	0.072	0.051	0.120	0.033	0.021	0.138	0.039	0.033
	1.25g	0.175	0.106	0.070	0.177	0.055	0.053	0.201	0.062	0.041
Case B	0.25g	0.003	0.001	0.001	0.004	0.000	0.000	0.007	0.001	0.001
	0.60g	0.036	0.006	0.006	0.023	0.012	0.007	0.027	0.016	0.017
	1.00g	0.102	0.027	0.044	0.072	0.045	0.035	0.070	0.048	0.039
	1.25g	0.133	0.067	0.056	0.099	0.049	0.058	0.091	0.039	0.043
Case C	0.25g	0.004	0.001	0.001	0.004	0.000	0.000	0.004	0.001	0.001
	0.60g	0.066	0.009	0.008	0.024	0.008	0.008	0.031	0.016	0.010
	1.00g	0.130	0.054	0.034	0.069	0.048	0.020	0.089	0.026	0.027
	1.25g	0.151	0.087	0.045	0.111	0.057	0.046	0.101	0.070	0.061
Case D	0.25g	0.005	0.001	0.001	0.002	0.000	0.000	0.002	0.001	0.001
	0.60g	0.038	0.009	0.005	0.025	0.005	0.004	0.022	0.004	0.004
	1.00g	0.093	0.055	0.027	0.087	0.035	0.029	0.080	0.020	0.025
	1.25g	0.114	0.057	0.041	0.149	0.061	0.047	0.257	0.065	0.038
Case E	0.25g	0.009	0.001	0.001	0.003	0.000	0.000	0.003	0.002	0.001
	0.60g	0.051	0.021	0.022	0.033	0.011	0.007	0.042	0.013	0.010
	1.00g	0.135	0.067	0.043	0.089	0.032	0.028	0.078	0.020	0.033
	1.25g	0.186	0.107	0.050	0.143	0.060	0.052	0.154	0.056	0.063

Table V.7: Peak Cask Rotations (deg), Cylindrical Cask, NUREG/CR-0098 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.034	0.007	0.006	0.009	0.001	0.001	0.012	0.003	0.008
	0.40g	0.116	0.351	0.426	0.100	0.206	0.345	0.109	0.456	1.116
	0.50g	0.211	1.134	1.114	0.225	1.362	1.217	0.239	0.856	2.417
	0.55g	---	---	2.082	---	---	2.221	---	---	---
	0.60g	0.356	2.464	Tips	0.397	1.905	Tips	0.409	2.099	2.433
	0.80g	---	Tips	2.425*	---	1.052	2.069*	---	1.591	2.057
	1.00g	1.105	Tips	Tips	1.162	Tips	Tips	1.150	Tips	Tips
Case 2	0.25g	0.040	0.026	0.029	0.026	0.003	0.003	0.027	0.008	0.021
	0.40g	0.103	0.077	0.304	0.112	0.096	0.355	0.113	0.084	0.076
	0.50g	0.120	0.356	0.145	0.187	0.615	0.194	0.199	0.234	0.262
	0.60g	0.162	0.331	2.009	0.269	0.777	1.374	0.264	1.396	1.736
	0.80g	---	Tips	0.946	---	1.933	Tips	---	Tips	---
	1.00g	0.406	Tips	Tips	0.488	Tips	Tips	0.568	Tips	2.758
Case 3	0.25g	0.041	0.010	0.009	0.012	0.002	0.002	0.012	0.008	0.008
	0.40g	0.092	0.065	0.067	0.031	0.338	0.393	0.059	0.125	0.672
	0.50g	0.129	0.837	0.732	0.065	1.422	0.716	0.114	0.180	0.667
	0.60g	0.166	0.873	3.097	0.144	1.560	1.007	0.185	0.897	1.918
	0.80g	---	1.410	Tips	---	1.526	1.437	---	Tips	2.882
	1.00g	0.757	Tips	Tips	0.712	Tips	Tips	0.728	Tips	Tips
Case 4	0.25g	0.118	0.259	0.299	0.013	0.002	0.002	0.016	0.006	0.008
	0.40g	0.264	0.497	0.889	0.076	0.141	0.473	0.092	0.036	0.858
	0.50g	0.349	0.542	0.671	0.164	0.386	0.178	0.186	0.405	0.651
	0.60g	0.427	0.587	1.062	0.291	0.270	0.809	0.319	0.415	0.850
	0.80g	---	---	3.484	---	1.405	Tips	---	---	0.818
	1.00g	1.169	2.081	Tips	0.716	Tips	Tips	0.802	1.114	Tips
Case 5	0.25g	0.031	0.006	0.006	0.018	0.002	0.002	0.019	0.004	0.004
	0.40g	0.085	0.397	0.479	0.073	0.473	0.432	0.100	0.510	0.444
	0.50g	0.138	0.610	0.194	0.119	0.681	1.377	0.138	0.446	0.484
	0.60g	0.198	0.582	0.395	0.177	0.686	0.506	0.190	0.461	1.200
	0.80g	---	Tips	Tips	---	Tips	Tips	---	1.861	Tips
	1.00g	0.765	Tips	Tips	0.558	Tips	Tips	0.588	Tips	Tips

Table V.8: Peak Cask Rotations (deg), Cylindrical Cask, Regulatory Guide 1.60 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.02	0.05	0.05	0.01	0.01	0.01	0.01	0.03	0.06
	0.40g	0.02	1.87	3.87	0.01	1.92	2.91	0.01	3.08	9.20
	0.50g	0.03	6.40	6.79	0.01	7.37	7.79	0.01	7.29	18.02
	0.55g	---	---	15.65	---	---	16.78	---	---	---
	0.60g	0.03	16.24	Tips	0.01	13.92	Tips	0.01	12.68	16.67
	0.80g	---	Tips	21.77*	---	9.35	21.42*	---	14.70	19.02
	1.00g	0.22	Tips	Tips	0.77	Tips	Tips	0.02	Tips	Tips
Case 2	0.25g	0.02	0.20	0.23	0.01	0.03	0.03	0.01	0.05	0.18
	0.40g	0.03	0.55	2.44	0.01	0.82	2.53	0.01	0.65	0.79
	0.50g	0.03	1.83	1.02	0.01	4.93	1.41	0.02	1.26	2.17
	0.60g	0.03	2.28	16.11	0.02	7.73	9.21	0.02	11.92	17.24
	0.80g	---	Tips	7.55	---	14.52	Tips	---	Tips	---
	1.00g	0.10	Tips	Tips	0.40	Tips	Tips	0.19	Tips	21.68
Case 3	0.25g	0.02	0.09	0.09	0.01	0.02	0.02	0.01	0.08	0.06
	0.40g	0.03	0.59	0.44	0.01	2.70	3.67	0.01	0.97	4.41
	0.50g	0.03	6.61	5.37	0.01	12.74	5.29	0.01	1.45	4.70
	0.60g	0.04	5.84	19.77	0.01	9.00	8.60	0.02	4.75	20.13
	0.80g	---	12.17	Tips	---	11.69	12.27	---	Tips	23.55
	1.00g	0.12	Tips	Tips	0.02	Tips	Tips	0.23	Tips	Tips
Case 4	0.25g	0.03	1.40	2.10	0.01	0.02	0.02	0.01	0.05	0.05
	0.40g	0.03	2.06	8.08	0.01	1.17	4.09	0.02	0.29	7.04
	0.50g	0.03	4.11	5.56	0.01	2.95	1.54	0.01	3.00	5.17
	0.60g	0.03	4.66	7.98	0.02	2.12	5.33	0.02	4.08	6.33
	0.80g	---	---	24.70	---	8.22	Tips	---	---	4.63
	1.00g	0.12	17.24	Tips	0.08	Tips	Tips	0.29	8.16	Tips
Case 5	0.25g	0.02	0.06	0.06	0.01	0.02	0.02	0.01	0.03	0.03
	0.40g	0.02	3.40	4.20	0.01	3.46	3.99	0.01	4.22	4.53
	0.50g	0.03	3.80	1.60	0.01	4.87	12.50	0.01	3.49	4.00
	0.60g	0.03	3.71	3.39	0.01	3.40	3.03	0.02	3.69	10.64
	0.80g	---	Tips	Tips	---	Tips	Tips	---	15.14	Tips
	1.00g	0.22	Tips	Tips	0.09	Tips	Tips	0.05	Tips	Tips

Table V.9: Peak Cask Rotations (deg), Cylindrical Cask, NUREG/CR-6728 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case A	0.25g	0.02	0.05	0.05	0.01	0.03	0.03	0.01	0.07	0.07
	0.60g	0.03	0.32	0.38	0.01	0.66	0.59	0.02	0.53	1.67
	1.00g	0.04	2.14	2.01	0.01	4.74	4.45	0.11	1.69	2.18
	1.25g	0.05	1.81	2.48	0.01	2.00	3.02	0.11	2.09	2.84
Case B	0.25g	0.02	0.06	0.05	0.01	0.04	0.04	0.01	0.06	0.05
	0.60g	0.03	0.60	1.39	0.01	0.48	2.97	0.08	0.54	0.29
	1.00g	0.04	2.79	4.19	0.02	1.85	3.25	0.23	0.79	2.84
	1.25g	0.04	1.66	3.24	0.04	2.96	4.17	0.26	2.81	2.15
Case C	0.25g	0.02	0.05	0.04	0.01	0.03	0.03	0.01	0.05	0.13
	0.60g	0.03	1.19	0.32	0.01	0.67	0.55	0.02	0.80	0.94
	1.00g	0.03	3.16	3.50	0.02	3.84	1.78	0.13	3.55	5.80
	1.25g	0.06	1.10	4.01	0.04	7.07	5.11	0.30	4.67	4.34
Case D	0.25g	0.02	0.04	0.04	0.01	0.02	0.02	0.01	0.04	0.04
	0.60g	0.02	0.37	0.44	0.01	0.36	0.67	0.02	0.44	0.45
	1.00g	0.03	0.51	0.66	0.02	2.01	5.43	0.16	1.81	1.45
	1.25g	0.04	0.95	1.38	0.03	2.02	2.66	0.25	1.91	2.30
Case E	0.25g	0.02	0.05	0.05	0.01	0.02	0.02	0.01	0.07	0.08
	0.60g	0.03	0.55	0.70	0.01	1.78	0.57	0.01	0.84	1.71
	1.00g	0.03	0.62	1.37	0.03	1.63	1.83	0.14	4.35	0.93
	1.25g	0.04	1.05	1.07	0.05	3.42	4.60	0.23	1.32	6.14

Table V.10: Peak Cask Rotations (deg), Rectangular Module, NUREG/CR-0098 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01
	0.60g	0.01	0.02	0.04	0.00	0.00	0.01	0.00	0.01	0.01
	1.00g	0.01	0.03	0.71	0.00	0.01	0.30	0.00	0.06	0.26
	1.25g	0.01	0.12	1.17	0.00	0.01	1.23	0.00	0.06	0.69
Case 2	0.25g	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	0.60g	0.01	0.02	0.04	0.00	0.01	0.04	0.00	0.01	0.02
	1.00g	0.01	0.03	0.55	0.00	0.03	0.72	0.00	0.03	0.32
	1.25g	0.01	0.07	1.18	0.00	0.05	0.87	0.00	0.02	1.15
Case 3	0.25g	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	0.60g	0.01	0.04	0.12	0.00	0.01	0.02	0.00	0.01	0.02
	1.00g	0.01	0.18	0.55	0.00	0.02	0.35	0.00	0.02	0.50
	1.25g	0.01	0.21	0.86	0.00	0.03	0.79	0.00	0.03	0.68
Case 4	0.25g	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.60g	0.01	0.01	0.02	0.00	0.00	0.01	0.00	0.01	0.01
	1.00g	0.01	0.02	0.55	0.00	0.01	0.30	0.00	0.02	0.28
	1.25g	0.01	0.03	0.81	0.00	0.01	0.95	0.01	0.29	0.80
Case 5	0.25g	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	0.60g	0.01	0.02	0.04	0.00	0.01	0.02	0.00	0.01	0.03
	1.00g	0.01	0.09	0.71	0.00	0.02	0.26	0.00	0.02	0.32
	1.25g	0.01	0.17	1.85	0.00	0.05	1.37	0.00	0.10	0.79

Table V.11: Peak Cask Rotations (deg), Rectangular Module, Regulatory Guide 1.60 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	0.60g	0.01	0.02	0.68	0.00	0.01	0.04	0.00	0.01	0.06
	1.00g	0.04	0.17	1.86	0.10	0.16	1.06	0.00	0.06	1.16
	1.25g	0.52	1.37	1.49	1.12	0.34	2.23	0.05	0.65	1.83
Case 2	0.25g	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	0.60g	0.01	0.02	0.23	0.00	0.01	0.30	0.00	0.03	0.27
	1.00g	0.05	0.08	1.48	0.08	0.07	2.45	0.01	0.06	0.96
	1.25g	0.09	0.24	2.59	0.15	0.10	1.78	0.07	0.15	2.39
Case 3	0.25g	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	0.60g	0.01	0.12	0.18	0.00	0.01	0.40	0.00	0.01	0.05
	1.00g	0.09	0.24	1.18	0.01	0.03	1.24	0.02	0.11	1.04
	1.25g	0.25	0.98	3.17	0.04	0.07	1.88	0.05	0.27	2.00
Case 4	0.25g	0.01	0.24	1.13	0.00	0.00	0.00	0.00	0.00	0.00
	0.60g	0.01	1.90	3.65	0.00	0.01	0.05	0.00	0.01	0.04
	1.00g	0.02	3.54	5.63	0.02	0.06	1.91	0.02	0.13	0.67
	1.25g	0.13	5.18	6.96	0.38	0.48	4.68	0.14	0.66	2.20
Case 5	0.25g	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
	0.60g	0.01	0.07	0.65	0.00	0.01	0.14	0.00	0.02	0.11
	1.00g	0.07	0.28	2.70	0.03	0.07	3.43	0.01	0.11	2.08
	1.25g	0.46	0.53	5.34	0.39	1.09	4.21	0.09	0.23	3.04

Table V.12: Peak Cask Rotations (deg), Rectangular Module, NUREG/CR-6728 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case A	0.25g	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
	0.60g	0.01	0.02	0.09	0.00	0.02	0.03	0.00	0.03	0.08
	1.00g	0.01	0.03	0.33	0.00	0.04	0.19	0.00	0.05	0.29
	1.25g	0.01	0.05	0.69	0.00	0.09	0.48	0.01	0.10	0.36
Case B	0.25g	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
	0.60g	0.01	0.02	0.06	0.00	0.04	0.06	0.00	0.02	0.11
	1.00g	0.01	0.07	0.41	0.00	0.08	0.26	0.09	0.10	0.41
	1.25g	0.01	0.17	0.56	0.00	0.12	0.31	0.11	0.18	0.37
Case C	0.25g	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
	0.60g	0.01	0.03	0.08	0.00	0.01	0.06	0.00	0.02	0.07
	1.00g	0.01	0.15	0.34	0.00	0.04	0.20	0.04	0.12	0.12
	1.25g	0.01	0.18	0.38	0.01	0.05	0.29	0.17	0.16	0.32
Case D	0.25g	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
	0.60g	0.01	0.02	0.04	0.00	0.01	0.03	0.00	0.01	0.03
	1.00g	0.01	0.07	0.26	0.00	0.03	0.14	0.01	0.08	0.15
	1.25g	0.01	0.09	0.32	0.00	0.04	0.21	0.15	0.21	0.32
Case E	0.25g	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
	0.60g	0.01	0.07	0.19	0.00	0.04	0.07	0.00	0.02	0.07
	1.00g	0.01	0.16	0.34	0.00	0.08	0.22	0.03	0.09	0.21
	1.25g	0.01	0.29	0.39	0.00	0.09	0.45	0.06	0.14	0.59

Table V.13: Peak Cask Bottom Displacements (m), Cylindrical Cask, NUREG/CR-0098 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.007	0.001	0.001	0.003	0.000	0.001	0.004	0.001	0.001
	0.60g	0.105	0.231	0.179	0.090	0.162	0.219	0.103	1.137	0.101
	1.00g	0.288	1.337	1.325	0.357	0.706	1.556	0.363	0.701	0.286
	1.10g	---	1.092	---	---	---	---	---	---	0.326
	1.25g	0.460	Tips	1.577	0.515	0.596	0.540	0.530	0.908	Tips
Case 2	0.25g	0.007	0.001	0.001	0.004	0.000	0.001	0.005	0.001	0.002
	0.60g	0.085	0.049	0.051	0.101	0.063	0.061	0.101	0.129	0.234
	0.80g	---	---	0.271	---	---	0.412	---	---	---
	0.90g	---	---	0.429	---	---	0.100	---	---	---
	1.00g	0.174	0.364	Tips	0.289	0.253	Tips	0.313	0.473	0.400
	1.10g	---	---	Tips	---	---	0.68*	---	---	1.126
	1.25g	0.266	1.272	Tips	0.415	0.454	1.072*	0.512	0.880	Tips
Case 3	0.25g	0.011	0.001	0.001	0.003	0.000	0.001	0.005	0.001	0.002
	0.60g	0.084	0.141	0.035	0.037	0.121	0.118	0.057	0.119	0.162
	1.00g	0.162	0.316	0.211	0.164	0.236	0.524	0.160	0.755	0.479
	1.10g	---	---	1.491	---	---	---	---	---	---
	1.25g	0.272	1.241	Tips	0.299	0.590	0.560	0.273	1.307	1.029
Case 4	0.25g	0.007	0.000	0.000	0.002	0.000	0.000	0.002	0.001	0.001
	0.60g	0.073	0.027	0.029	0.047	0.008	0.051	0.054	0.082	0.064
	1.00g	0.228	0.687	0.519	0.204	0.130	0.550	0.193	0.364	0.333
	1.25g	0.304	0.727	0.552	0.300	0.337	0.471	0.320	0.731	0.350
Case 5	0.25g	0.012	0.000	0.001	0.005	0.001	0.001	0.005	0.001	0.002
	0.60g	0.064	0.058	0.151	0.063	0.048	0.185	0.101	0.338	0.226
	1.00g	0.178	0.379	0.123	0.162	0.385	1.053	0.162	1.192	0.119
	1.10g	---	---	---	---	---	Tips	---	---	---
	1.25g	0.291	0.406	1.009	0.237	0.984	Tips	0.241	0.535	1.290

Table V.14: Peak Cask Bottom Displacements (m), Cylindrical Cask, Regulatory Guide 1.60 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.033	0.003	0.002	0.009	0.000	0.000	0.011	0.001	0.003
	0.40g	0.115	0.194	0.151	0.100	0.084	0.172	0.108	0.247	0.263
	0.50g	0.210	0.710	0.657	0.225	0.903	0.729	0.239	0.309	0.933
	0.55g	---	---	1.007	---	---	1.046	---	---	---
	0.60g	0.356	1.581	Tips	0.397	0.982	Tips	0.409	1.531	1.064
	0.80g	---	Tips	1.08*	---	0.292	0.610*	---	0.653	1.004
	1.00g	1.108	Tips	Tips	1.161	Tips	Tips	1.150	Tips	Tips
Case 2	0.25g	0.039	0.014	0.007	0.026	0.001	0.001	0.026	0.004	0.003
	0.40g	0.103	0.039	0.073	0.112	0.039	0.151	0.113	0.039	0.025
	0.50g	0.120	0.232	0.050	0.187	0.229	0.114	0.199	0.126	0.102
	0.60g	0.161	0.189	0.931	0.269	0.241	0.805	0.264	0.317	0.346
	0.80g	---	Tips	0.392	---	1.462	Tips	---	Tips	---
	1.00g	0.406	Tips	Tips	0.488	Tips	Tips	0.567	Tips	0.845
Case 3	0.25g	0.040	0.004	0.003	0.012	0.001	0.001	0.011	0.003	0.003
	0.40g	0.092	0.033	0.026	0.031	0.117	0.162	0.059	0.050	0.281
	0.50g	0.128	0.441	0.373	0.065	0.404	0.261	0.114	0.097	0.375
	0.60g	0.165	0.444	1.315	0.144	1.088	0.645	0.185	0.574	0.842
	0.80g	---	0.717	Tips	---	0.816	0.589	---	Tips	1.307
	1.00g	0.757	Tips	Tips	0.712	Tips	Tips	0.728	Tips	Tips
Case 4	0.25g	0.118	0.138	0.148	0.013	0.000	0.001	0.016	0.003	0.003
	0.40g	0.264	0.342	0.335	0.076	0.054	0.152	0.091	0.017	0.340
	0.50g	0.348	0.285	0.513	0.163	0.171	0.085	0.186	0.199	0.191
	0.60g	0.427	0.394	0.719	0.291	0.096	0.389	0.319	0.172	0.411
	0.80g	---	---	2.285	---	0.870	Tips	---	---	0.378
	1.00g	1.166	0.961	Tips	0.716	Tips	Tips	0.802	0.640	Tips
Case 5	0.25g	0.031	0.002	0.002	0.018	0.001	0.001	0.019	0.002	0.002
	0.40g	0.084	0.139	0.113	0.073	0.234	0.117	0.100	0.242	0.187
	0.50g	0.138	0.298	0.096	0.119	0.408	0.388	0.138	0.197	0.219
	0.60g	0.198	0.352	0.161	0.177	0.455	0.228	0.190	0.230	0.717
	0.80g	---	Tips	Tips	---	Tips	Tips	---	0.638	Tips
	1.00g	0.764	Tips	Tips	0.558	Tips	Tips	0.587	Tips	Tips

Table V.15: Peak Cask Bottom Displacements (m), Cylindrical Cask, NUREG/CR-6728 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case A	0.25g	0.018	0.001	0.001	0.005	0.001	0.001	0.006	0.004	0.002
	0.60g	0.037	0.031	0.032	0.038	0.029	0.018	0.036	0.043	0.071
	1.00g	0.111	0.152	0.082	0.122	0.246	0.205	0.124	0.203	0.095
	1.25g	0.189	0.180	0.112	0.177	0.149	0.129	0.185	0.160	0.136
Case B	0.25g	0.008	0.001	0.001	0.004	0.001	0.001	0.004	0.006	0.003
	0.60g	0.049	0.054	0.067	0.029	0.018	0.079	0.026	0.019	0.037
	1.00g	0.095	0.151	0.201	0.072	0.219	0.146	0.072	0.100	0.161
	1.25g	0.140	0.110	0.263	0.096	0.181	0.183	0.096	0.145	0.156
Case C	0.25g	0.013	0.001	0.001	0.005	0.001	0.001	0.007	0.003	0.006
	0.60g	0.072	0.068	0.025	0.026	0.039	0.015	0.025	0.016	0.044
	1.00g	0.113	0.154	0.133	0.087	0.243	0.098	0.077	0.067	0.128
	1.25g	0.142	0.131	0.206	0.127	0.208	0.332	0.114	0.351	0.164
Case D	0.25g	0.011	0.001	0.001	0.004	0.000	0.000	0.003	0.001	0.001
	0.60g	0.026	0.019	0.018	0.034	0.017	0.023	0.024	0.015	0.023
	1.00g	0.071	0.122	0.094	0.095	0.047	0.161	0.047	0.079	0.069
	1.25g	0.099	0.106	0.127	0.156	0.085	0.178	0.073	0.110	0.168
Case E	0.25g	0.016	0.001	0.001	0.004	0.002	0.002	0.004	0.003	0.003
	0.60g	0.061	0.030	0.030	0.031	0.051	0.022	0.034	0.056	0.060
	1.00g	0.140	0.081	0.048	0.088	0.100	0.056	0.100	0.143	0.043
	1.25g	0.173	0.124	0.060	0.147	0.229	0.159	0.149	0.103	0.223

Table V.16: Peak Cask Bottom Displacements (m), Rectangular Module, NUREG/CR-0098 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.004	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000
	0.60g	0.113	0.010	0.001	0.094	0.001	0.000	0.108	0.004	0.001
	1.00g	0.299	0.085	0.019	0.362	0.034	0.019	0.355	0.079	0.015
	1.25g	0.474	0.165	0.057	0.513	0.116	0.031	0.524	0.169	0.041
Case 2	0.25g	0.008	0.000	0.000	0.002	0.000	0.000	0.001	0.000	0.000
	0.60g	0.086	0.014	0.000	0.103	0.007	0.003	0.102	0.006	0.001
	1.00g	0.187	0.133	0.037	0.274	0.093	0.026	0.300	0.071	0.024
	1.25g	0.295	0.217	0.046	0.414	0.186	0.031	0.467	0.135	0.041
Case 3	0.25g	0.004	0.000	0.000	0.002	0.000	0.000	0.003	0.000	0.000
	0.60g	0.091	0.010	0.002	0.031	0.003	0.000	0.061	0.007	0.001
	1.00g	0.176	0.129	0.038	0.146	0.024	0.008	0.178	0.042	0.018
	1.25g	0.251	0.215	0.034	0.278	0.057	0.025	0.281	0.088	0.037
Case 4	0.25g	0.004	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000
	0.60g	0.066	0.008	0.000	0.046	0.001	0.000	0.056	0.005	0.001
	1.00g	0.236	0.083	0.033	0.211	0.044	0.037	0.215	0.068	0.057
	1.25g	0.319	0.116	0.026	0.314	0.109	0.071	0.314	0.154	0.060
Case 5	0.25g	0.007	0.000	0.000	0.003	0.000	0.000	0.003	0.000	0.000
	0.60g	0.060	0.016	0.002	0.062	0.006	0.001	0.095	0.005	0.002
	1.00g	0.163	0.085	0.047	0.160	0.080	0.018	0.164	0.077	0.024
	1.25g	0.270	0.113	0.087	0.234	0.141	0.042	0.243	0.177	0.042

Table V.17: Peak Cask Bottom Displacements (m), Rectangular Module, Regulatory Guide 1.60 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case 1	0.25g	0.032	0.000	0.000	0.006	0.000	0.000	0.009	0.000	0.000
	0.60g	0.359	0.074	0.045	0.393	0.030	0.007	0.411	0.048	0.007
	1.00g	1.123	0.223	0.073	1.114	0.226	0.097	1.134	0.202	0.069
	1.25g	1.705	0.410	0.188	1.696	0.456	0.280	1.679	0.388	0.256
Case 2	0.25g	0.038	0.000	0.000	0.023	0.000	0.000	0.020	0.000	0.000
	0.60g	0.167	0.092	0.024	0.249	0.052	0.018	0.261	0.042	0.015
	1.00g	0.470	0.292	0.096	0.541	0.306	0.063	0.523	0.245	0.089
	1.25g	0.712	0.361	0.181	0.615	0.441	0.174	0.576	0.404	0.173
Case 3	0.25g	0.021	0.000	0.000	0.006	0.000	0.000	0.009	0.000	0.000
	0.60g	0.169	0.080	0.015	0.141	0.013	0.008	0.194	0.019	0.003
	1.00g	0.702	0.243	0.073	0.749	0.125	0.063	0.816	0.159	0.075
	1.25g	1.105	0.308	0.192	1.091	0.287	0.135	1.169	0.319	0.144
Case 4	0.25g	0.130	0.067	0.008	0.009	0.000	0.000	0.011	0.000	0.000
	0.60g	0.411	0.252	0.124	0.291	0.037	0.016	0.312	0.049	0.017
	1.00g	0.978	0.407	0.091	0.767	0.295	0.144	0.832	0.228	0.076
	1.25g	1.462	0.589	0.195	0.835	0.416	0.090	1.142	0.566	0.301
Case 5	0.25g	0.024	0.000	0.000	0.016	0.000	0.000	0.014	0.000	0.000
	0.60g	0.182	0.060	0.036	0.170	0.048	0.007	0.184	0.040	0.003
	1.00g	0.728	0.184	0.142	0.554	0.171	0.147	0.595	0.259	0.107
	1.25g	1.245	0.309	0.219	1.428	0.255	0.202	1.092	0.322	0.151

Table V.18: Peak Cask Bottom Displacements (m), Rectangular Module, NUREG/CR-6728 Earthquakes

		Soft Soil			Stiff Soil			Rock		
		μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8	μ=0.2	μ=0.55	μ=0.8
Case A	0.25g	0.006	0.000	0.000	0.002	0.000	0.000	0.004	0.000	0.000
	0.60g	0.030	0.013	0.001	0.039	0.004	0.001	0.046	0.008	0.002
	1.00g	0.100	0.072	0.038	0.120	0.030	0.009	0.138	0.038	0.025
	1.25g	0.175	0.106	0.034	0.177	0.051	0.015	0.201	0.061	0.021
Case B	0.25g	0.003	0.000	0.000	0.004	0.000	0.000	0.006	0.001	0.000
	0.60g	0.036	0.006	0.001	0.023	0.012	0.003	0.027	0.014	0.007
	1.00g	0.101	0.026	0.026	0.072	0.045	0.016	0.070	0.047	0.018
	1.25g	0.133	0.066	0.038	0.100	0.049	0.049	0.092	0.035	0.030
Case C	0.25g	0.004	0.000	0.000	0.003	0.000	0.000	0.004	0.001	0.000
	0.60g	0.065	0.008	0.001	0.024	0.007	0.002	0.031	0.015	0.006
	1.00g	0.129	0.053	0.015	0.069	0.047	0.014	0.088	0.025	0.025
	1.25g	0.151	0.087	0.033	0.110	0.056	0.019	0.101	0.069	0.043
Case D	0.25g	0.004	0.000	0.000	0.002	0.000	0.000	0.002	0.001	0.000
	0.60g	0.038	0.008	0.002	0.025	0.005	0.004	0.022	0.004	0.003
	1.00g	0.092	0.055	0.012	0.087	0.035	0.025	0.080	0.017	0.017
	1.25g	0.114	0.057	0.031	0.149	0.060	0.043	0.257	0.062	0.035
Case E	0.25g	0.009	0.000	0.000	0.003	0.000	0.000	0.003	0.001	0.000
	0.60g	0.051	0.016	0.005	0.033	0.010	0.002	0.042	0.012	0.008
	1.00g	0.135	0.061	0.026	0.089	0.032	0.017	0.078	0.018	0.018
	1.25g	0.186	0.106	0.033	0.143	0.056	0.039	0.154	0.056	0.014

V.2 Graphical Presentation of Results

Graphical plots of a subset of the data presented in Section V.1 are provided in this section to aid in understanding the results. Plots are provided for the peak cask top displacement and peak cask rotation. These two parameters are the most important for evaluating cask designs. A number of sets are grouped into each of the figures shown here. Each plot shows either the peak top displacement or rotation of a given cask design subjected to all of the earthquakes conforming to a given spectral shape. A separate line is shown for a set of results where everything is kept equal except for the magnitude of the ground motion. In each figure, there are 15 lines to represent the analysis results for the five ground motion records and three friction coefficients.

For the cylindrical cask, which tips over in some cases, there is a dilemma of how to plot the results for the cases that overturn. There is no meaningful value for the peak rotation or top displacement in these cases, so the approach taken here is to assign very high values for these cases, so that if a cask tips over in a series of analyses, the line representing that series extends vertically from the highest point before tipping over occurs. This provides a visual representation of these results, which is important because omitting them could be potentially misleading. In a few cases, the cask overturns at one level of PGA but then does not overturn with a higher PGA. In these cases, the vertical line comes back down to the data point at the higher ground motion level.

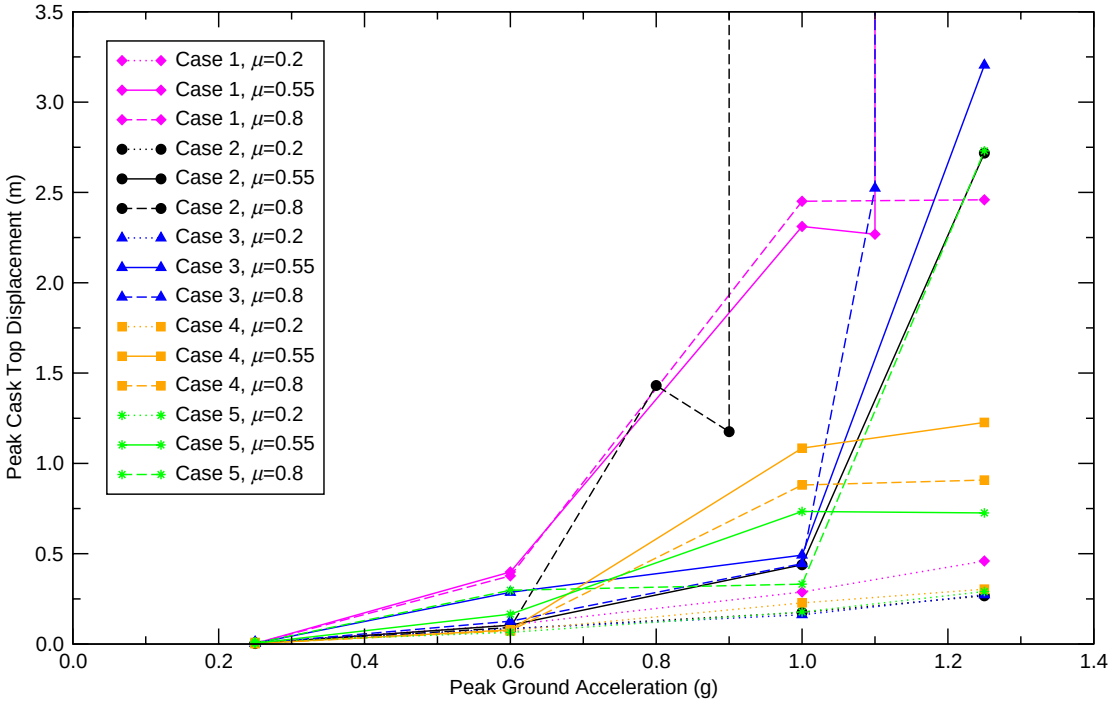

Figure V.1: Peak Cask Top Displacements, Cylindrical Cask, Soft Soil, NUREG/CR-0098 Earthquakes

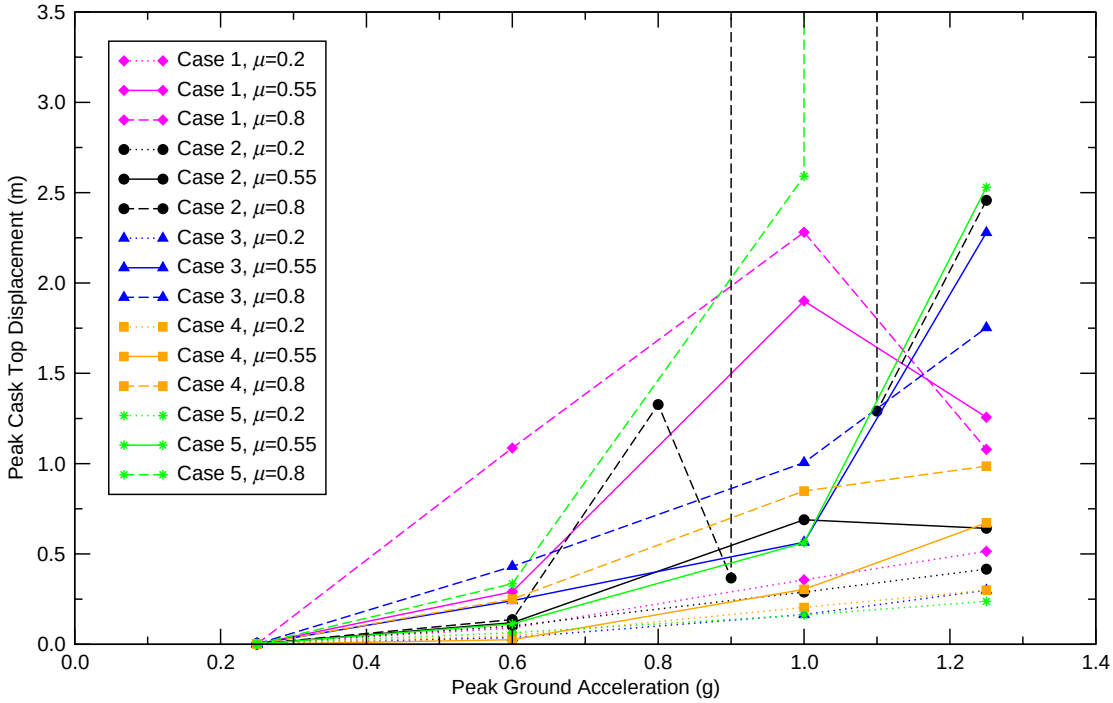

Figure V.2: Peak Cask Top Displacements, Cylindrical Cask, Stiff Soil, NUREG/CR-0098 Earthquakes

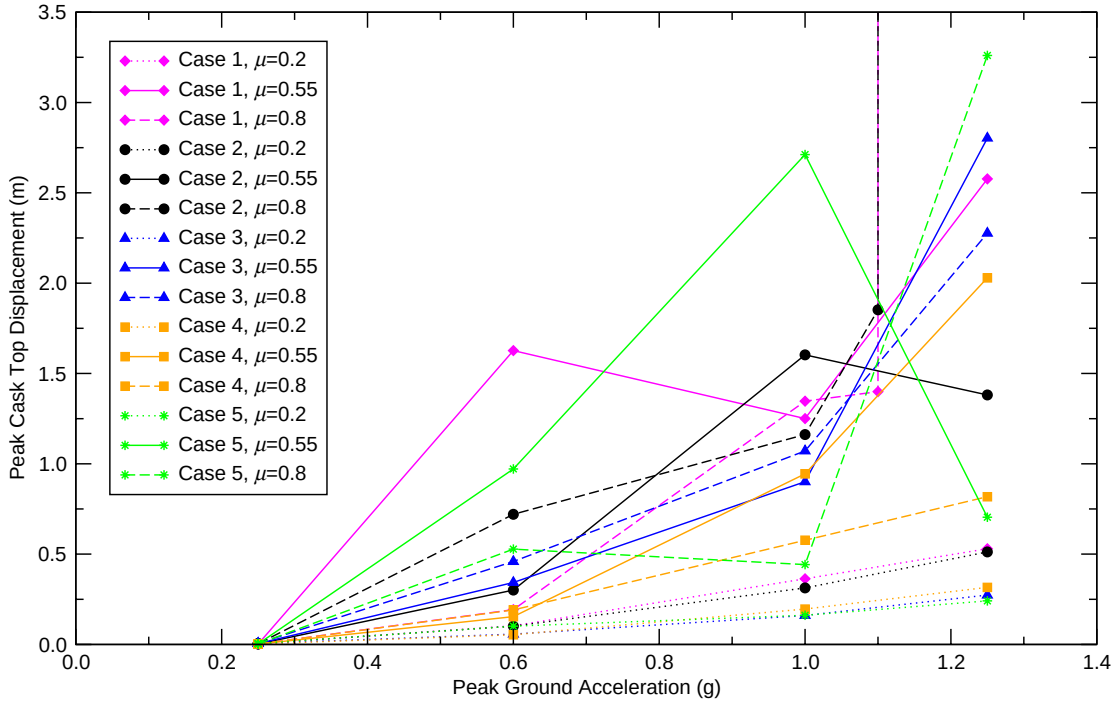

Figure V.3: Peak Cask Top Displacements, Cylindrical Cask, Rock, NUREG/CR-0098 Earthquakes

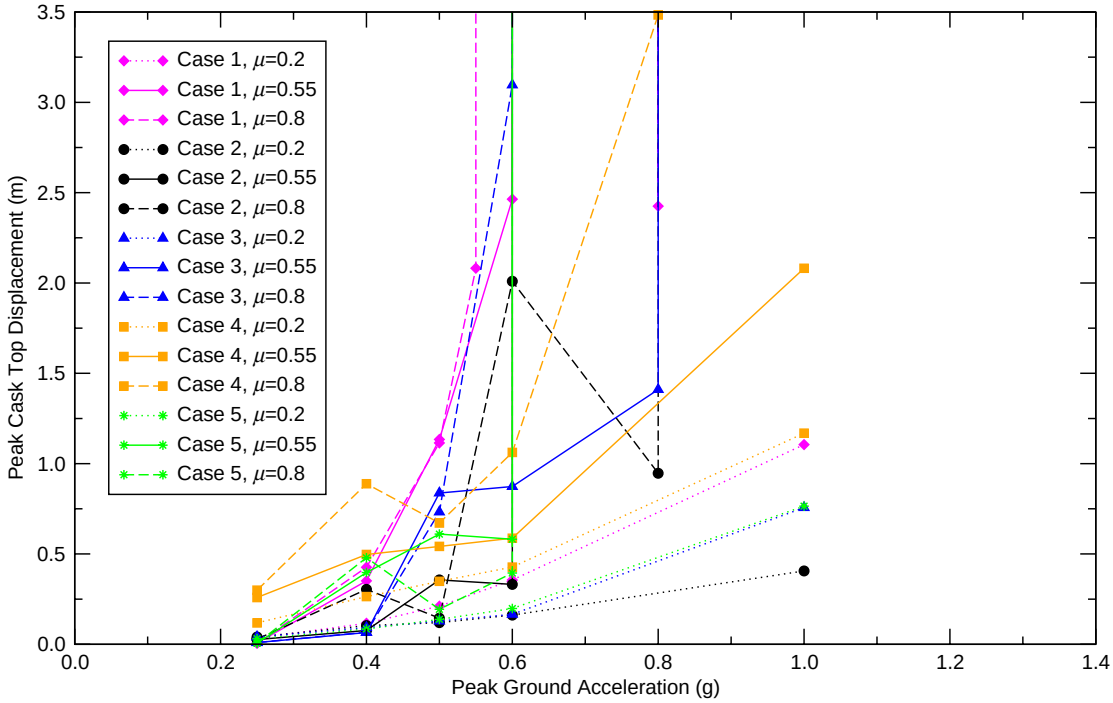

Figure V.4: Peak Cask Top Displacements, Cylindrical Cask, Soft Soil, Regulatory Guide 1.60 Earthquakes

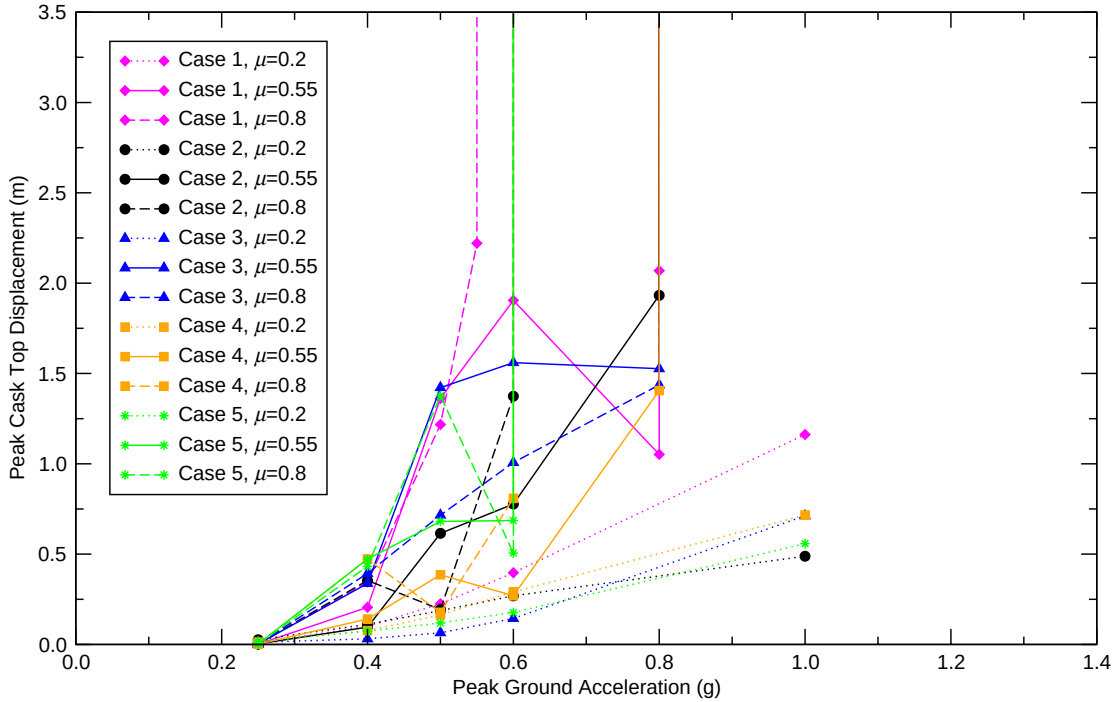

Figure V.5: Peak Cask Top Displacements, Cylindrical Cask, Stiff Soil, Regulatory Guide 1.60 Earthquakes

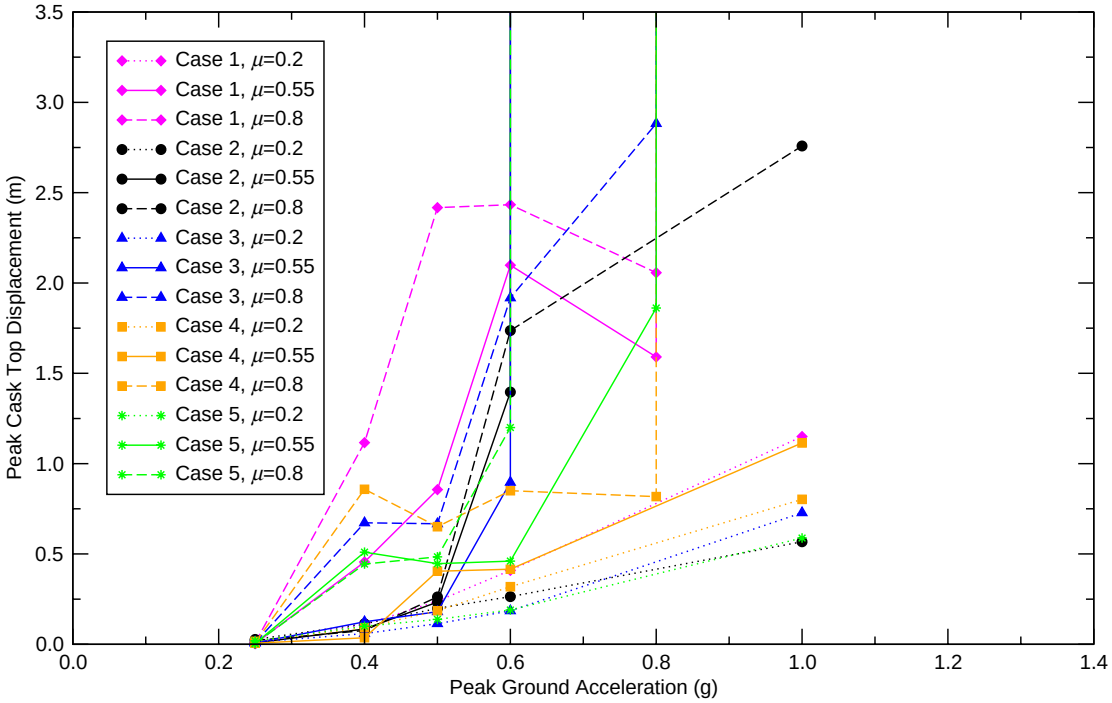

Figure V.6: Peak Cask Top Displacements, Cylindrical Cask, Rock, Regulatory Guide 1.60 Earthquakes

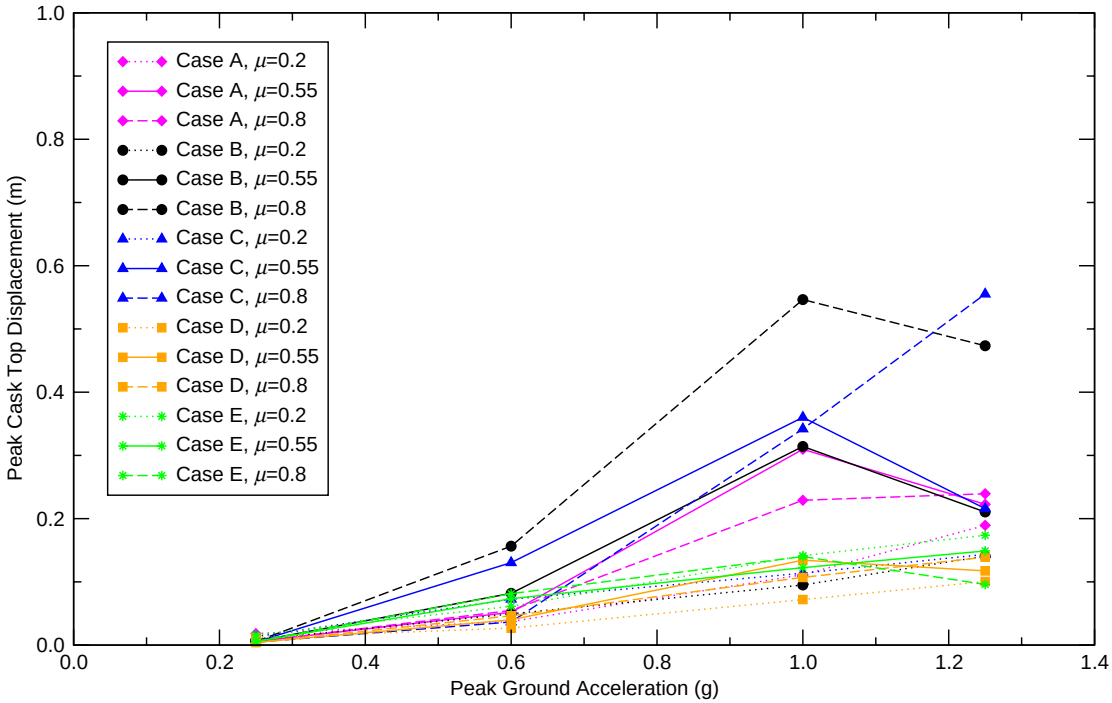

Figure V.7: Peak Cask Top Displacements, Cylindrical Cask, Soft Soil, NUREG/CR-6728 Earthquakes

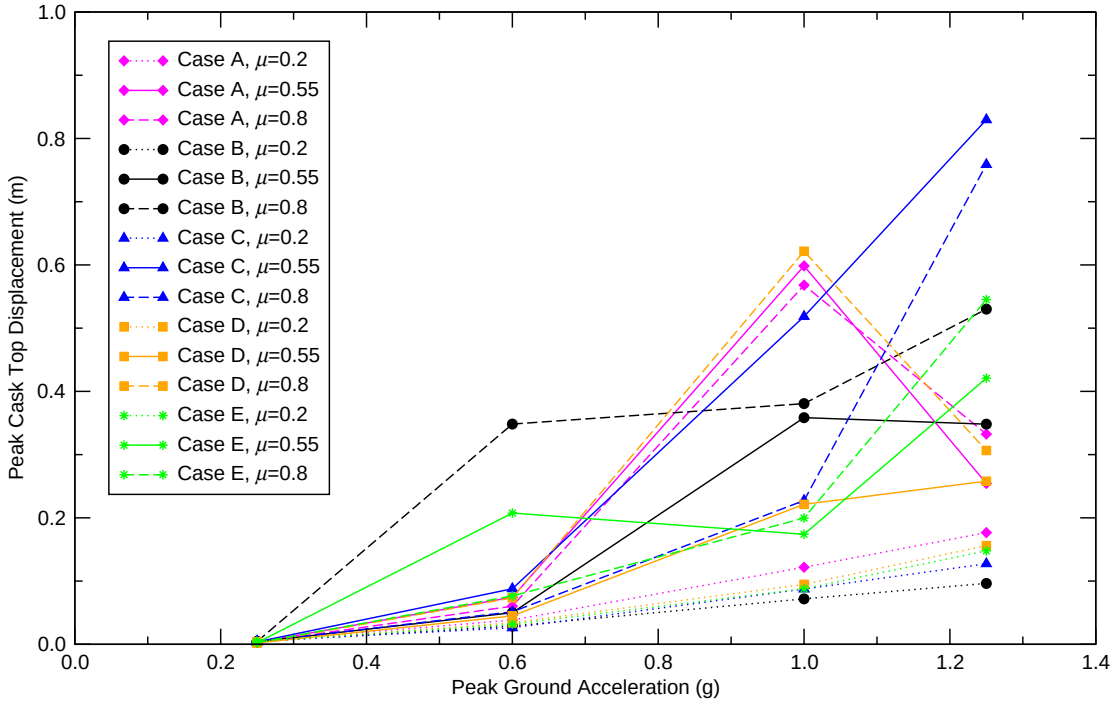

Figure V.8: Peak Cask Top Displacements, Cylindrical Cask, Stiff Soil, NUREG/CR-6728 Earthquakes

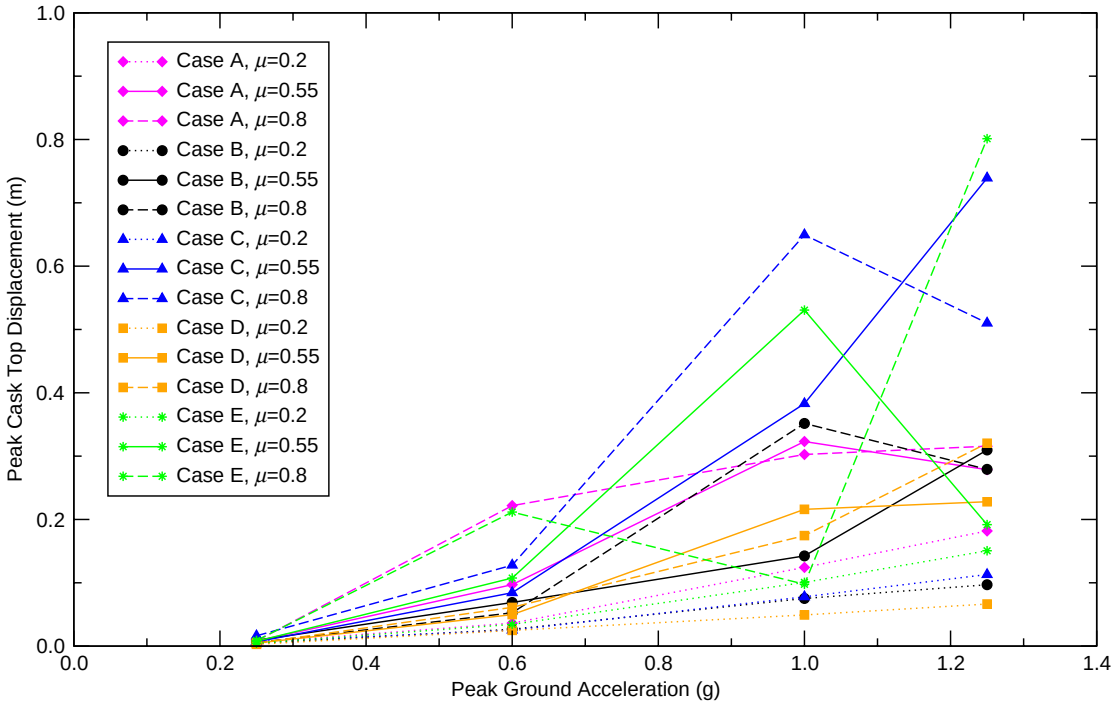

Figure V.9: Peak Cask Top Displacements, Cylindrical Cask, Rock, NUREG/CR-6728 Earthquakes

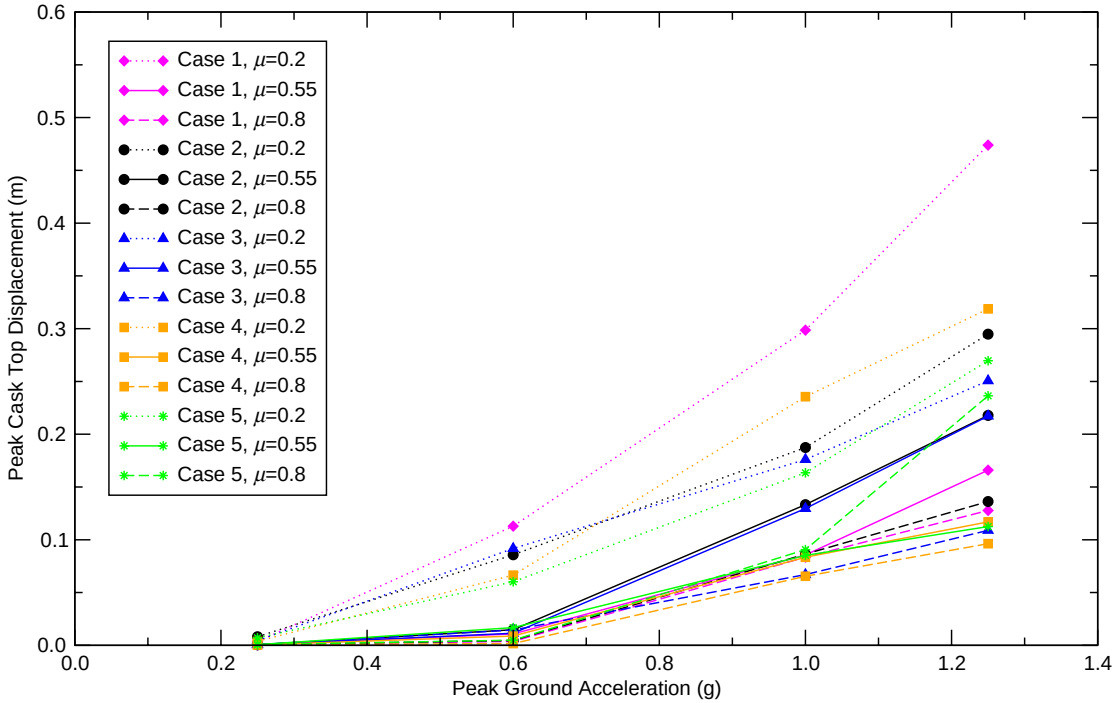

Figure V.10: Peak Cask Top Displacements, Rectangular Module, Soft Soil, NUREG/CR-0098 Earthquakes

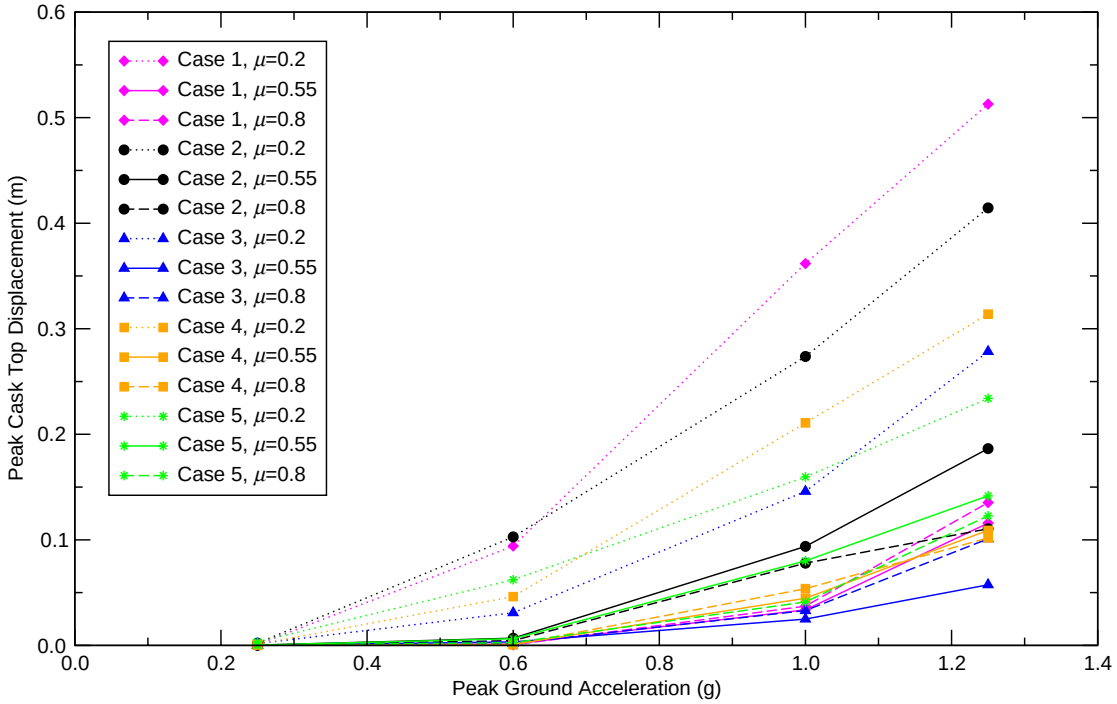

Figure V.11: Peak Cask Top Displacements, Rectangular Module, Stiff Soil, NUREG/CR-0098 Earthquakes

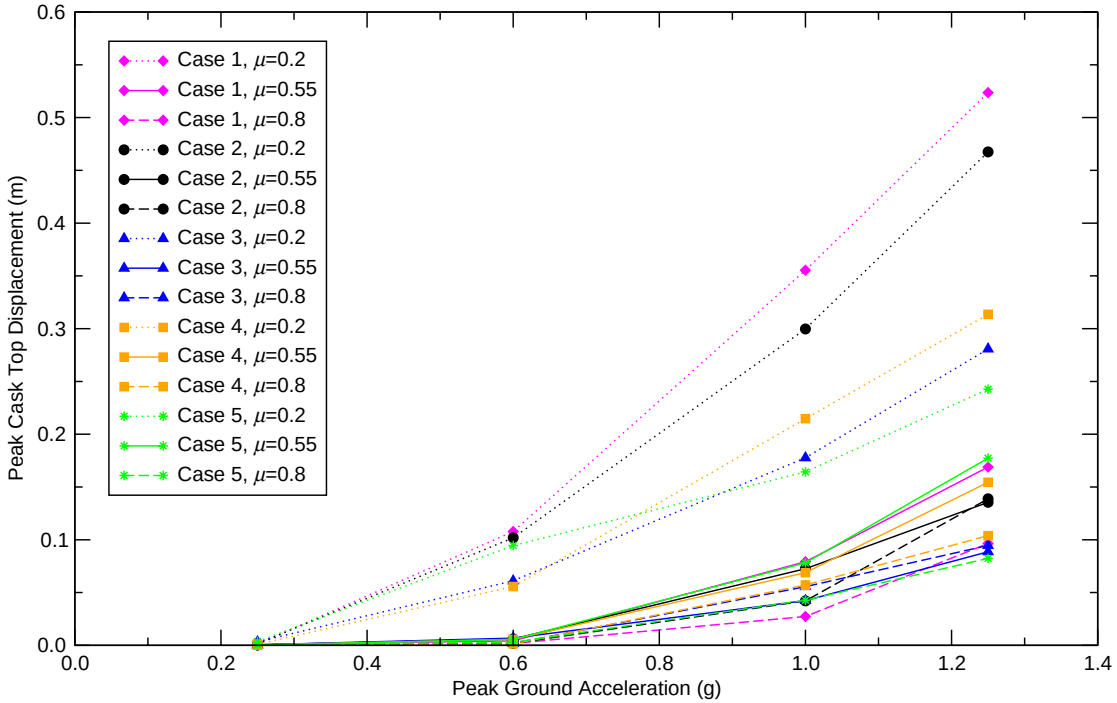

Figure V.12: Peak Cask Top Displacements, Rectangular Module, Rock, NUREG/CR-0098 Earthquakes

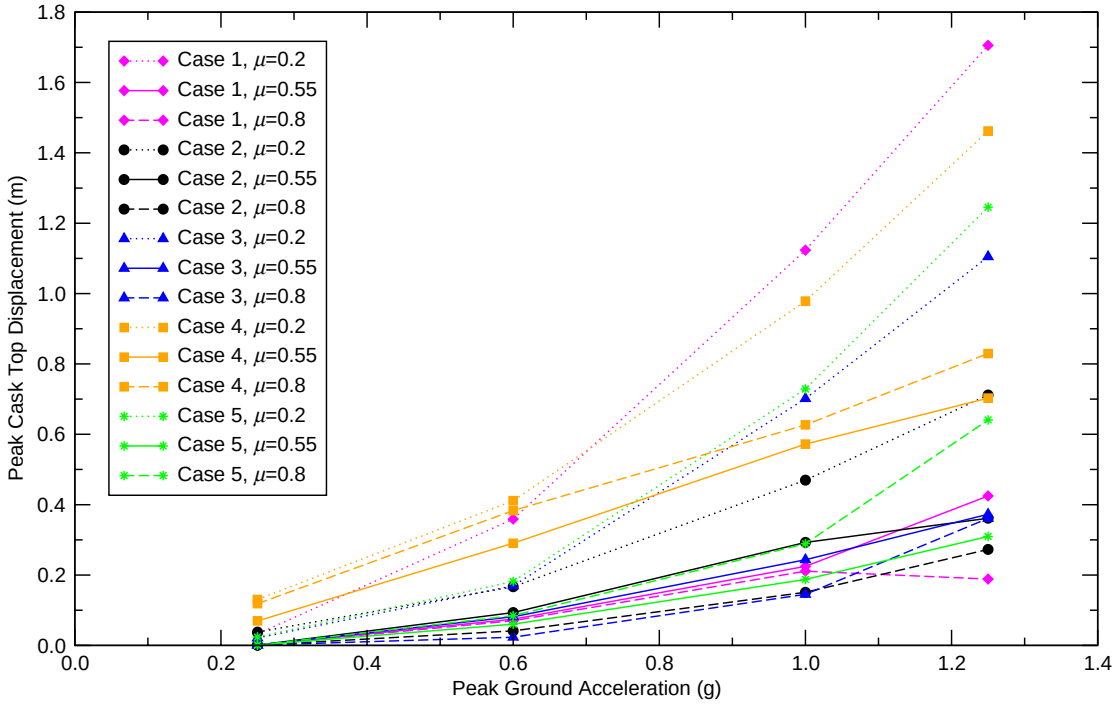

Figure V.13: Peak Cask Top Displacements, Rectangular Module, Soft Soil, Regulatory Guide 1.60 Earthquakes

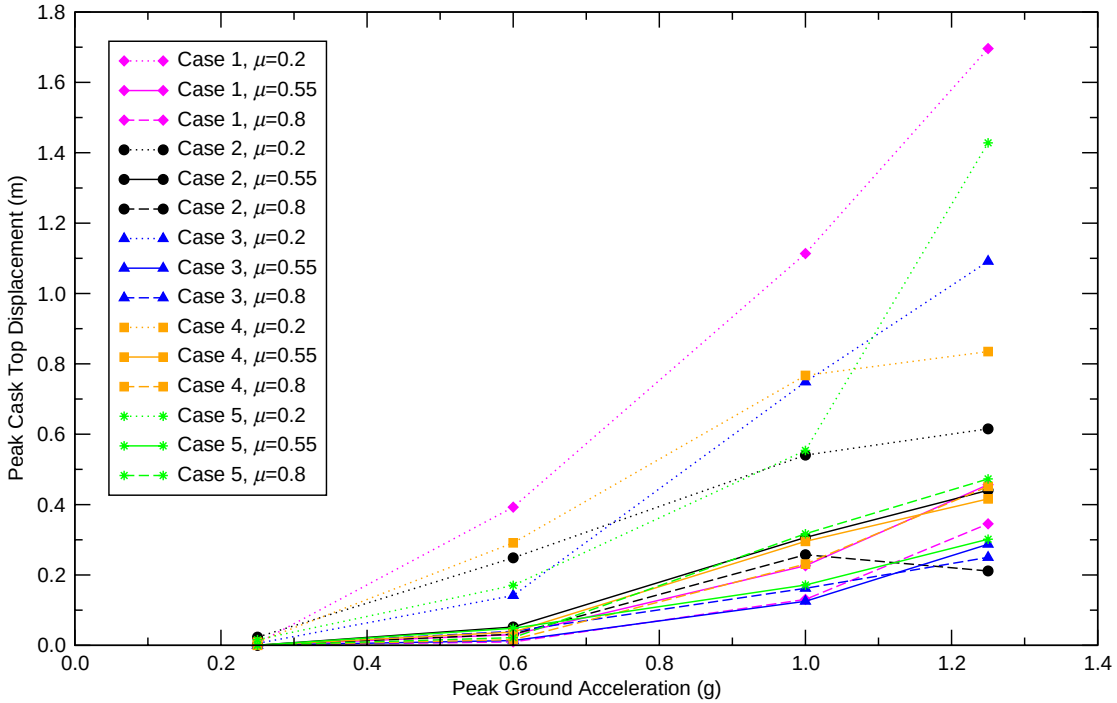

Figure V.14: Peak Cask Top Displacements, Rectangular Module, Stiff Soil, Regulatory Guide 1.60 Earthquakes

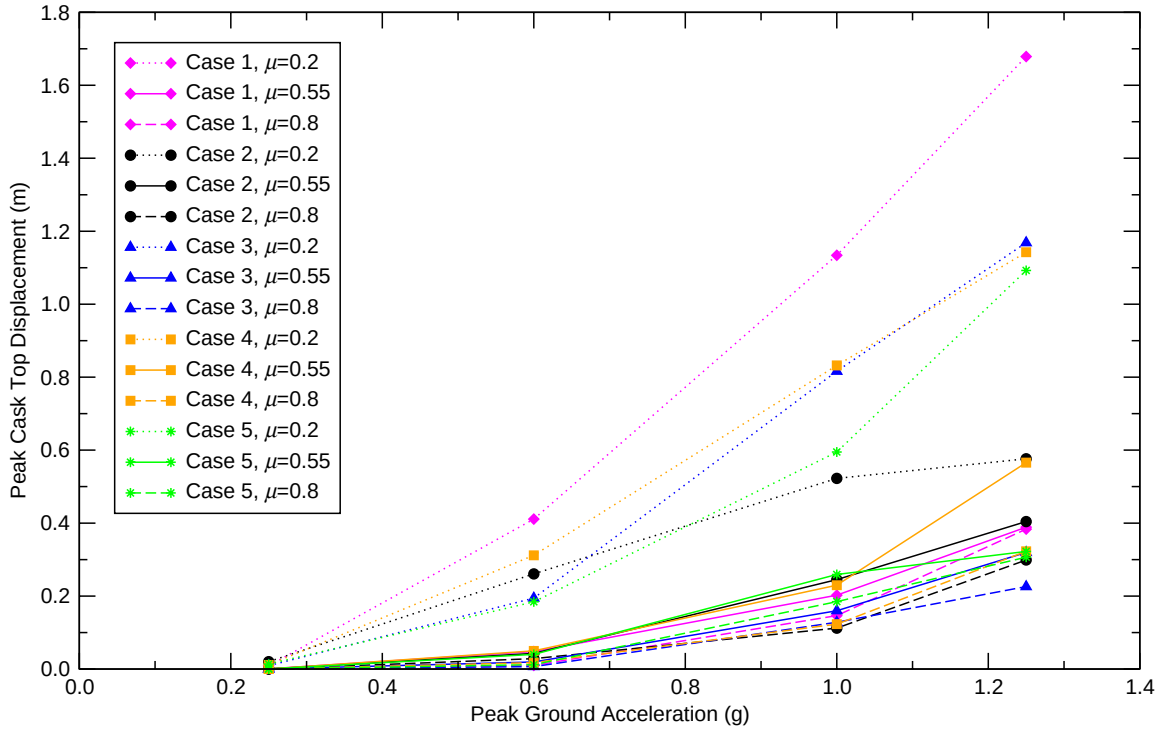

Figure V.15: Peak Cask Top Displacements, Rectangular Module, Rock, Regulatory Guide 1.60 Earthquakes

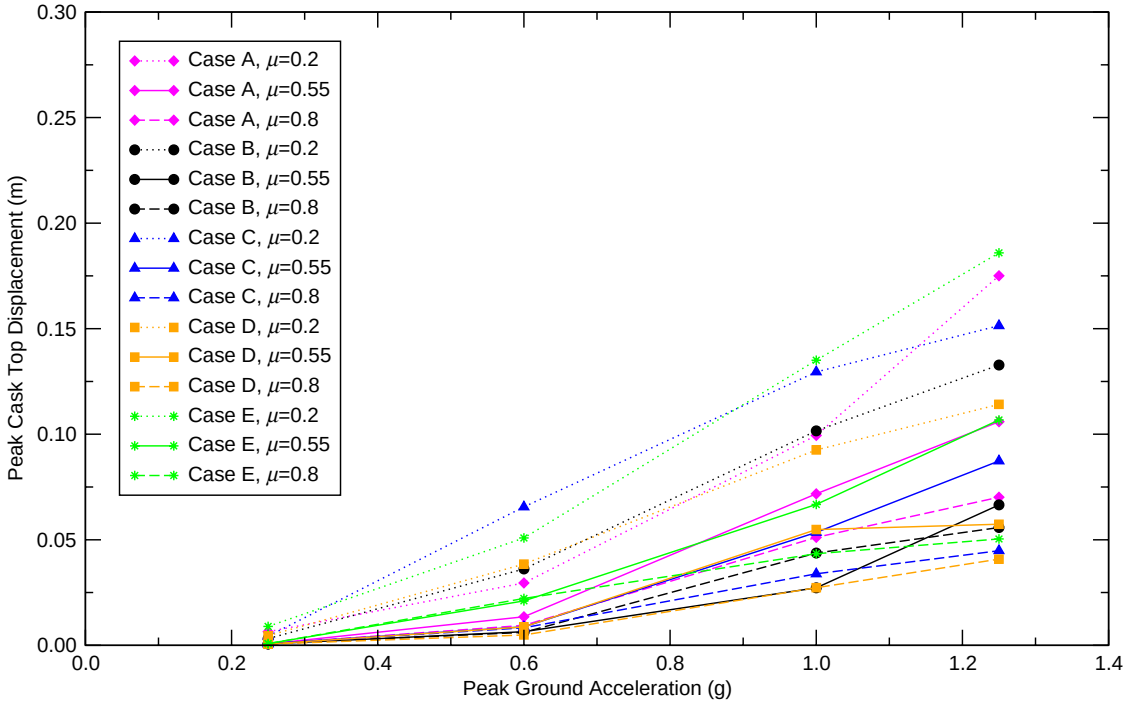

Figure V.16: Peak Cask Top Displacements, Rectangular Module, Soft Soil, NUREG/CR-6728 Earthquakes

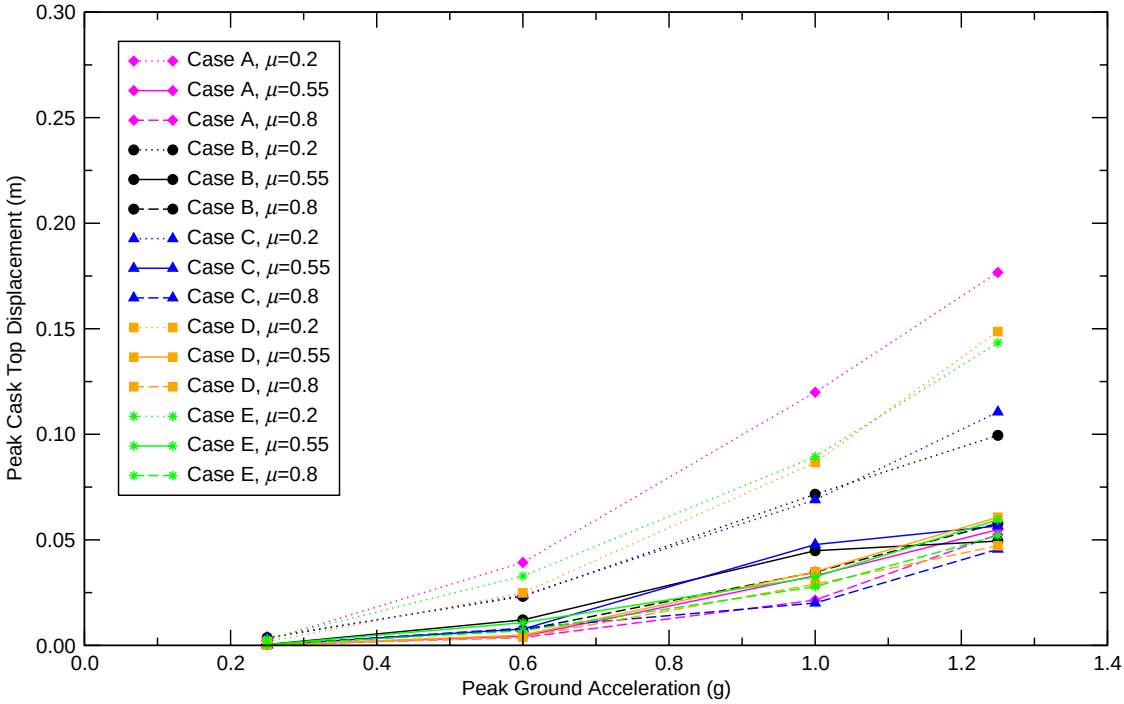

Figure V.17: Peak Cask Top Displacements, Rectangular Module, Stiff Soil, NUREG/CR-6728 Earthquakes

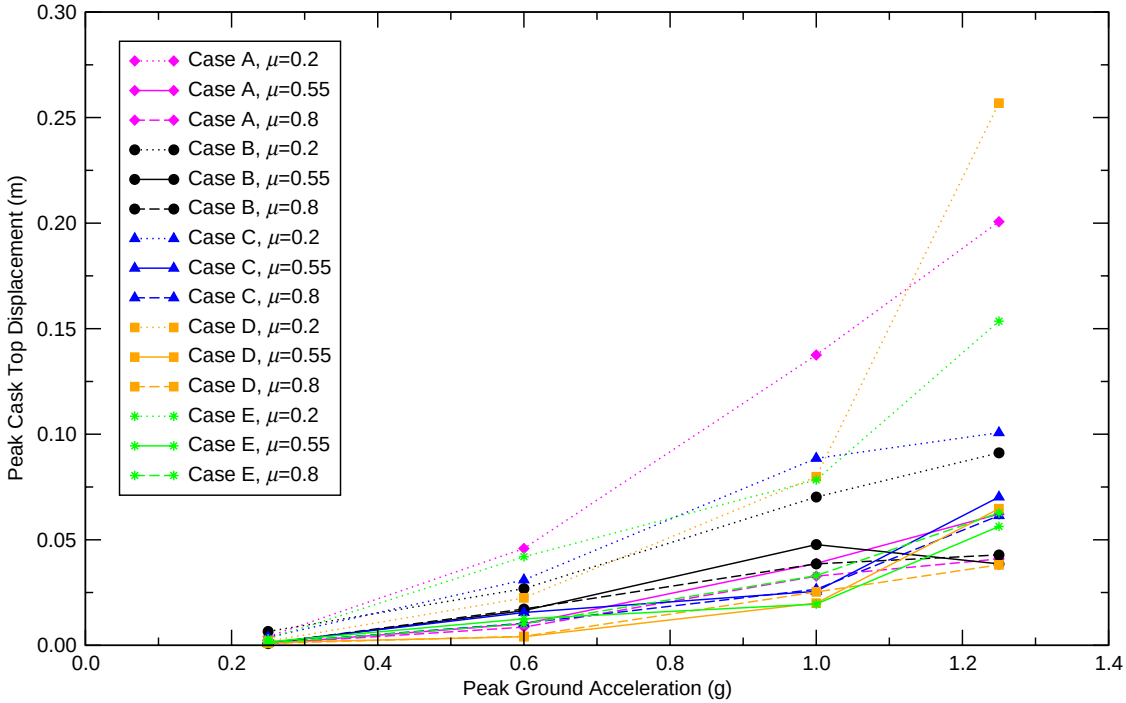

Figure V.18: Peak Cask Top Displacements, Rectangular Module, Rock, NUREG/CR-6728 Earthquakes

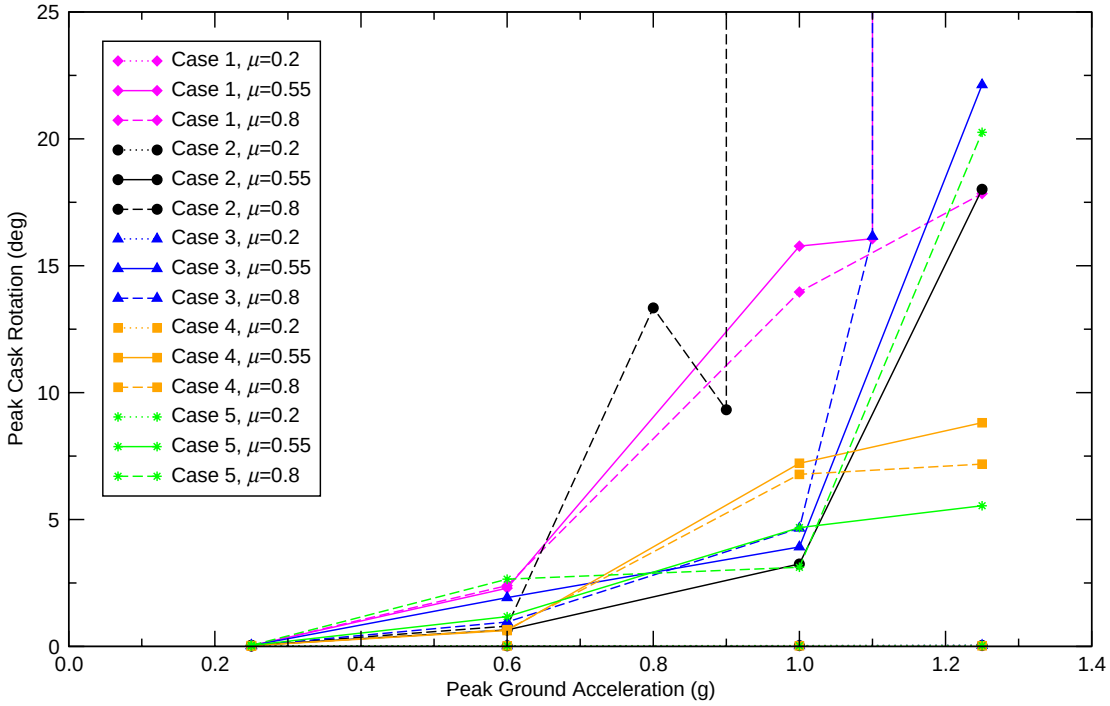

Figure V.19: Peak Cask Rotations, Cylindrical Cask, Soft Soil, NUREG/CR-0098 Earthquakes

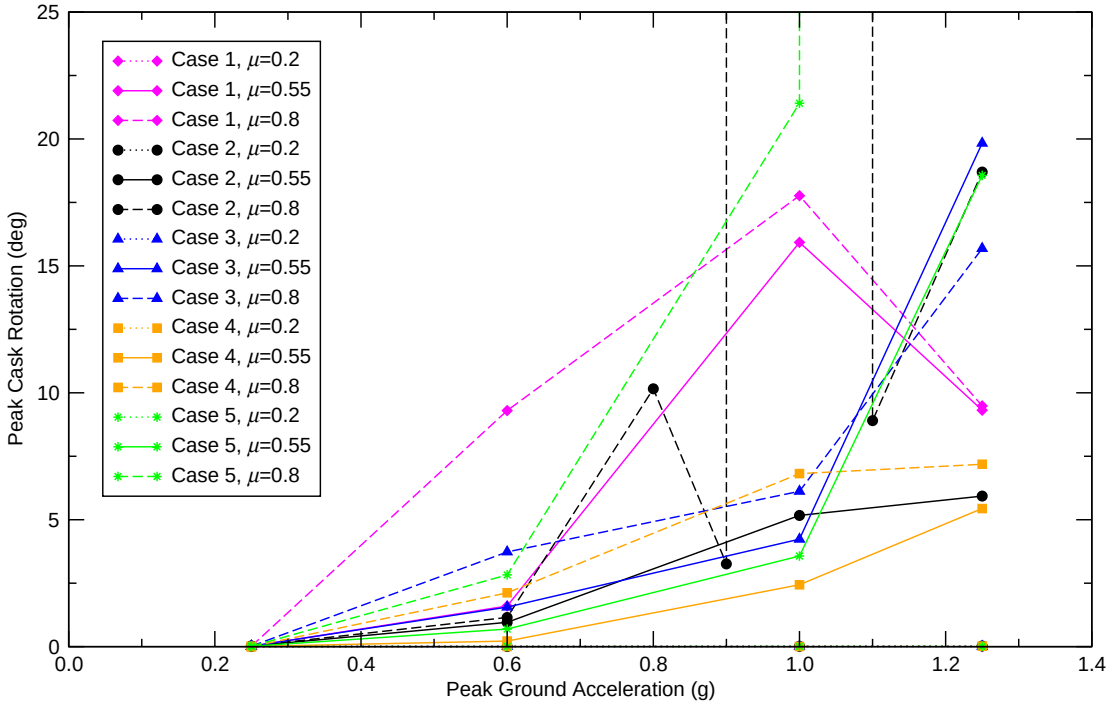

Figure V.20: Peak Cask Rotations, Cylindrical Cask, Stiff Soil, NUREG/CR-0098 Earthquakes

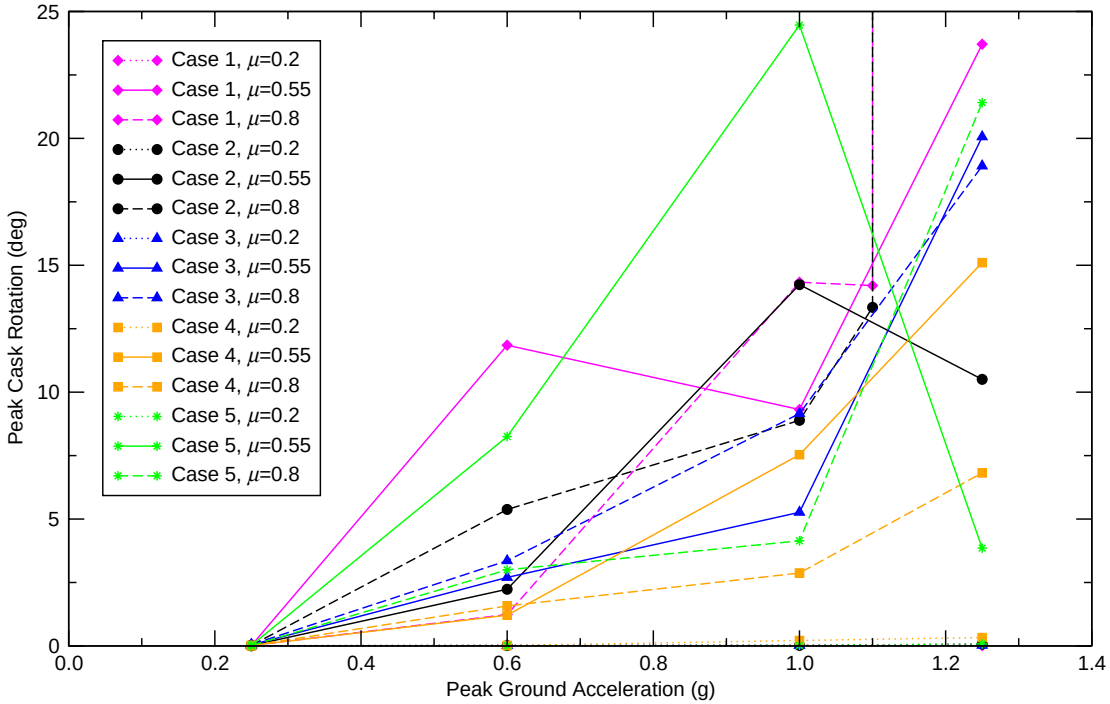

Figure V.21: Peak Cask Rotations, Cylindrical Cask, Rock, NUREG/CR-0098 Earthquakes

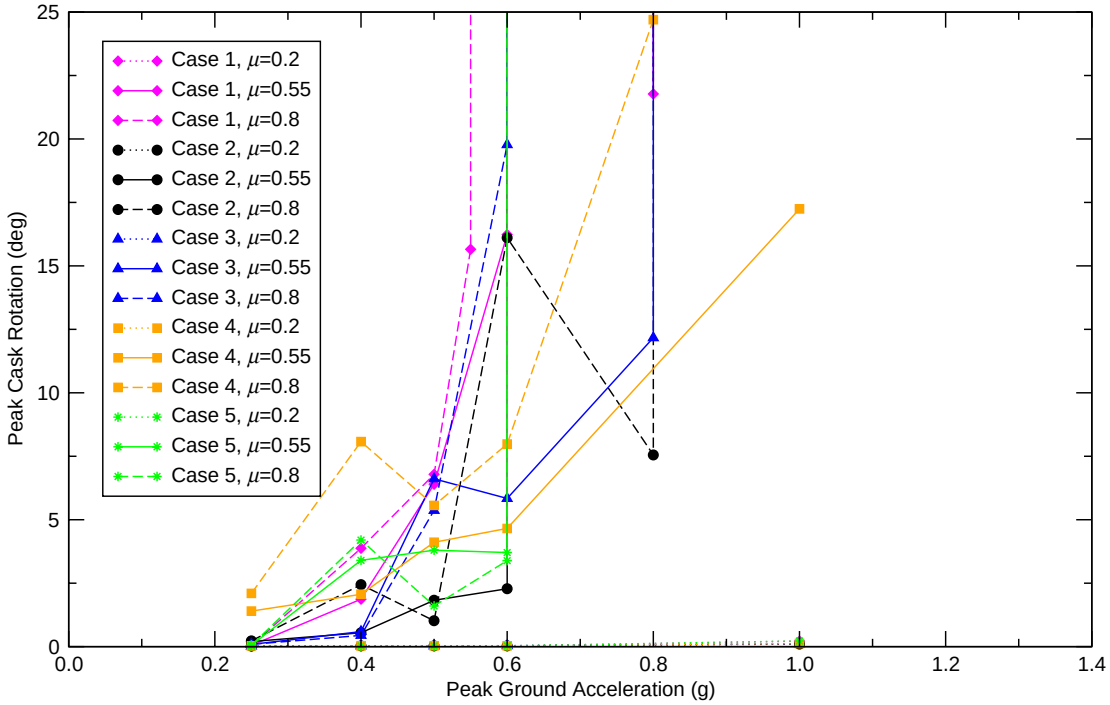

Figure V.22: Peak Cask Rotations, Cylindrical Cask, Soft Soil, Regulatory Guide 1.60 Earthquakes

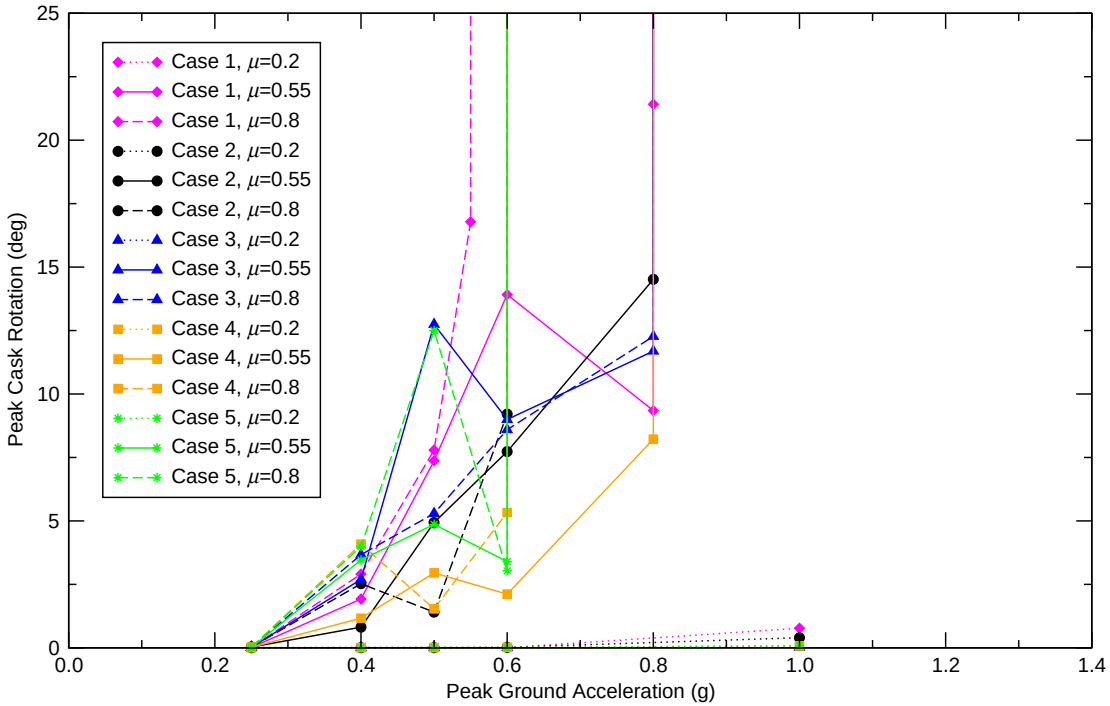

Figure V.23: Peak Cask Rotations, Cylindrical Cask, Stiff Soil, Regulatory Guide 1.60 Earthquakes

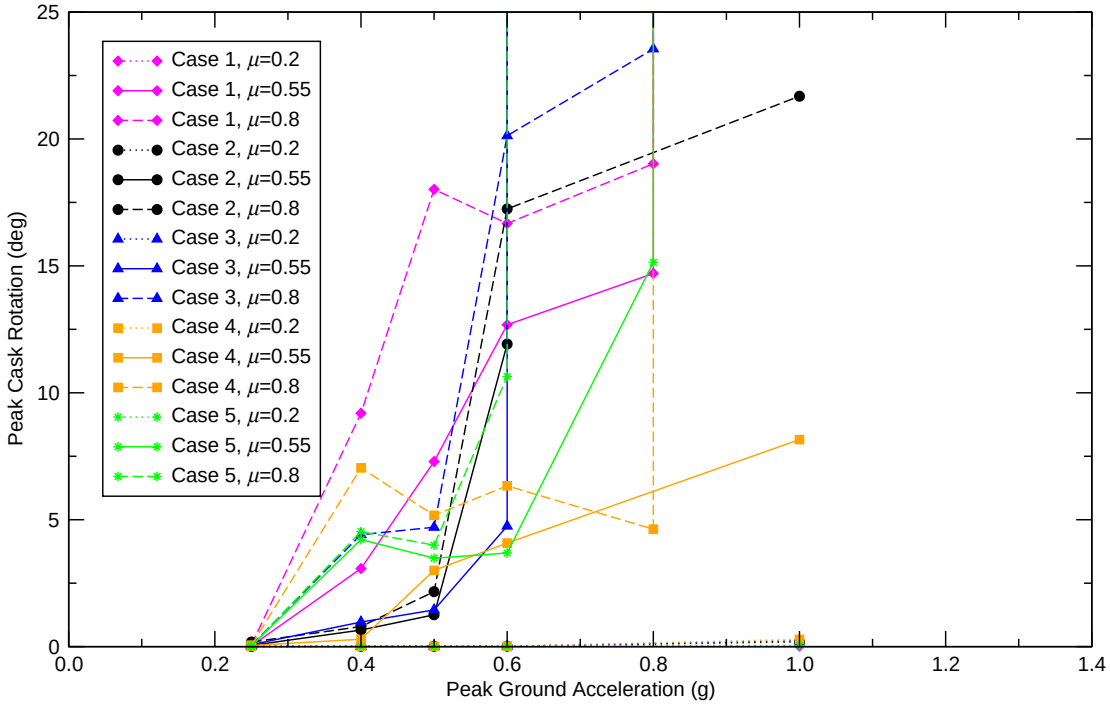

Figure V.24: Peak Cask Rotations, Cylindrical Cask, Rock, Regulatory Guide 1.60 Earthquakes

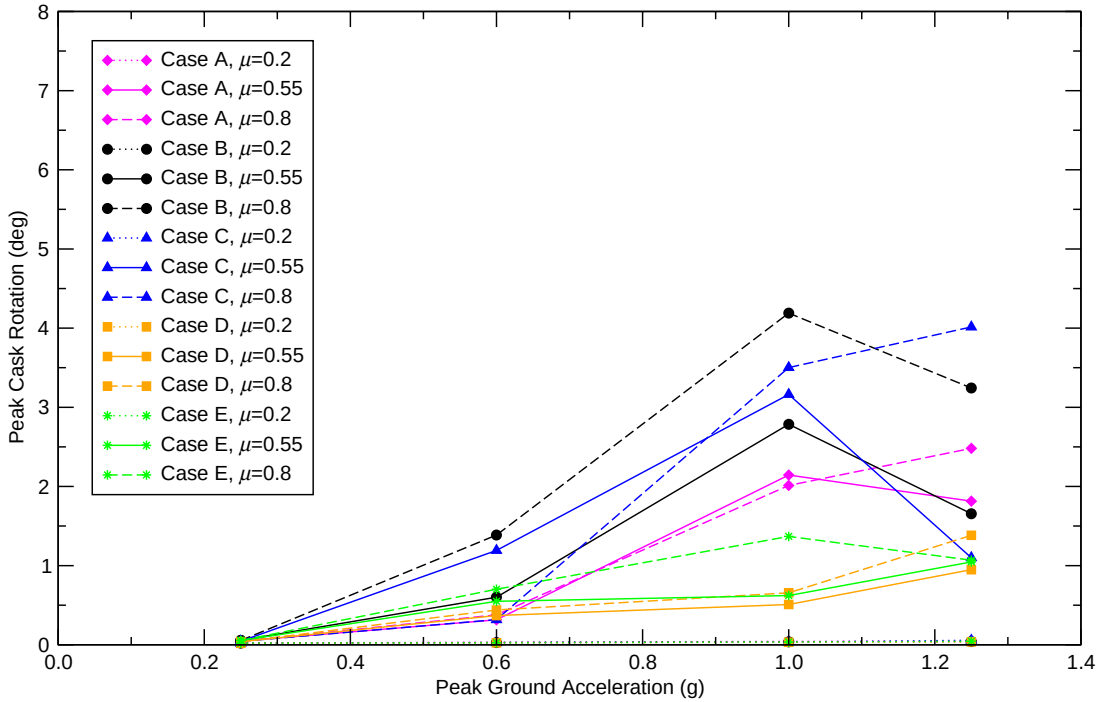

Figure V.25: Peak Cask Rotations, Cylindrical Cask, Soft Soil, NUREG/CR-6728 Earthquakes

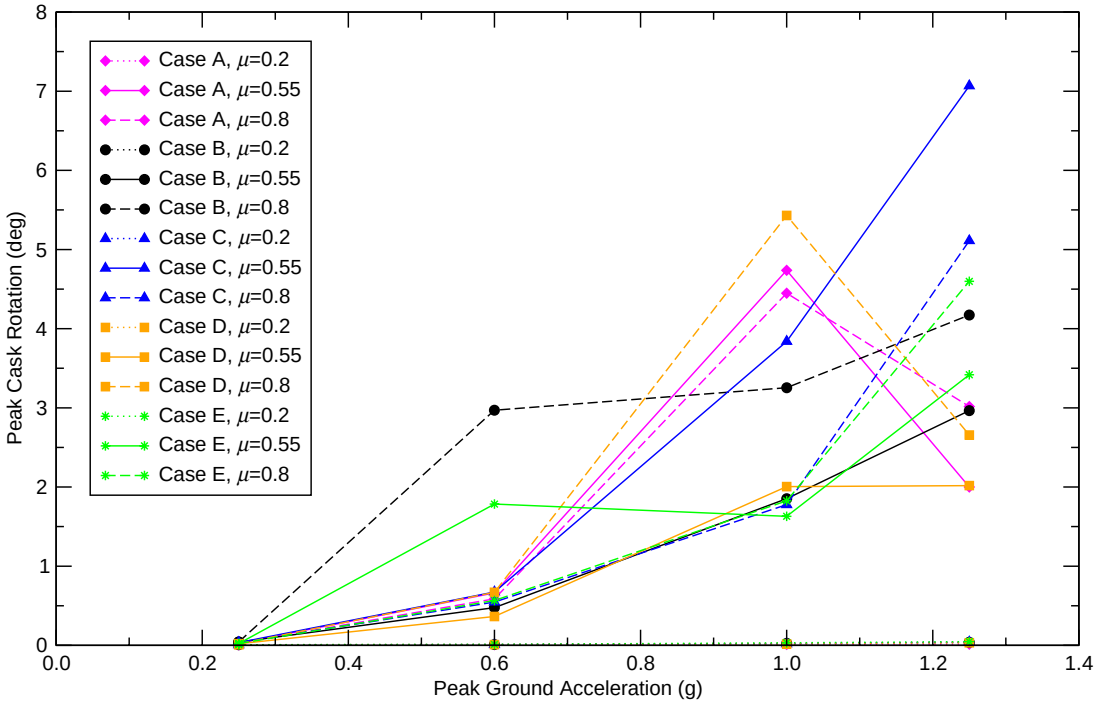

Figure V.26: Peak Cask Rotations, Cylindrical Cask, Stiff Soil, NUREG/CR-6728 Earthquakes

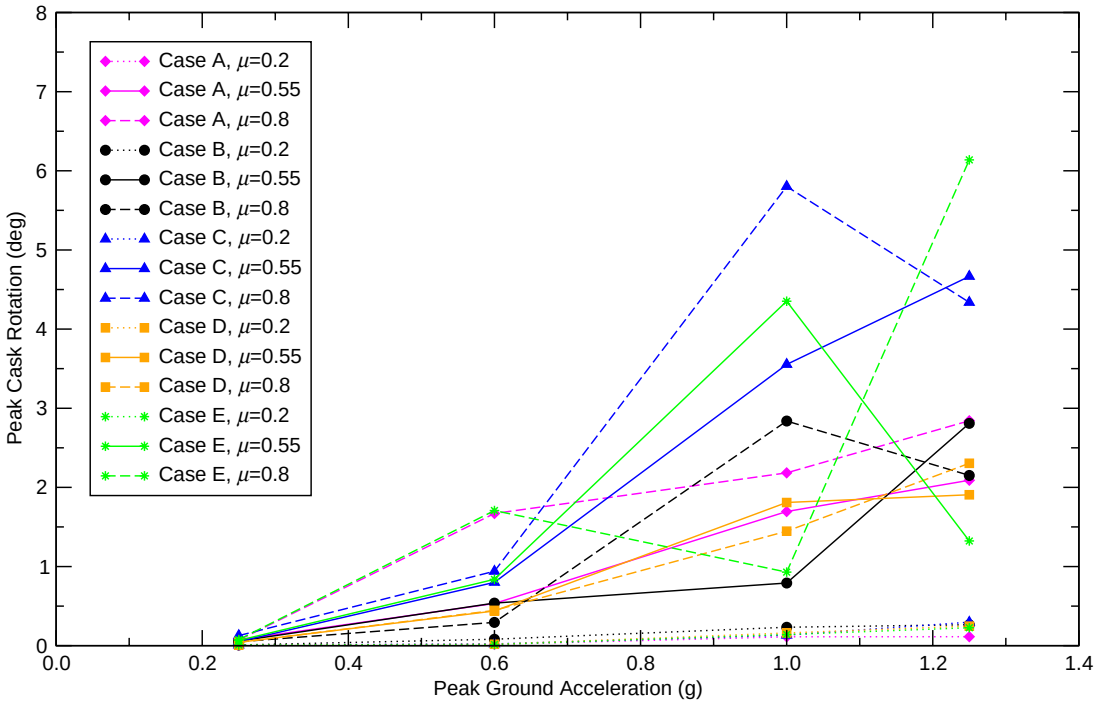

Figure V.27: Peak Cask Rotations, Cylindrical Cask, Rock, NUREG/CR-6728 Earthquakes

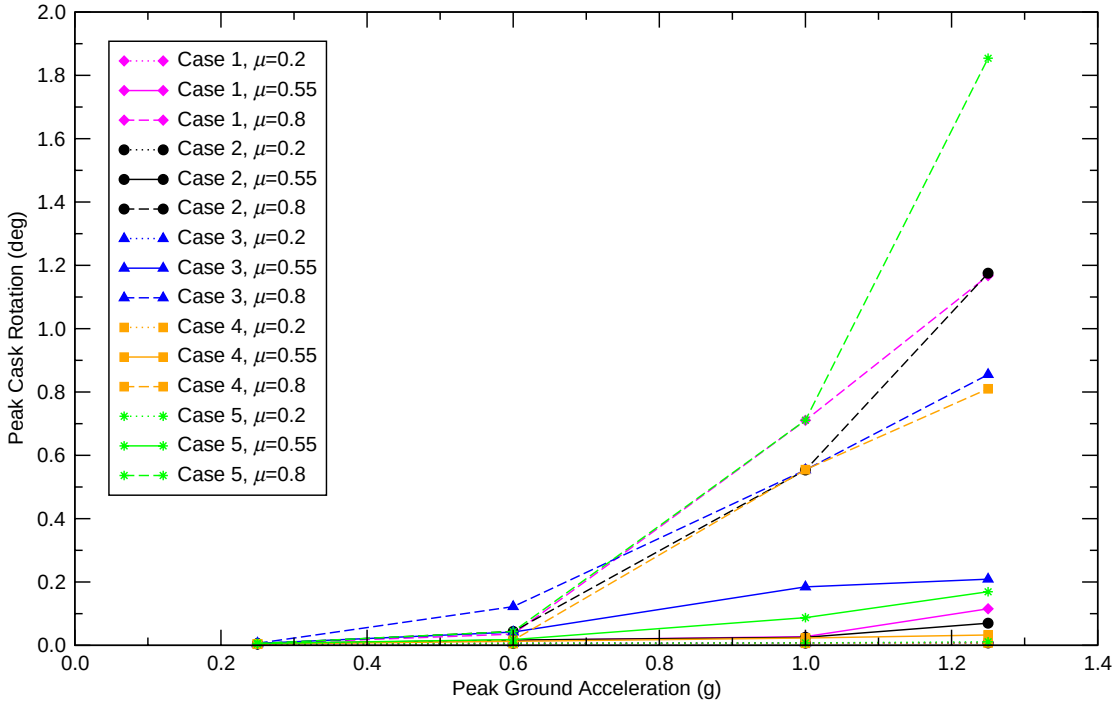

Figure V.28: Peak Cask Rotations, Rectangular Module, Soft Soil, NUREG/CR-0098 Earthquakes

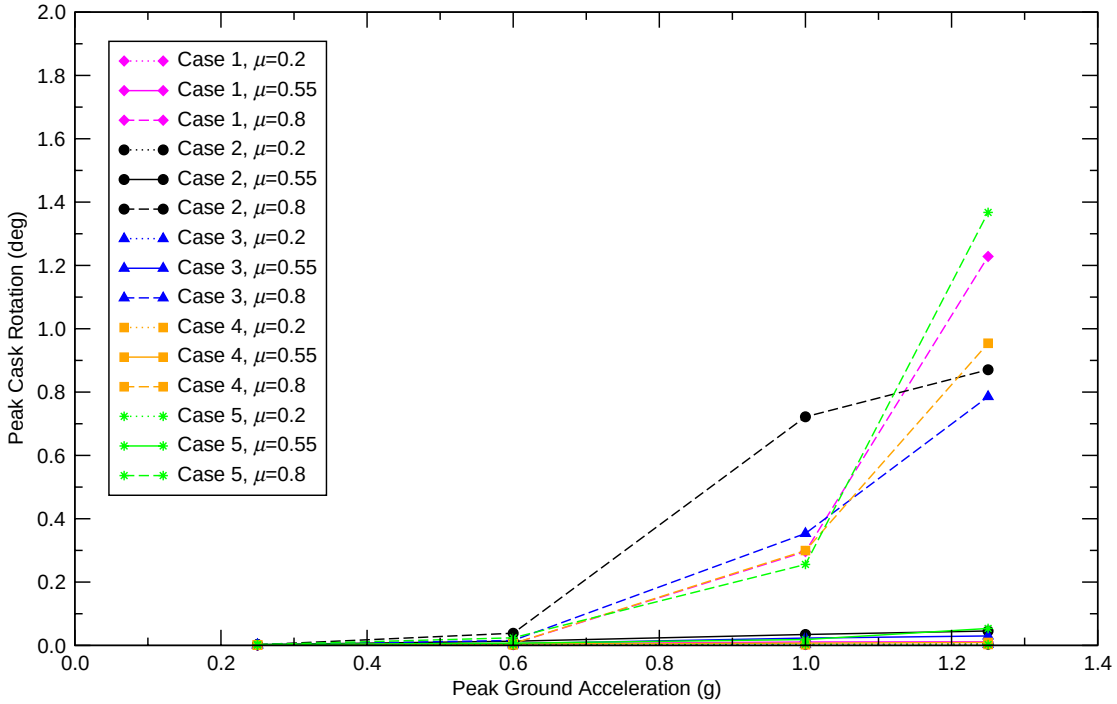

Figure V.29: Peak Cask Rotations, Rectangular Module, Stiff Soil, NUREG/CR-0098 Earthquakes

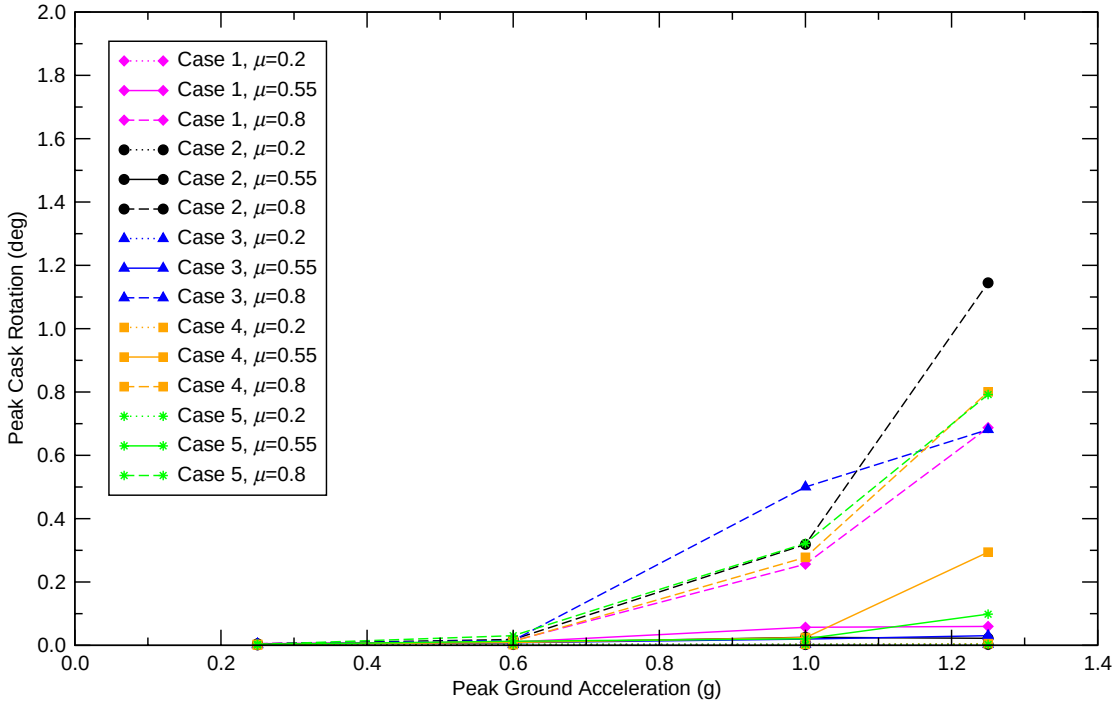

Figure V.30: Peak Cask Rotations, Rectangular Module, Rock, NUREG/CR-0098 Earthquakes

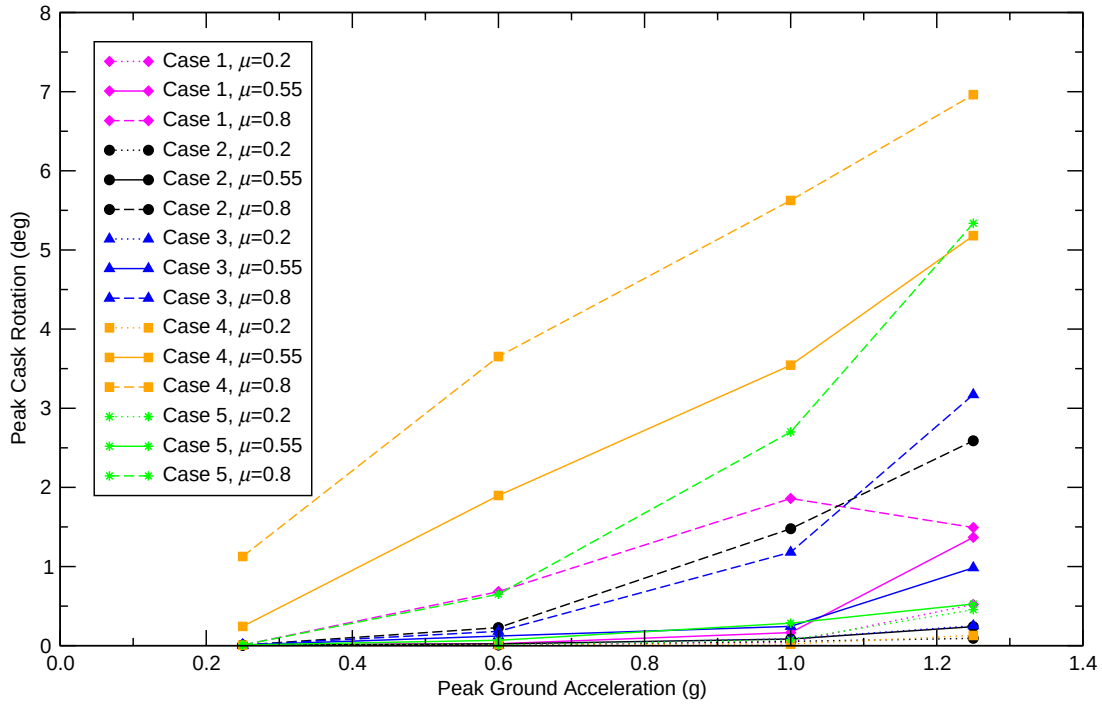

Figure V.31: Peak Cask Rotations, Rectangular Module, Soft Soil, Regulatory Guide 1.60 Earthquakes

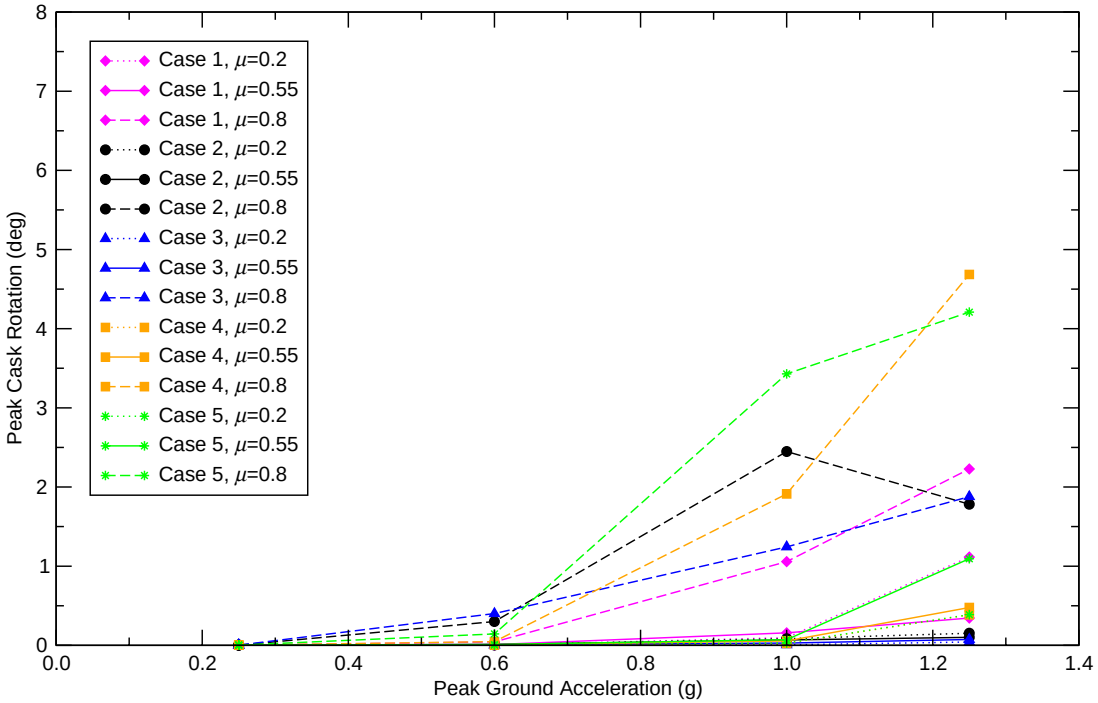

Figure V.32: Peak Cask Rotations, Rectangular Module, Stiff Soil, Regulatory Guide 1.60 Earthquakes

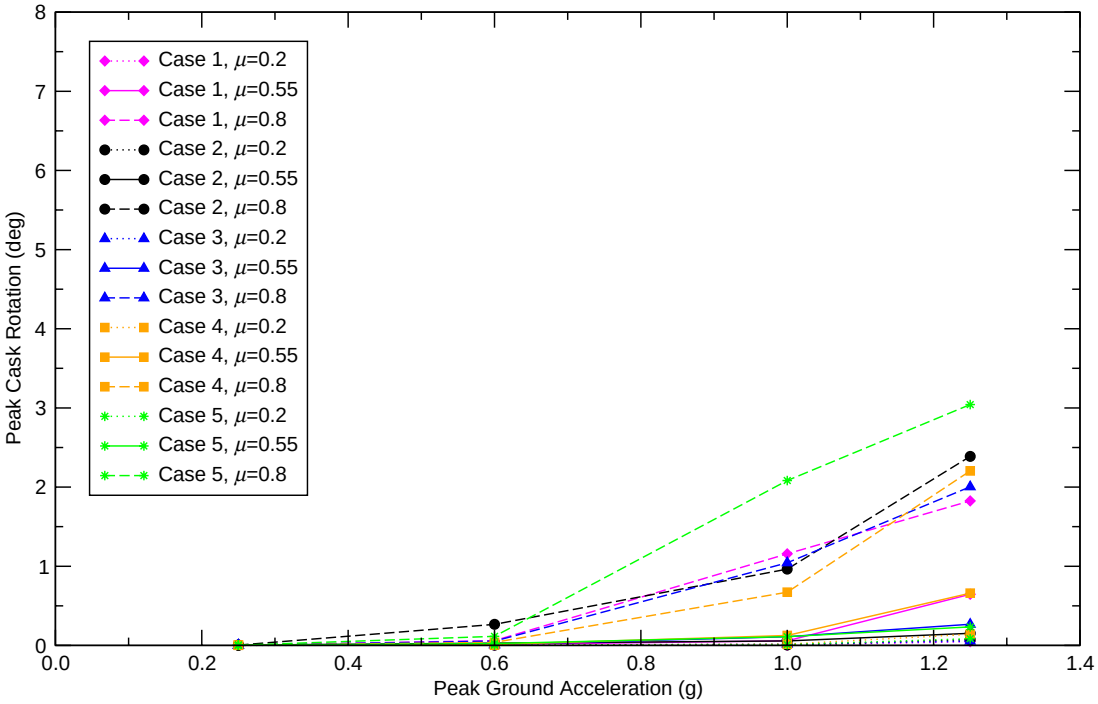

Figure V.33: Peak Cask Rotations, Rectangular Module, Rock, Regulatory Guide 1.60 Earthquakes

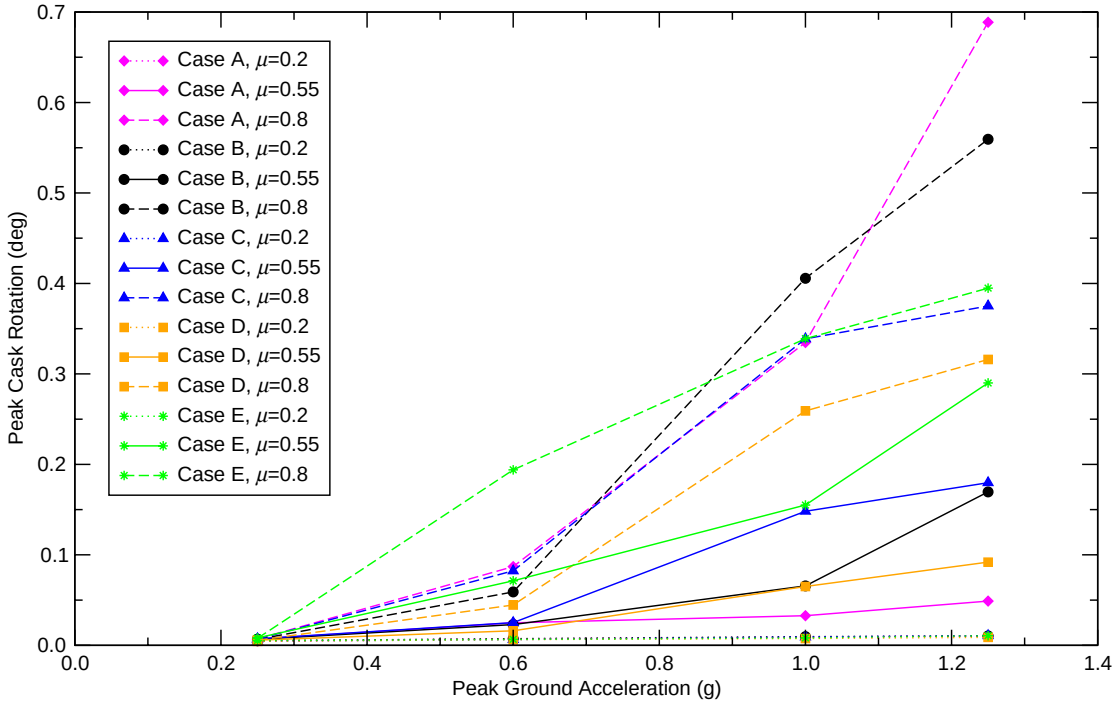

Figure V.34: Peak Cask Rotations, Rectangular Module, Soft Soil, NUREG/CR-6728 Earthquakes

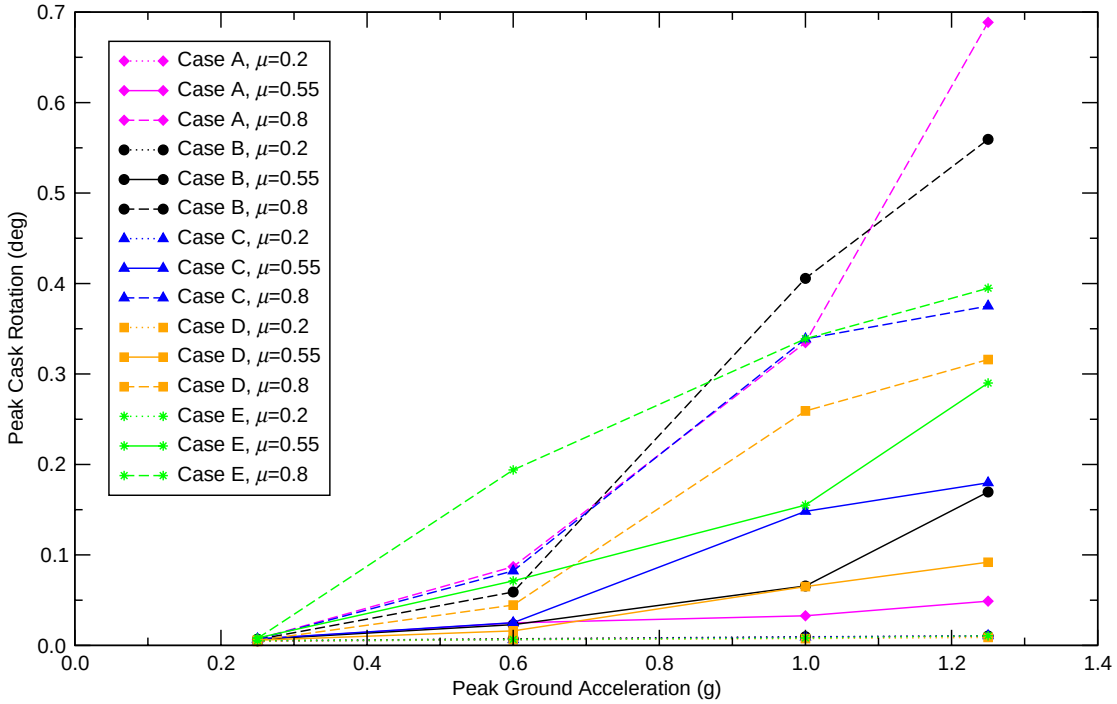

Figure V.35: Peak Cask Rotations, Rectangular Module, Stiff Soil, NUREG/CR-6728 Earthquakes

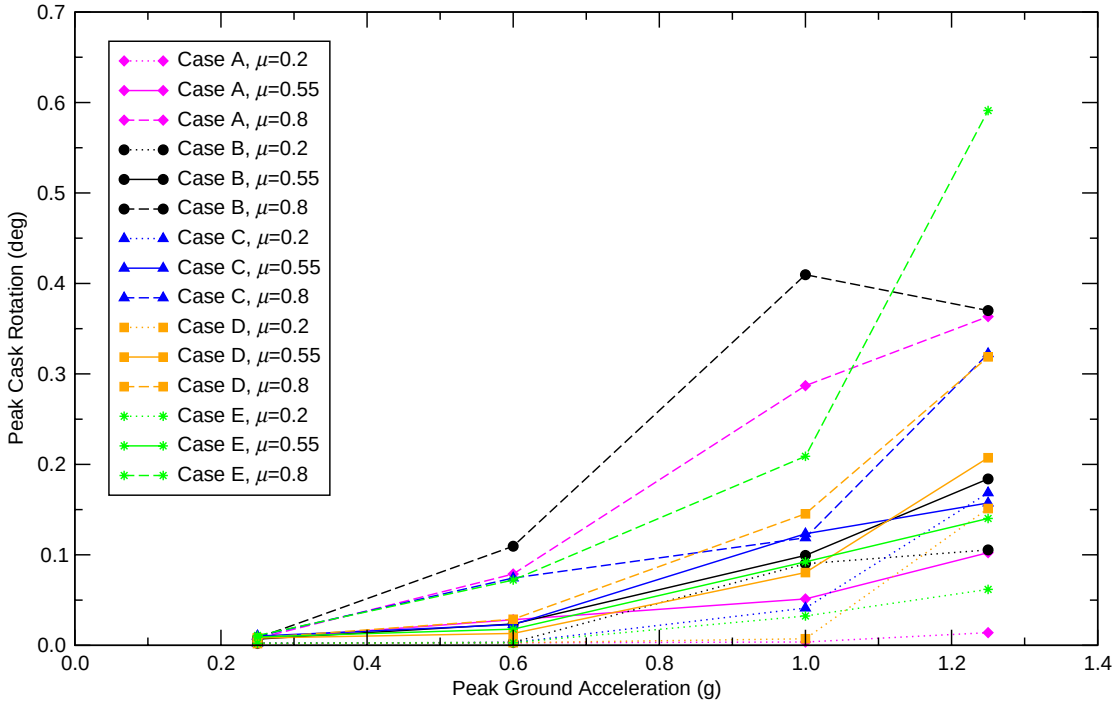

Figure V.36: Peak Cask Rotations, Rectangular Module, Rock, NUREG/CR-6728 Earthquakes

Appendix VI: Nomograms of Cask Responses

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Appendix VI: Nomograms of Cask Responses

This appendix provides regression fits of the cask response results in terms of the peak horizontal cask top displacement relative to the pad and the peak cask rotation. The response of the cask as a function of the ground motion is fit reasonably by an exponential equation, which appears as a linear plot if logarithmic scales are used for the two axes. Two types of plots are provided. In Section VI.1, curve fits are provided for sets of analysis results coming from the same spectral shape. In Section VI.2, the results from all three spectral shapes are grouped together, and these are plotted in terms of the 5% damped 1 Hz pseudo-spectral acceleration (PSA) rather than the peak ground acceleration (PGA).

In all of these plots, if an analysis result in a series indicated that the cask tipped over, that result, as well as any results from analyses with higher levels of ground motion, was omitted from the data set used for curve fitting and is not plotted. A heavy vertical line and annotation are used to indicate the ground motion level at which the first cask overturning is observed. In all of the regression plots shown here, curves and equations are provided for the median least squares fit as well as the 84% and 16% confidence bands (median plus and minus one standard deviation). These plots can be used as nomograms for determining the cask response at a given level of confidence under a given level of ground motion.

VI.1 Nomograms for Individual Spectral Shapes with Combined Soil Types

The cask response is not very sensitive to the soil type, so the results from all three soil types used in this study have been grouped together to provide larger data sets for regression analysis. The cask response is much more sensitive to the coefficient of friction between the cask and pad, and the cask design. In this section, analysis results from a given cask design, spectral shape, and cask/pad friction coefficient are grouped together. These plots are shown on logarithmic scales. The individual analysis results obtained using the soft soil, stiff soil, and rock profiles are color-coded separately and shown on these plots. Regression fits are provided for the peak cask top displacement and peak cask rotation as a function of PGA.

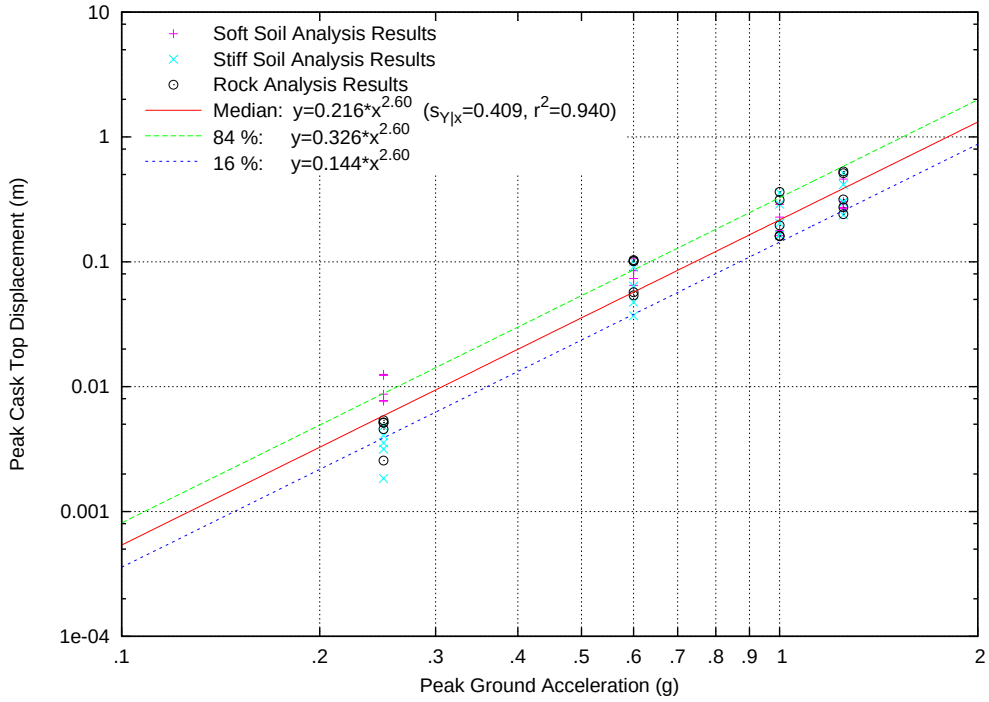

Figure VI.1: Peak Top Displacement Regression Fit, Cylindrical Cask, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

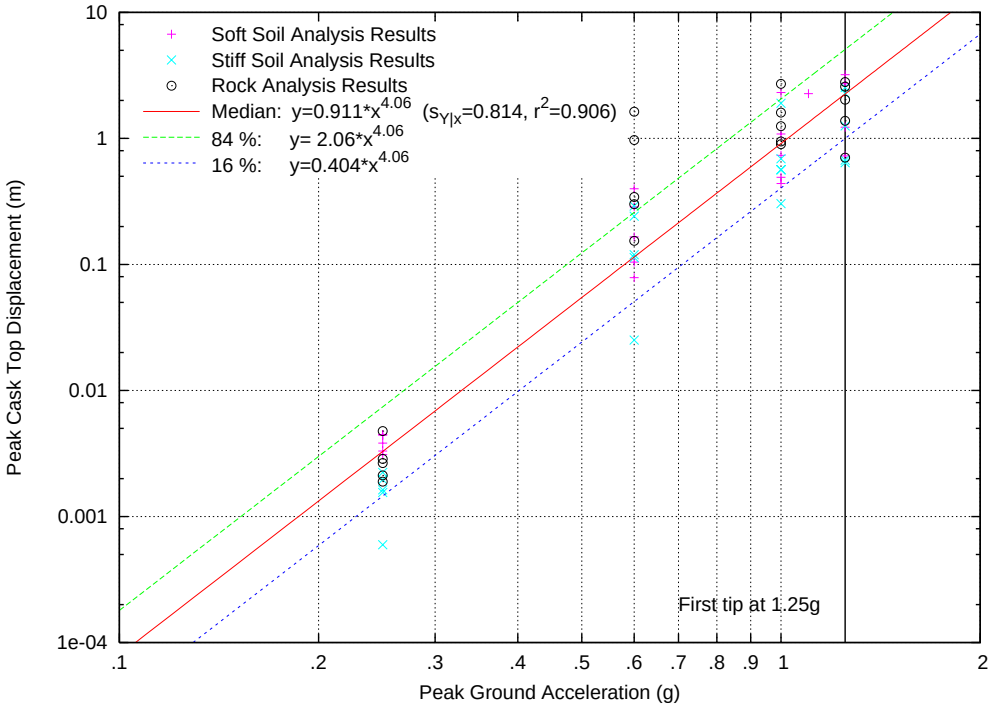

Figure VI.2: Peak Top Displacement Regression Fit, Cylindrical Cask, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

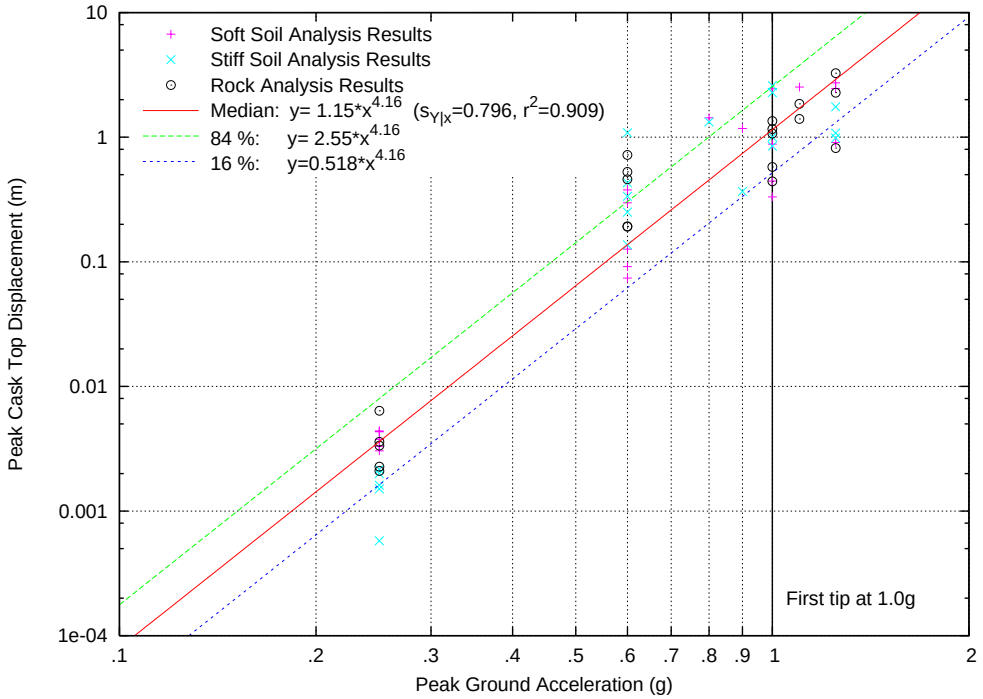

Figure VI.3: Peak Top Displacement Regression Fit, Cylindrical Cask, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

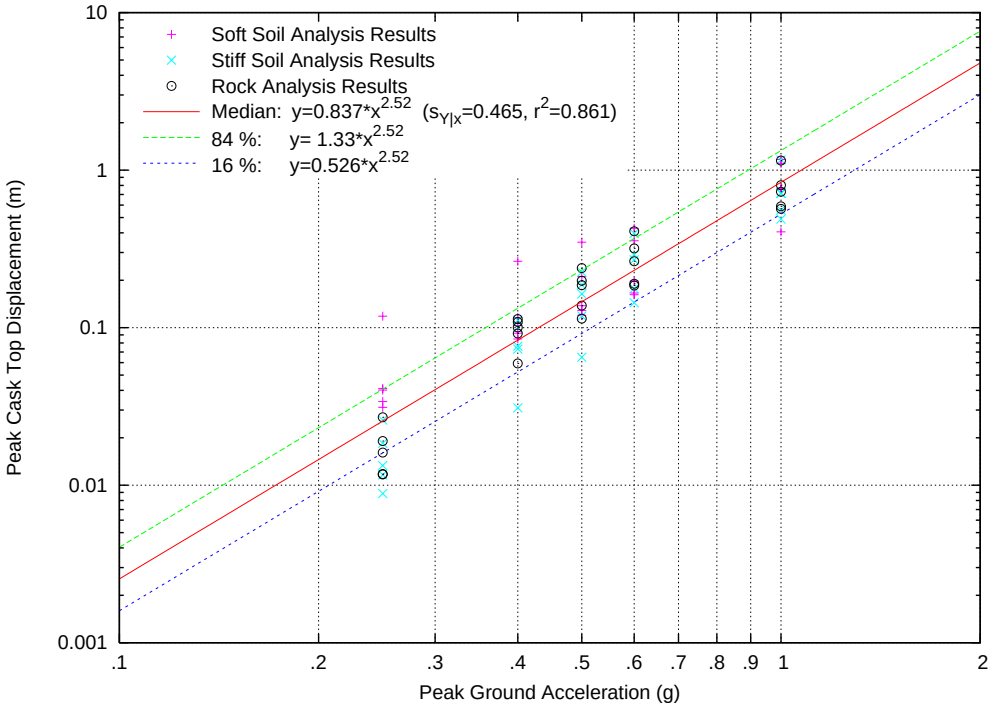

Figure VI.4: Peak Top Displacement Regression Fit, Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

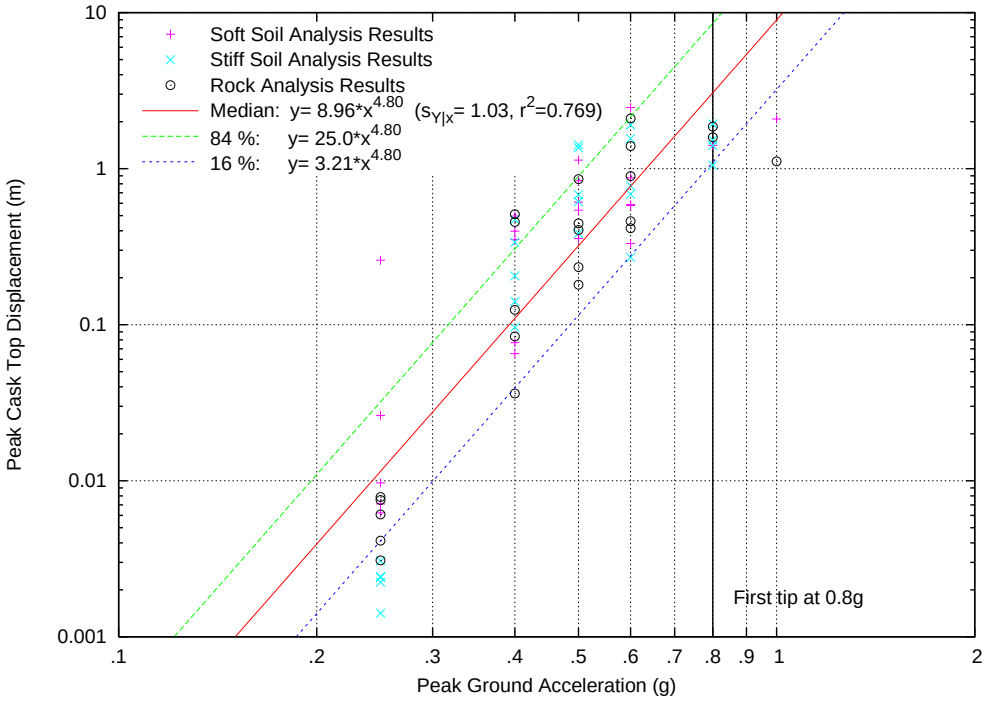

Figure VI.5: Peak Top Displacement Regression Fit, Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

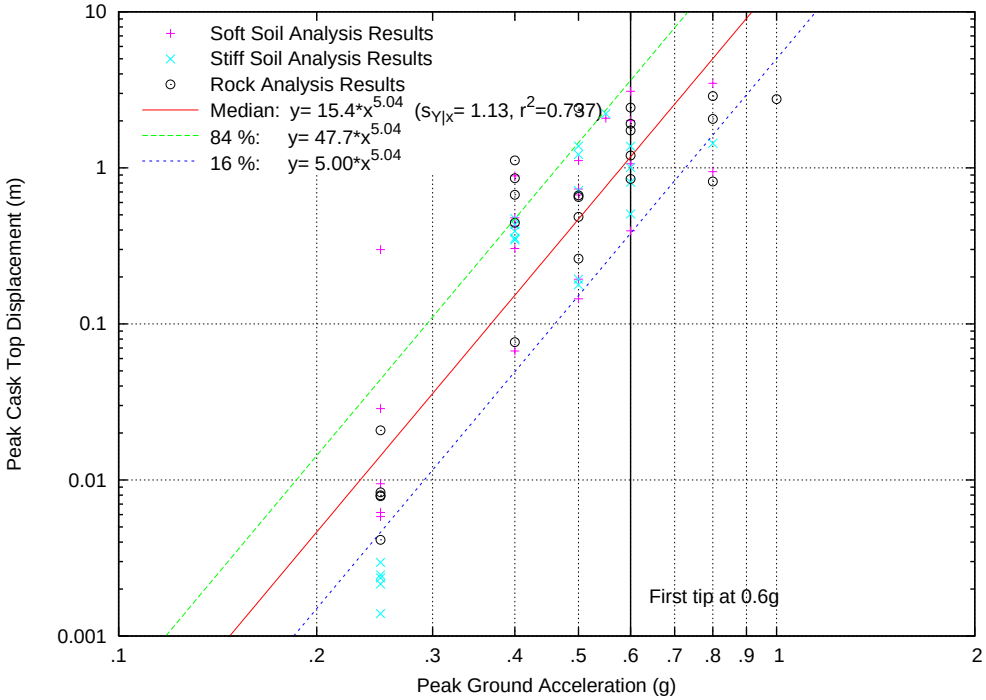

Figure VI.6: Peak Top Displacement Regression Fit, Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

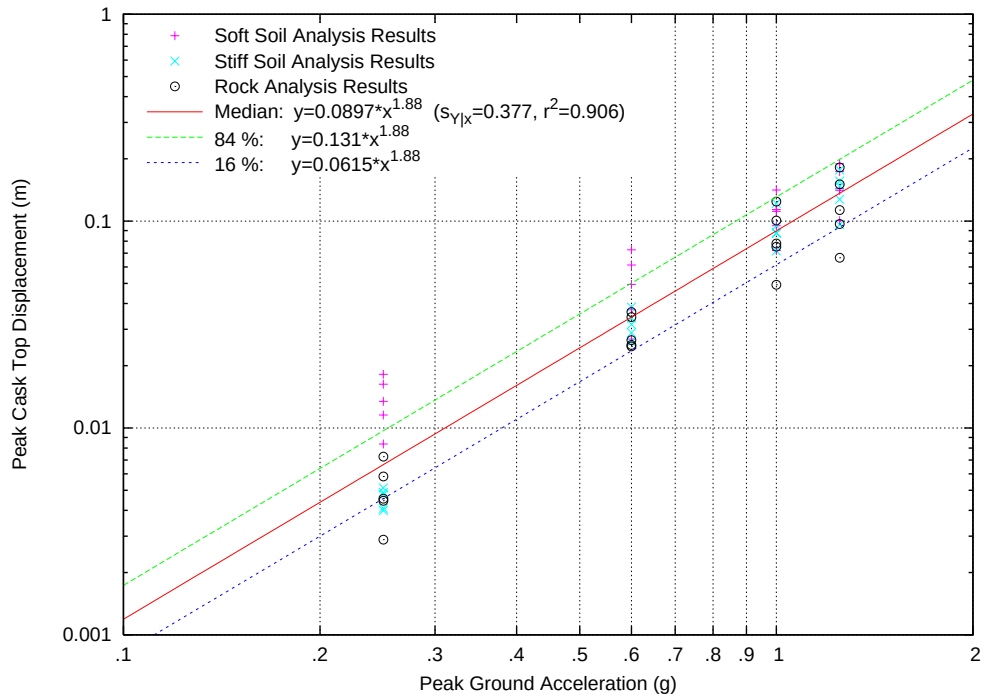

Figure VI.7: Peak Top Displacement Regression Fit, Cylindrical Cask, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

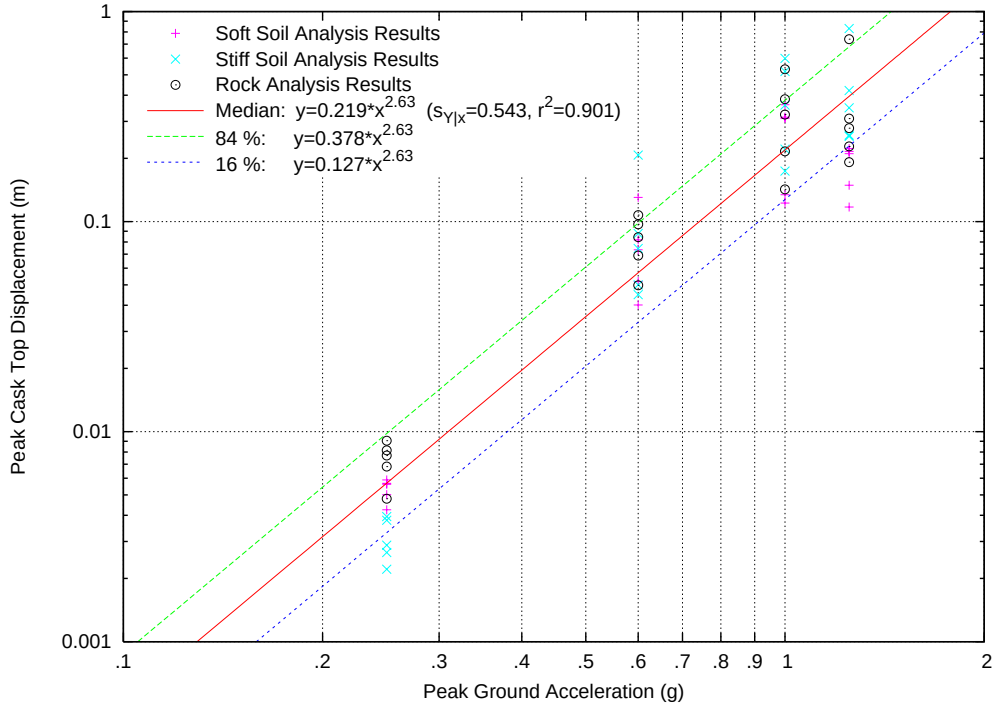

Figure VI.8: Peak Top Displacement Regression Fit, Cylindrical Cask, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

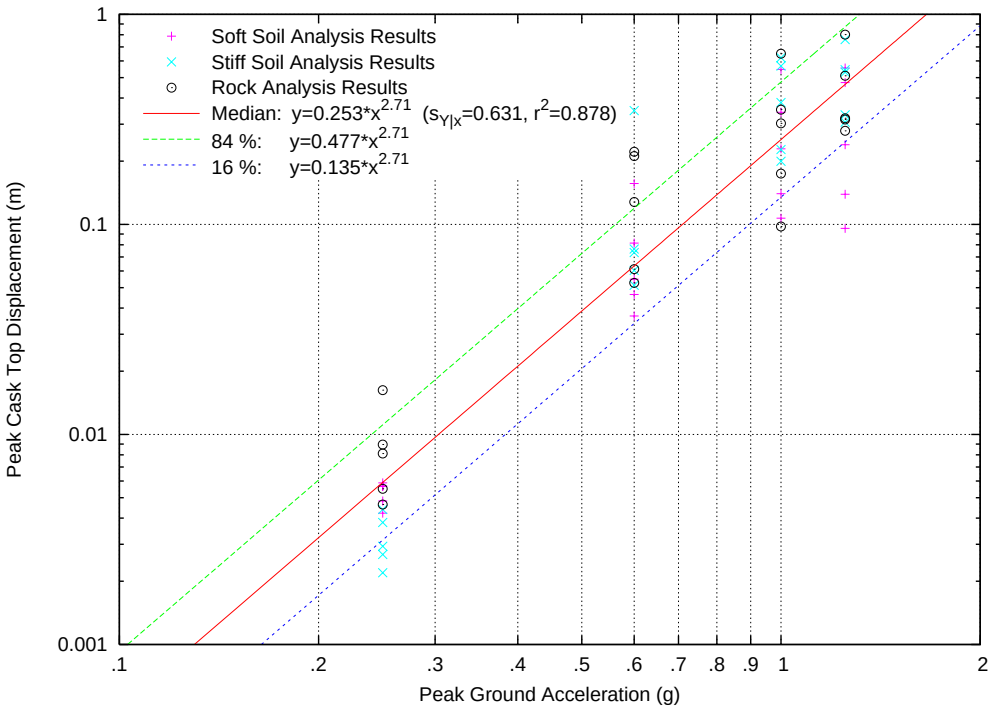

Figure VI.9: Peak Top Displacement Regression Fit, Cylindrical Cask, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

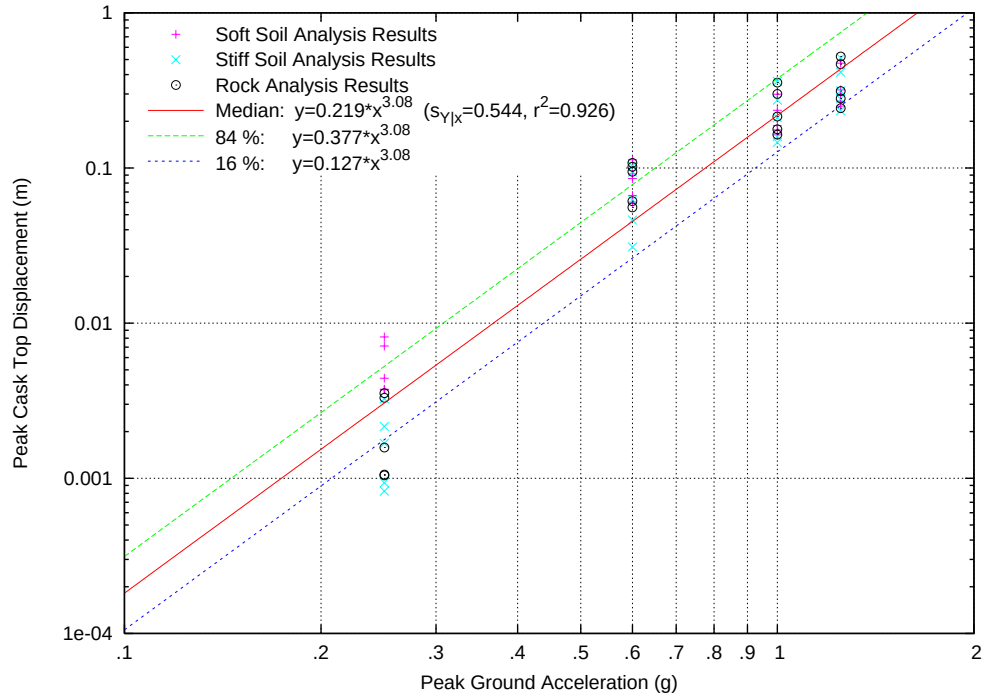

Figure VI.10: Peak Top Displacement Regression Fit, Rectangular Module, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

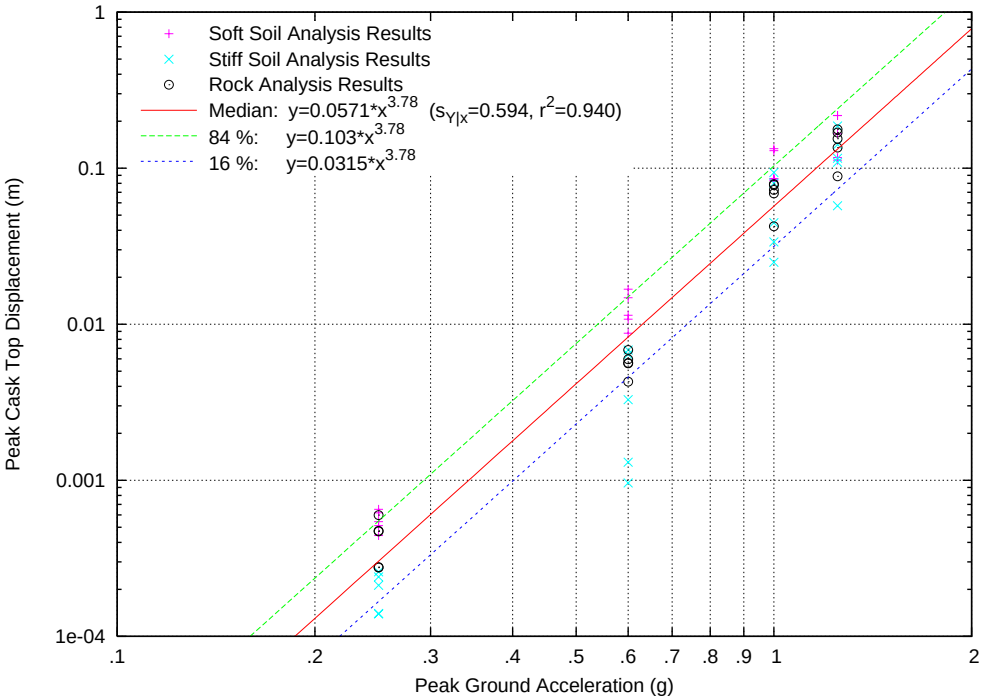

Figure VI.11: Peak Top Displacement Regression Fit, Rectangular Module, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

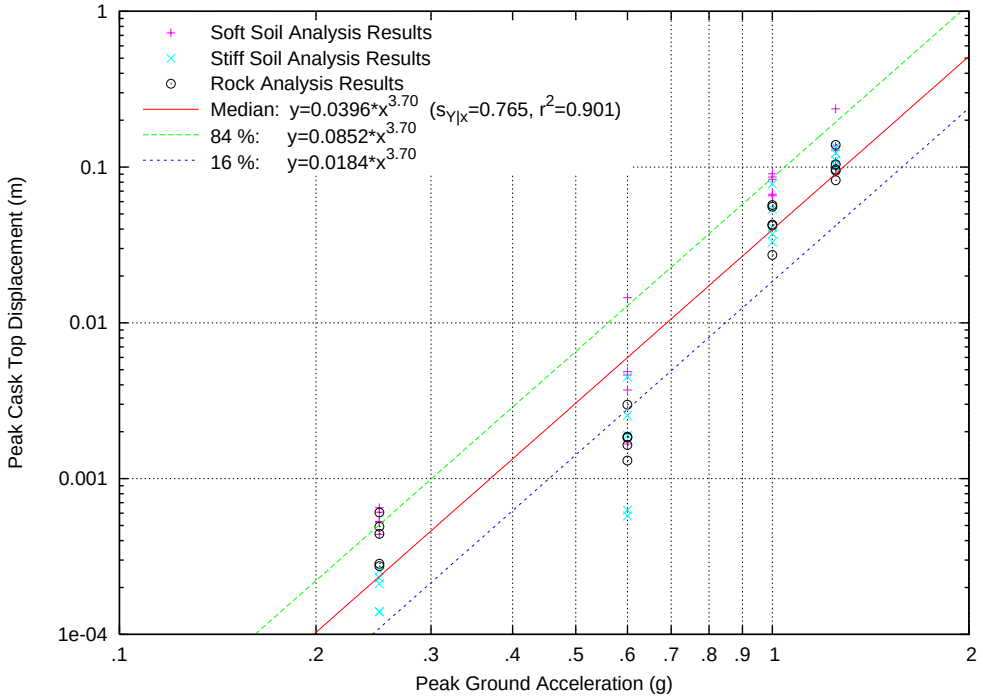

Figure VI.12: Peak Top Displacement Regression Fit, Rectangular Module, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

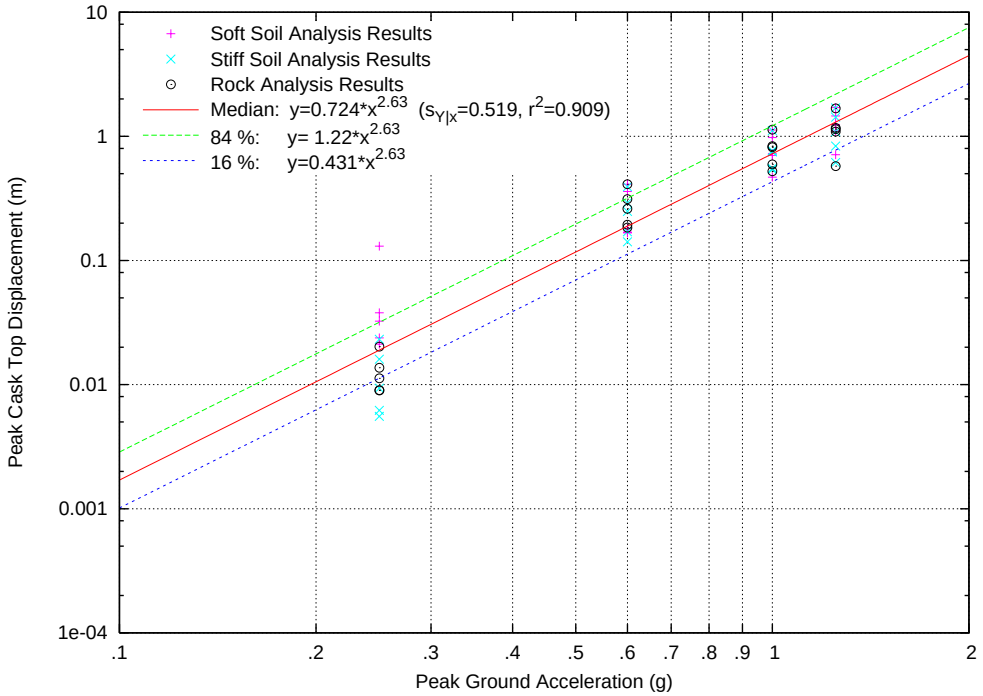

Figure VI.13: Peak Top Displacement Regression Fit, Rectangular Module, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

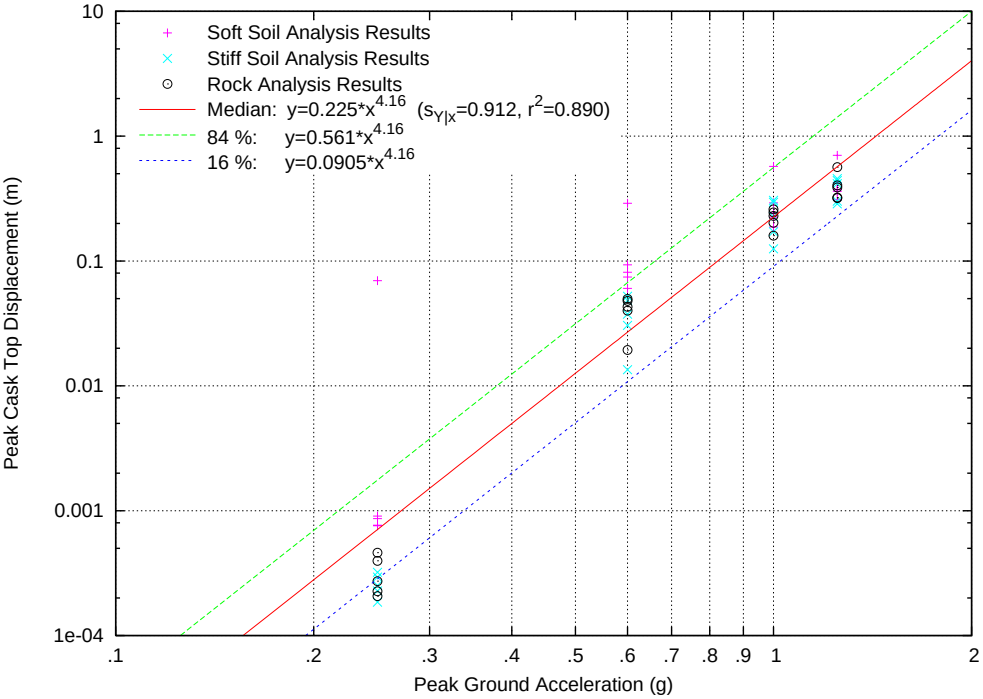

Figure VI.14: Peak Top Displacement Regression Fit, Rectangular Module, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

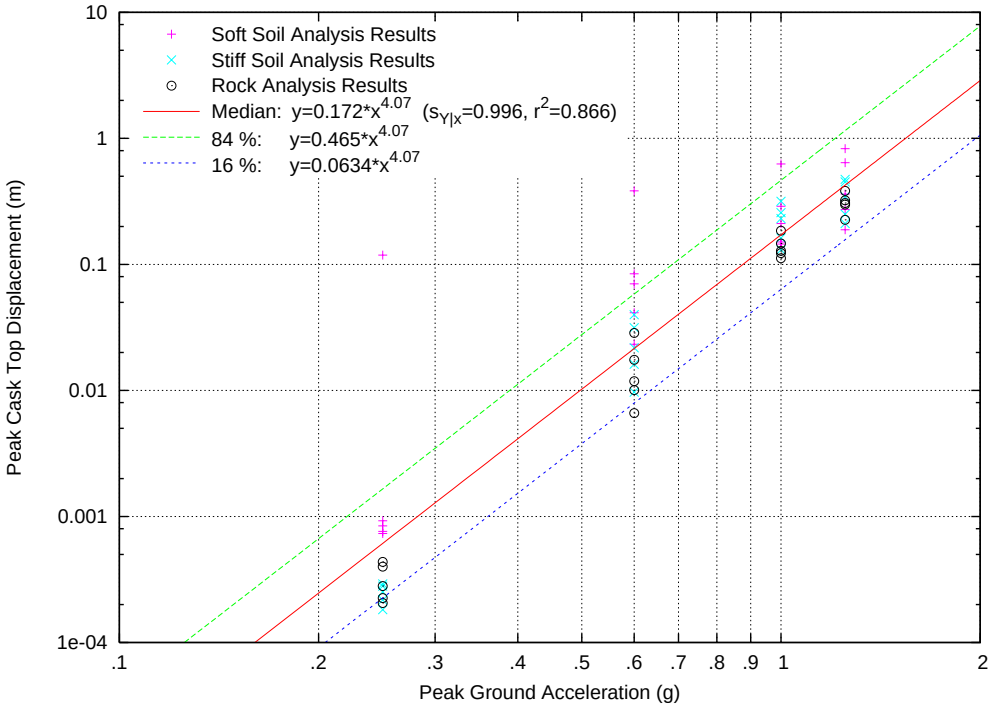

Figure VI.15: Peak Top Displacement Regression Fit, Rectangular Module, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

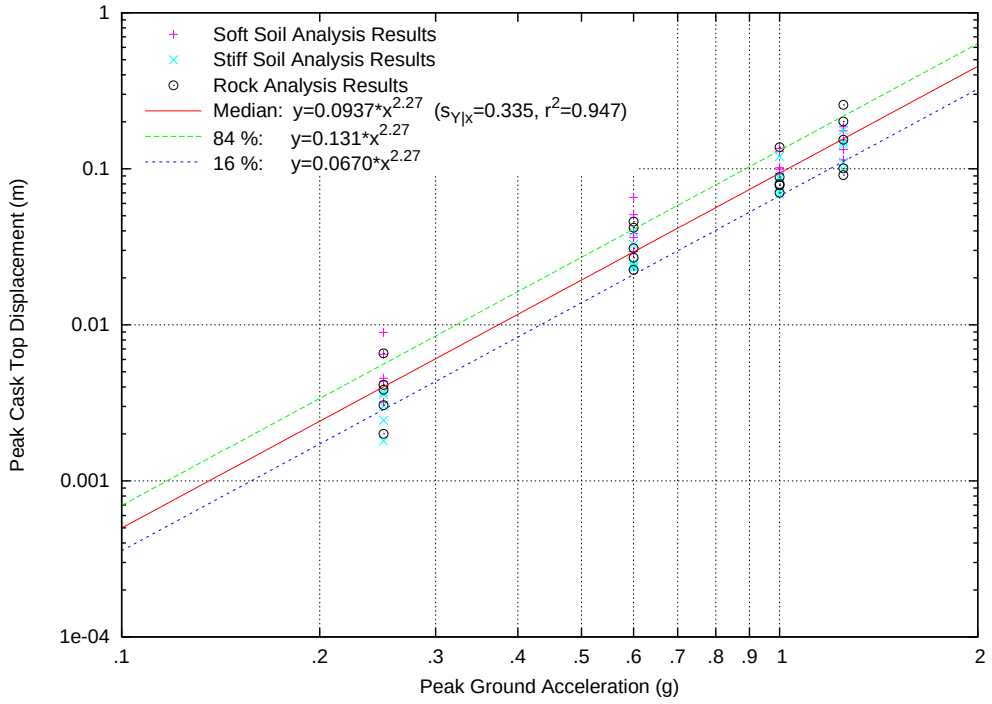

Figure VI.16: Peak Top Displacement Regression Fit, Rectangular Module, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

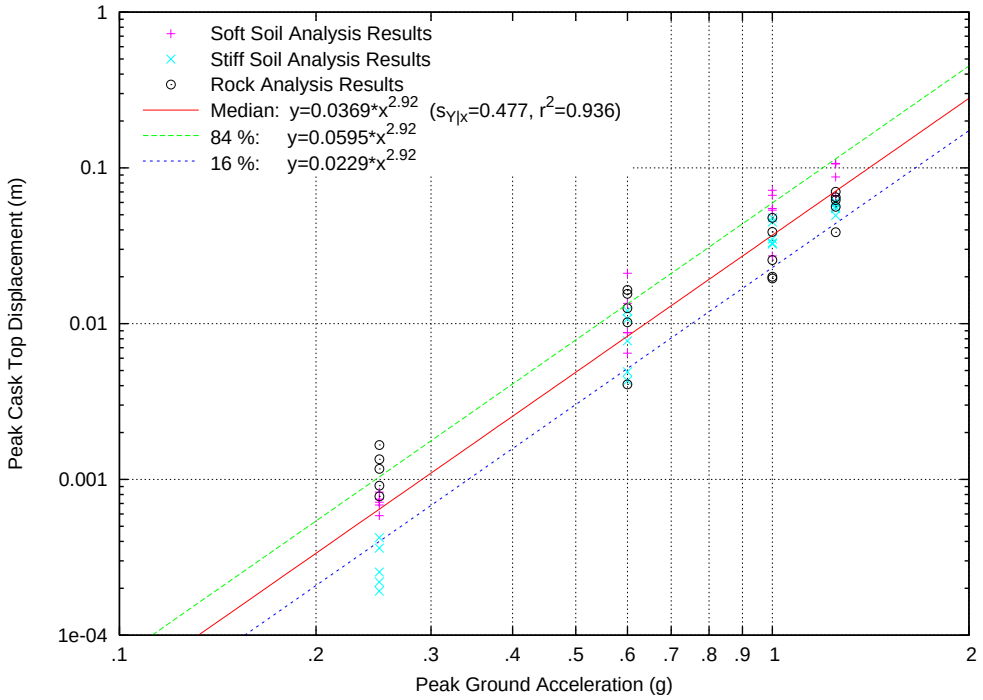

Figure VI.17: Peak Top Displacement Regression Fit, Rectangular Module, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

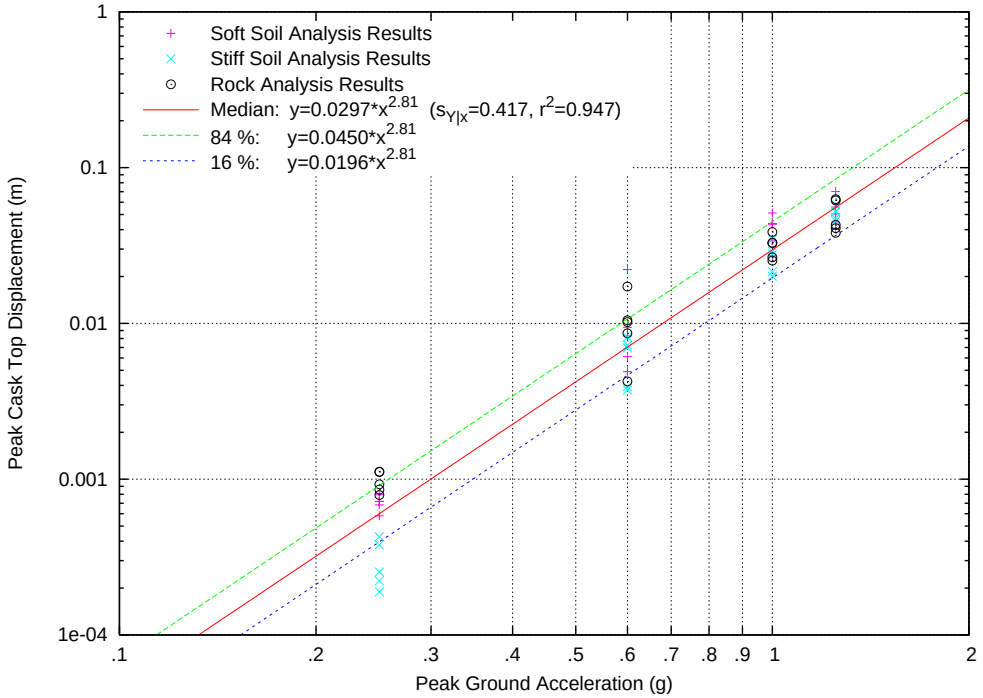

Figure VI.18: Peak Top Displacement Regression Fit, Rectangular Module, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

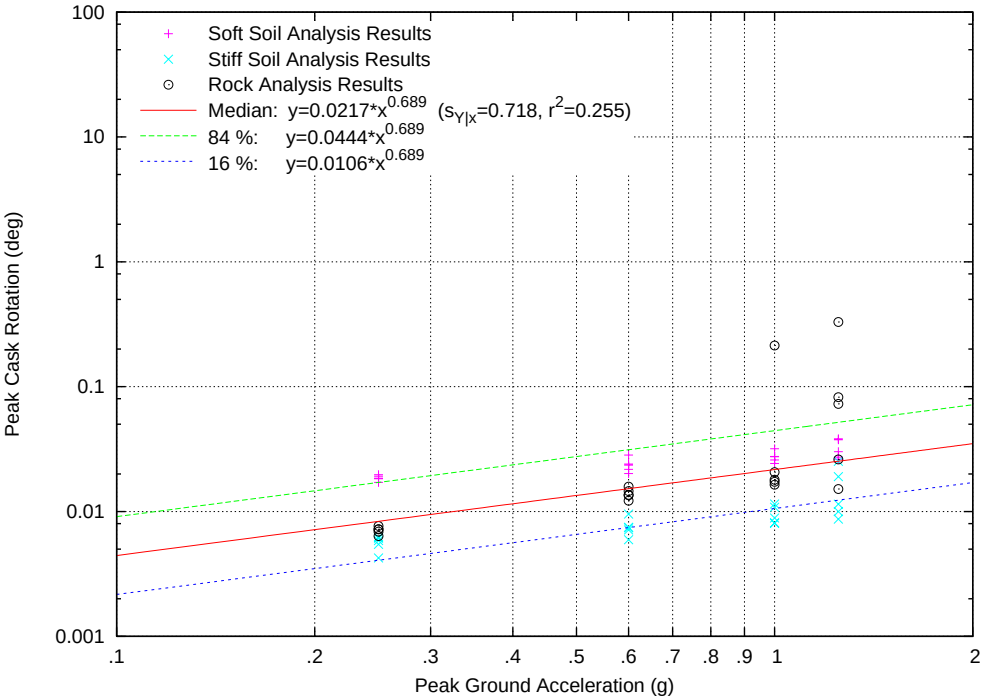

Figure VI.19: Peak Rotation Regression Fit, Cylindrical Cask, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

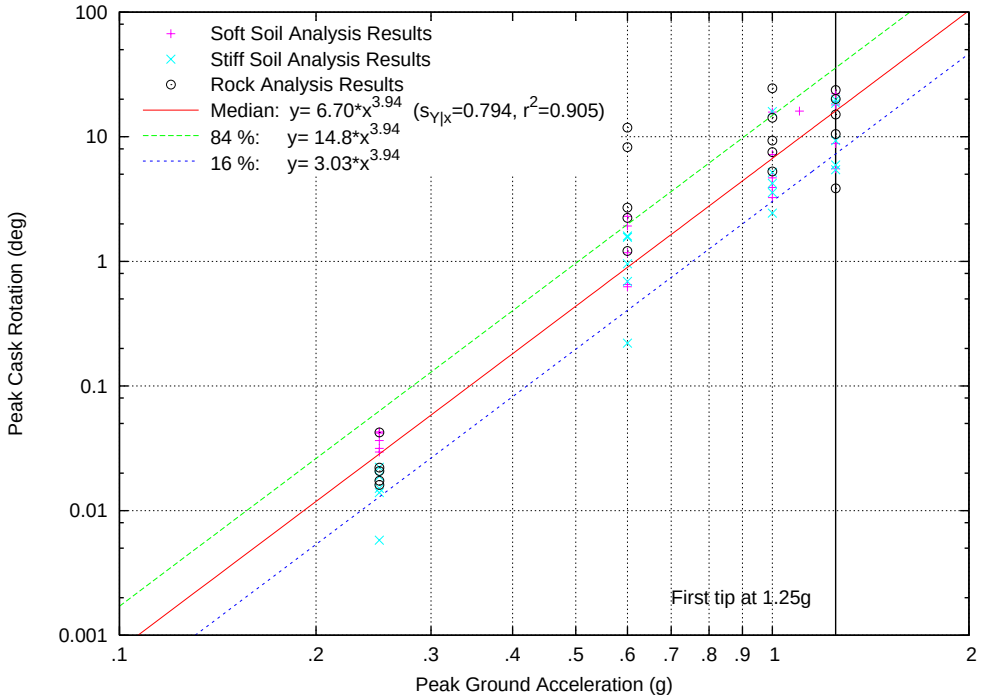

Figure VI.20: Peak Rotation Regression Fit, Cylindrical Cask, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

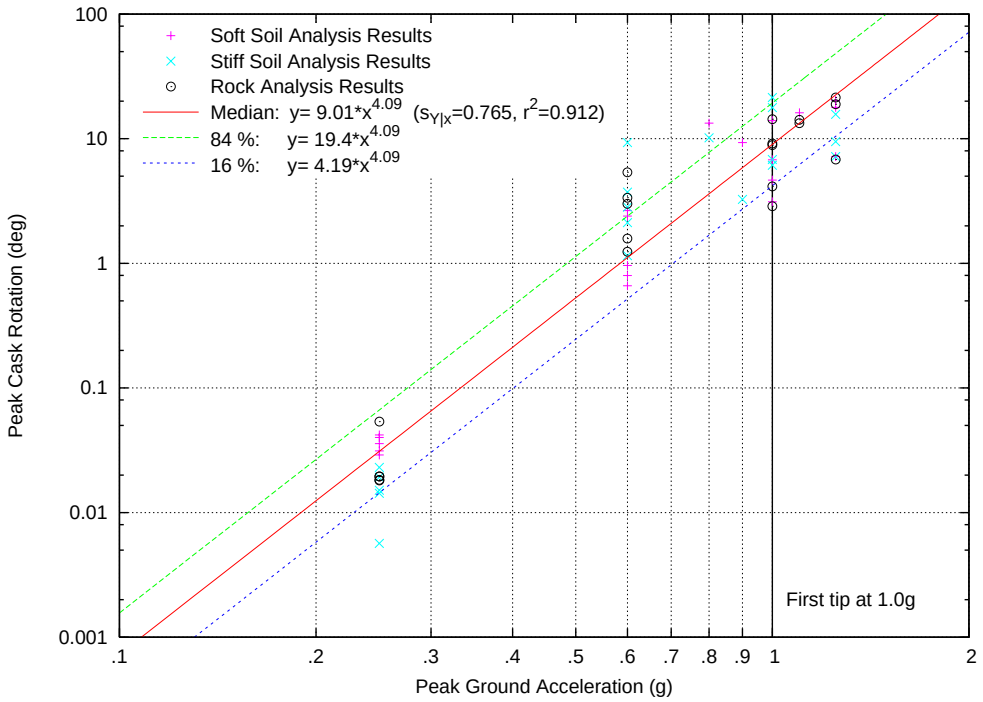

Figure VI.21: Peak Rotation Regression Fit, Cylindrical Cask, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

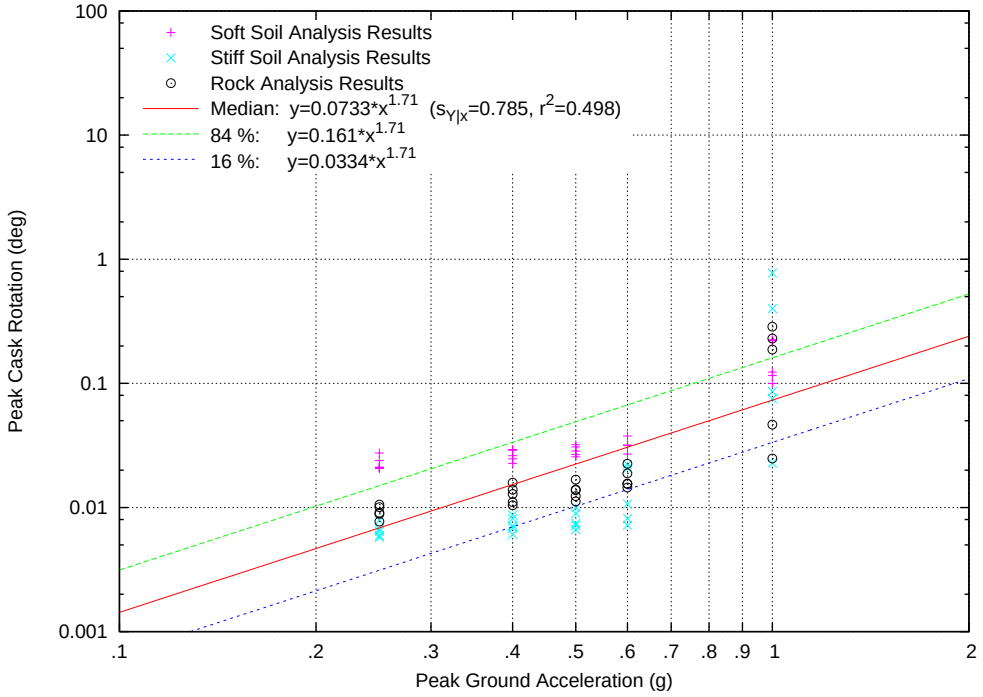

Figure VI.22: Peak Rotation Regression Fit, Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

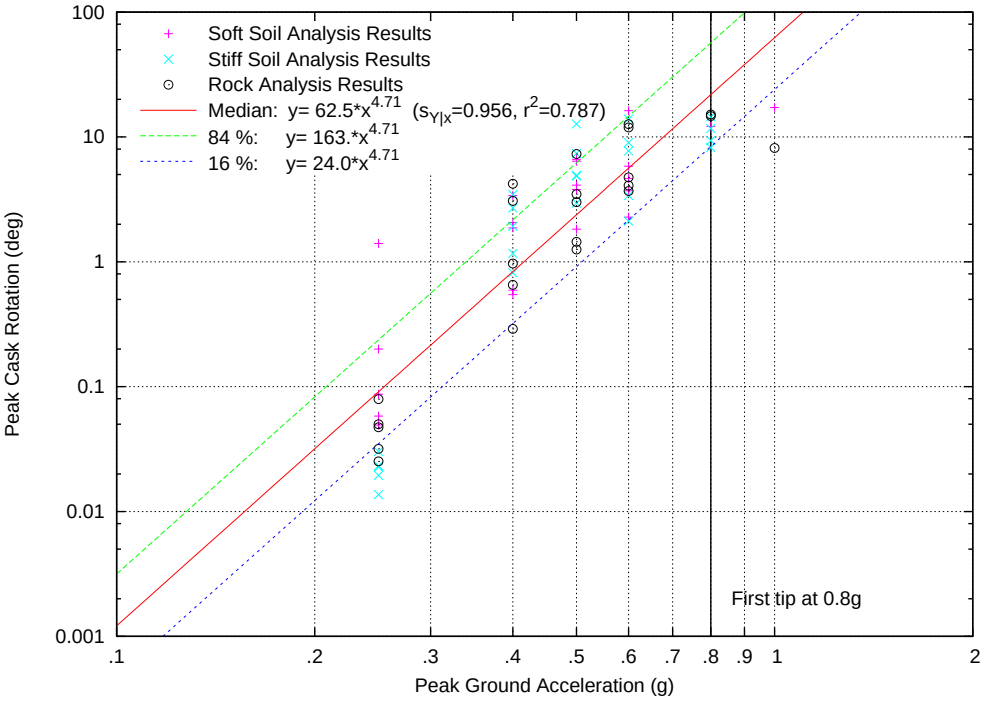

Figure VI.23: Peak Rotation Regression Fit, Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

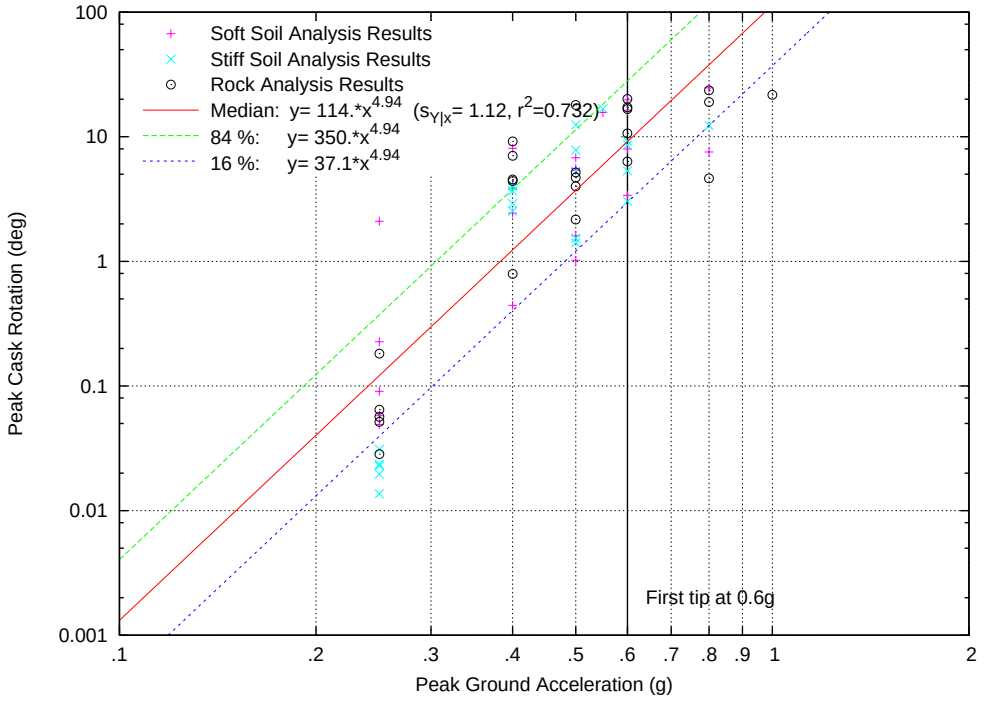

Figure VI.24: Peak Rotation Regression Fit, Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

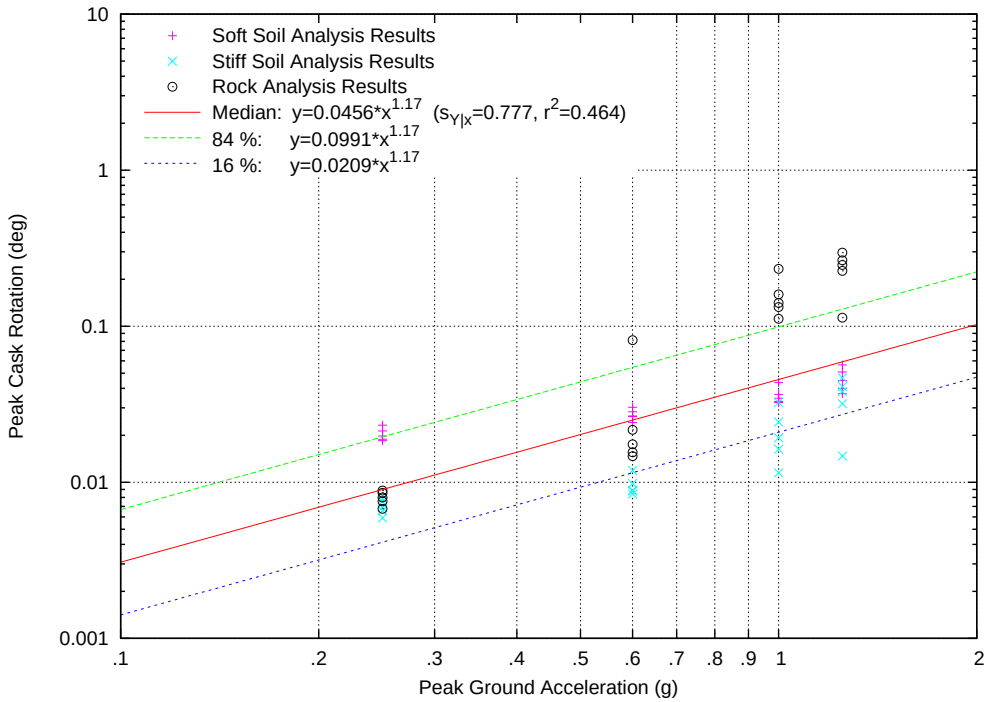

Figure VI.25: Peak Rotation Regression Fit, Cylindrical Cask, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

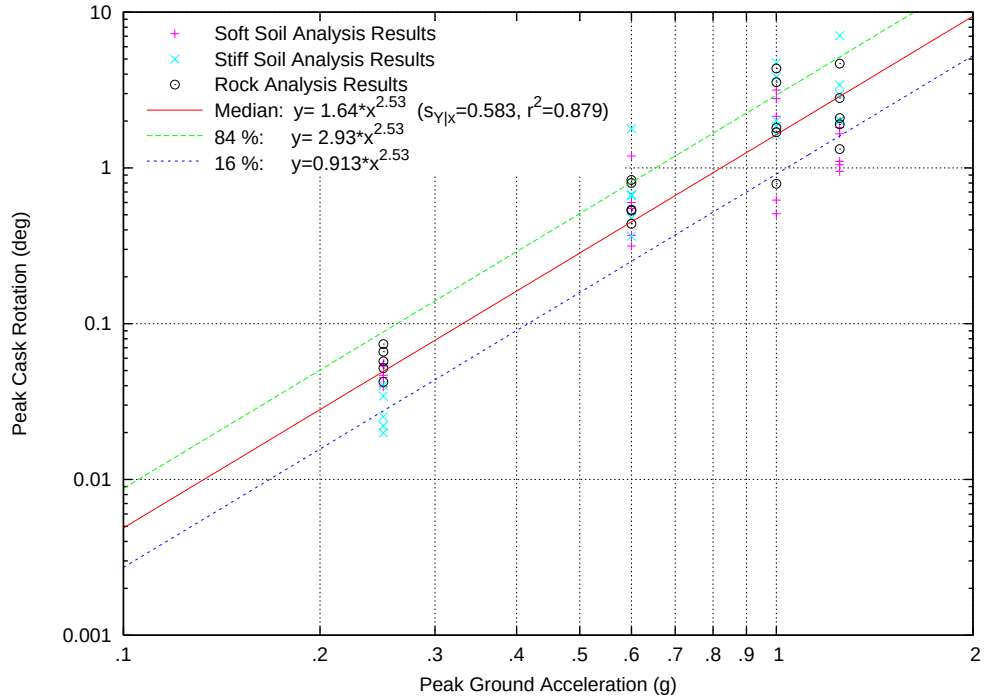

Figure VI.26: Peak Rotation Regression Fit, Cylindrical Cask, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

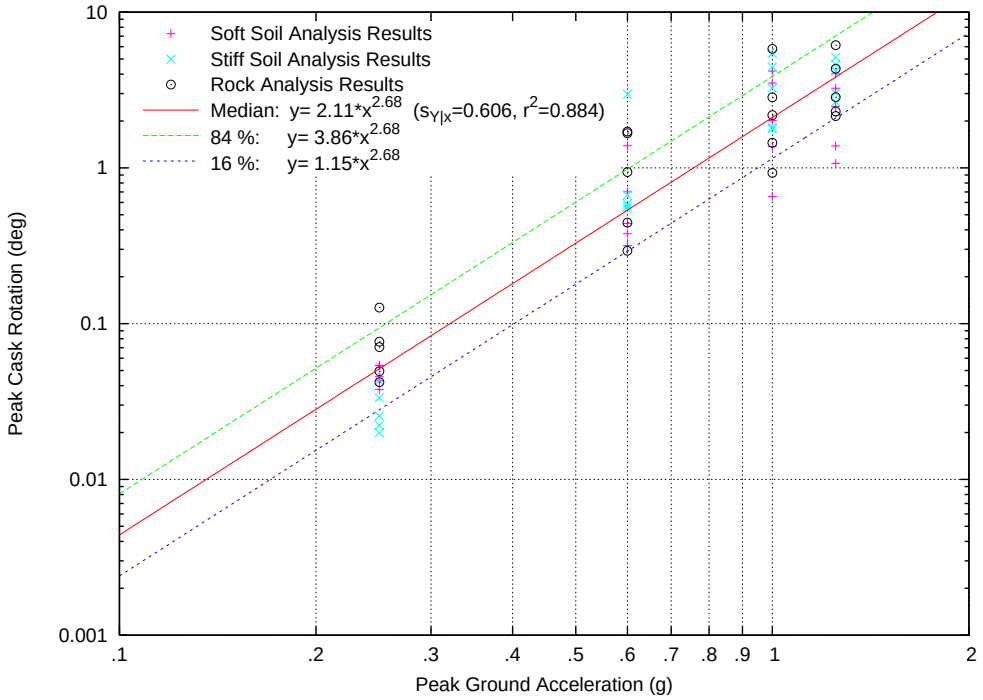

Figure VI.27: Peak Rotation Regression Fit, Cylindrical Cask, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

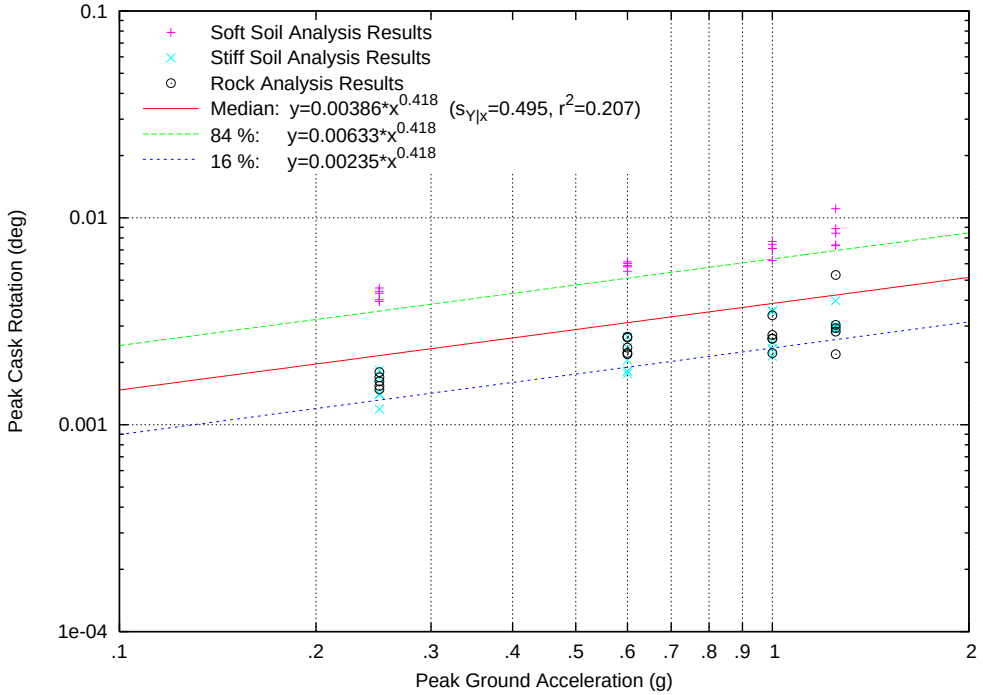

Figure VI.28: Peak Rotation Regression Fit, Rectangular Module, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

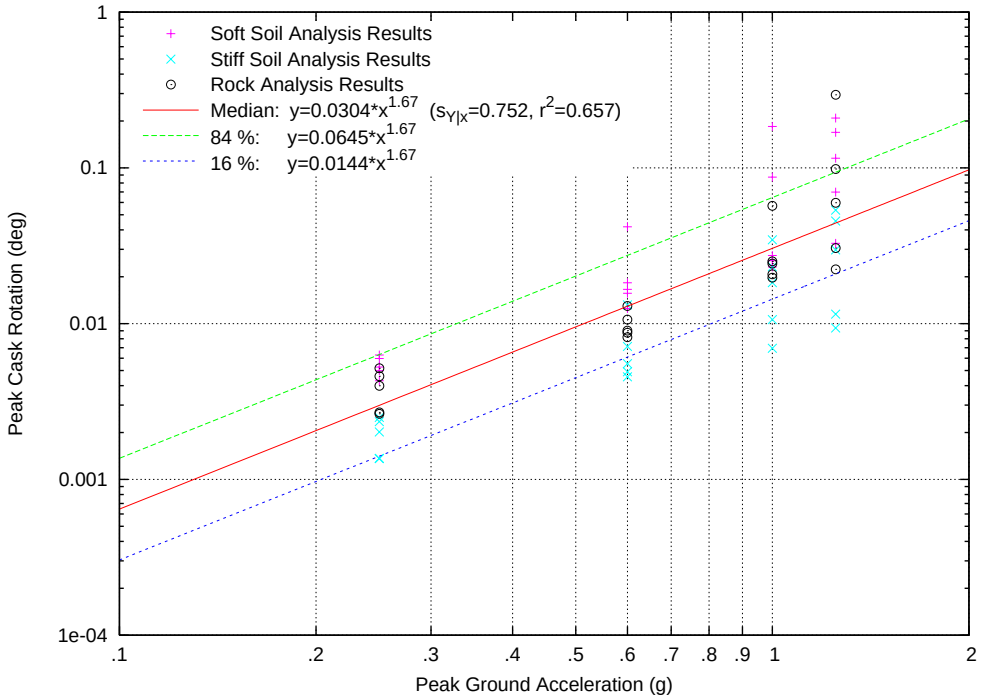

Figure VI.29: Peak Rotation Regression Fit, Rectangular Module, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

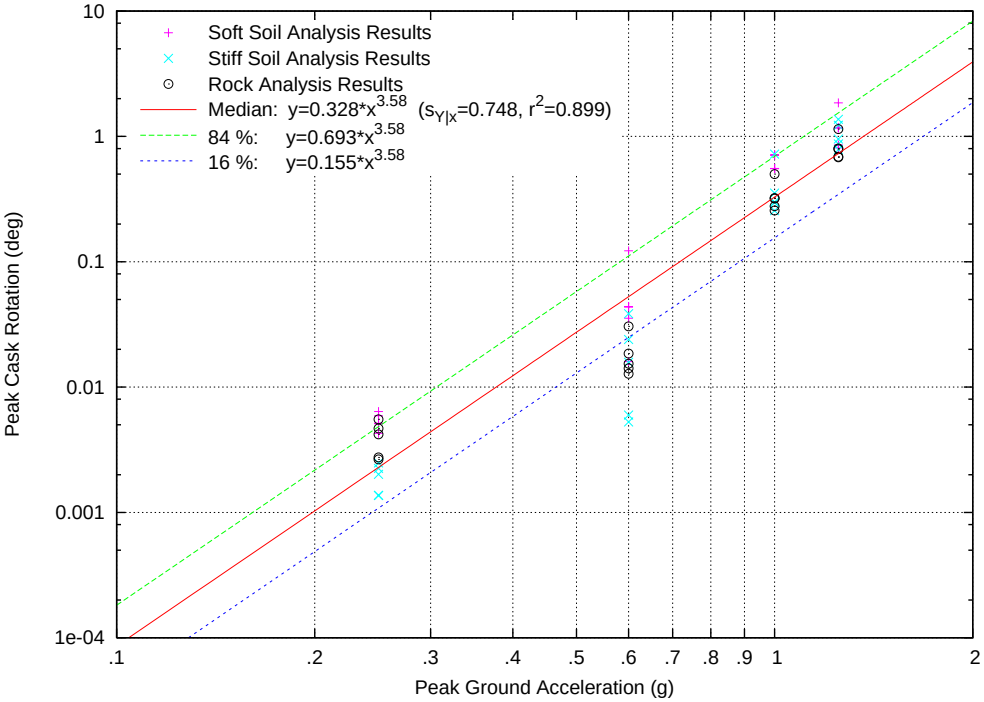

Figure VI.30: Peak Rotation Regression Fit, Rectangular Module, NUREG/CR-0098 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

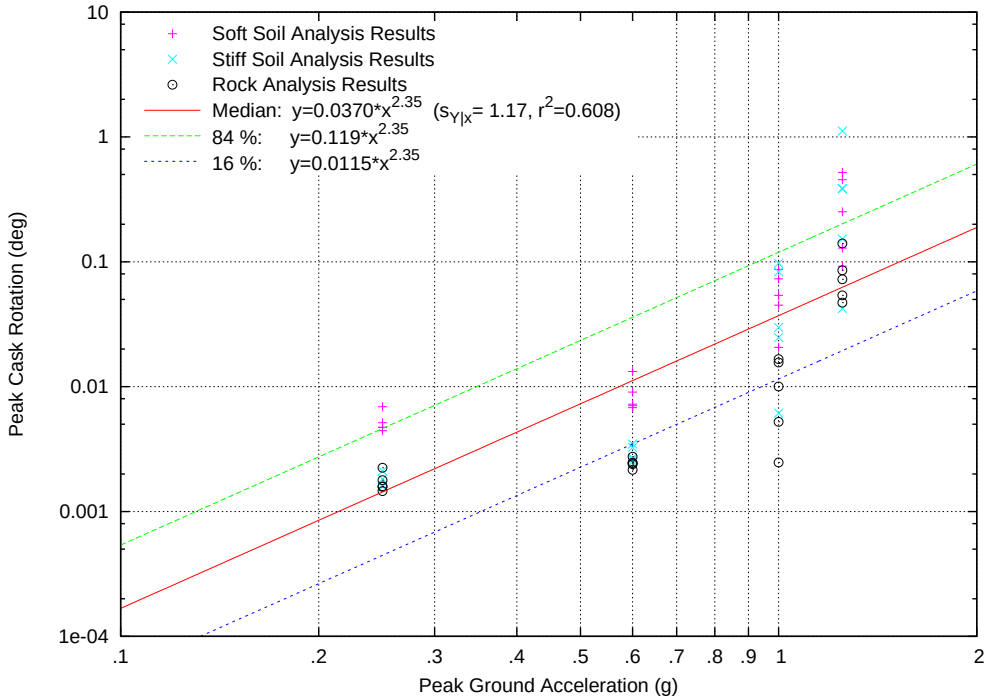

Figure VI.31: Peak Rotation Regression Fit, Rectangular Module, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

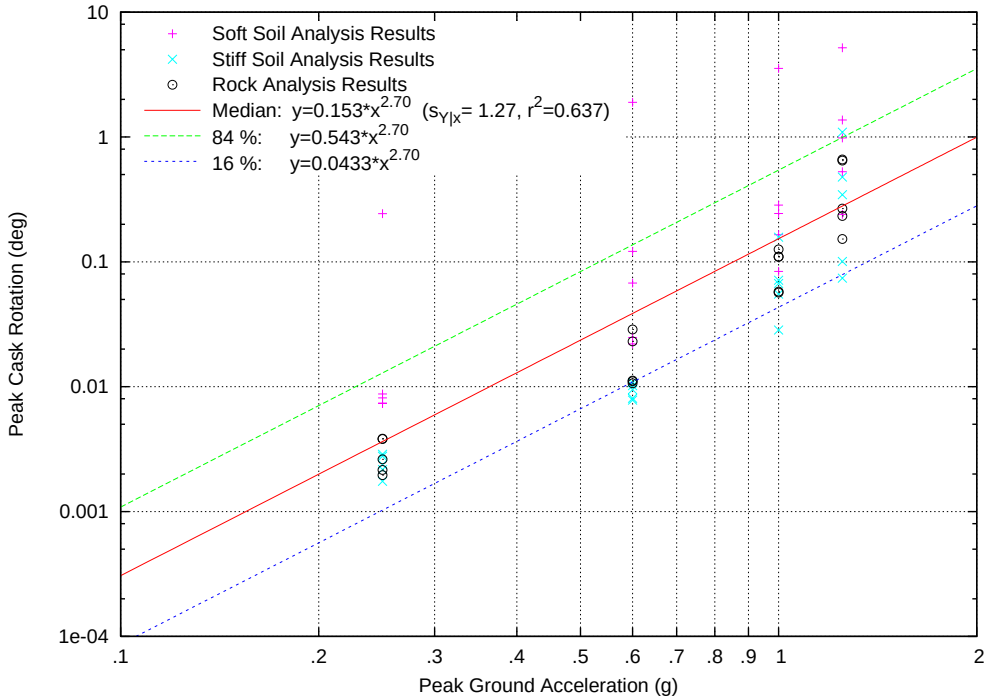

Figure VI.32: Peak Rotation Regression Fit, Rectangular Module, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

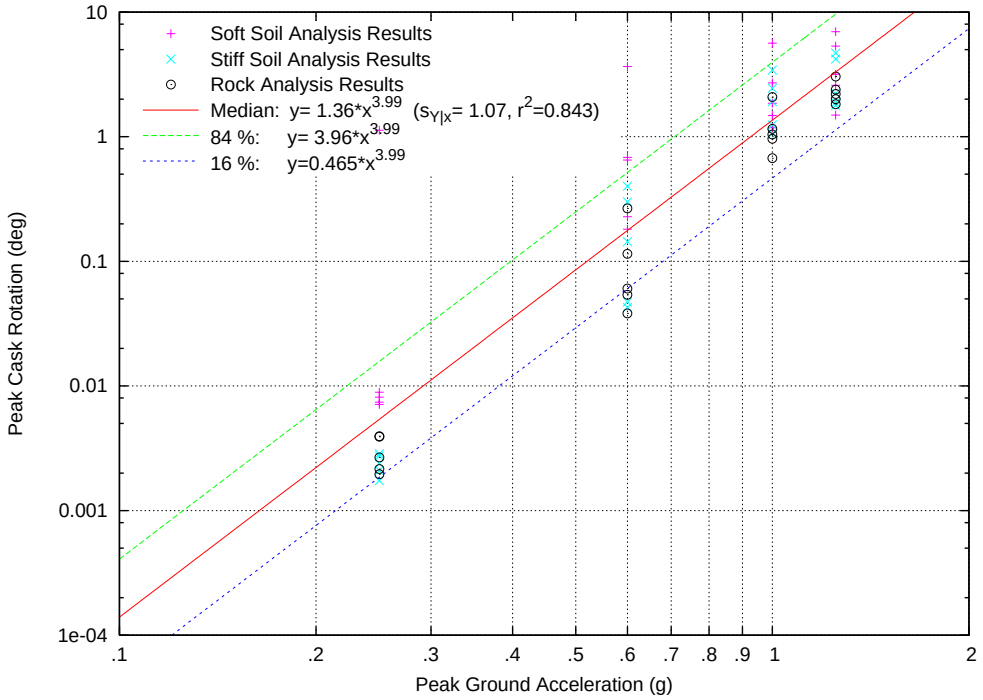

Figure VI.33: Peak Rotation Regression Fit, Rectangular Module, Regulatory Guide 1.60 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

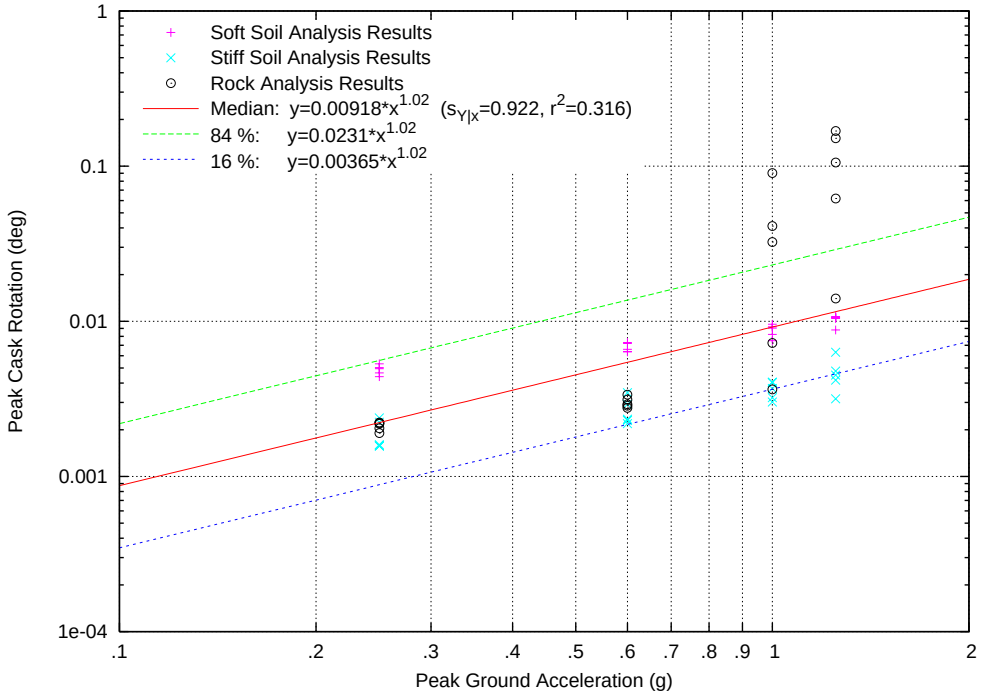

Figure VI.34: Peak Rotation Regression Fit, Rectangular Module, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

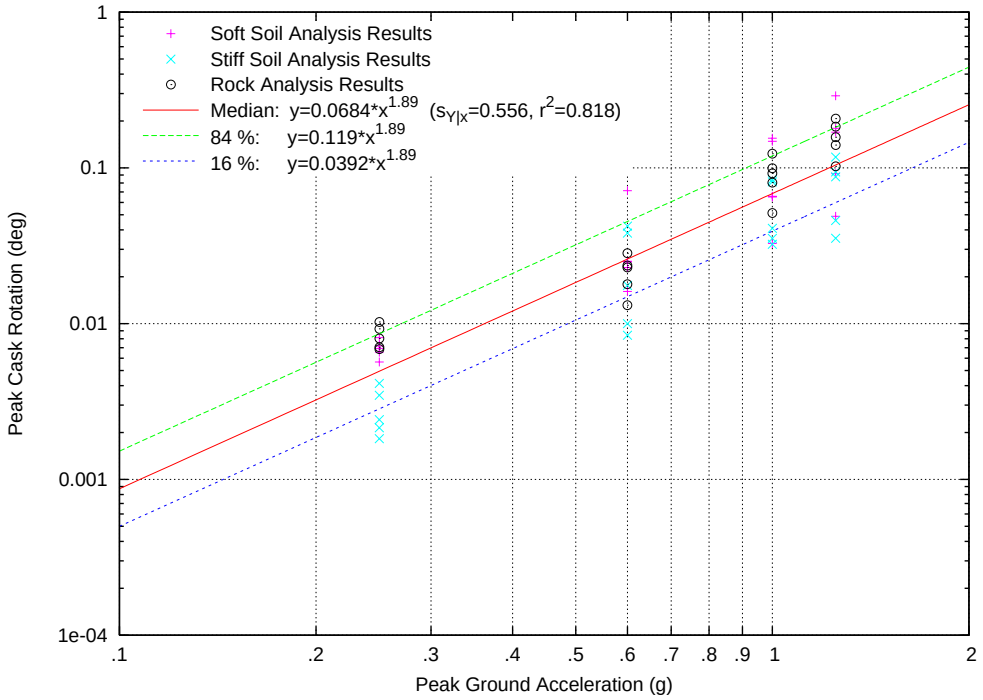

Figure VI.35: Peak Rotation Regression Fit, Rectangular Module, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

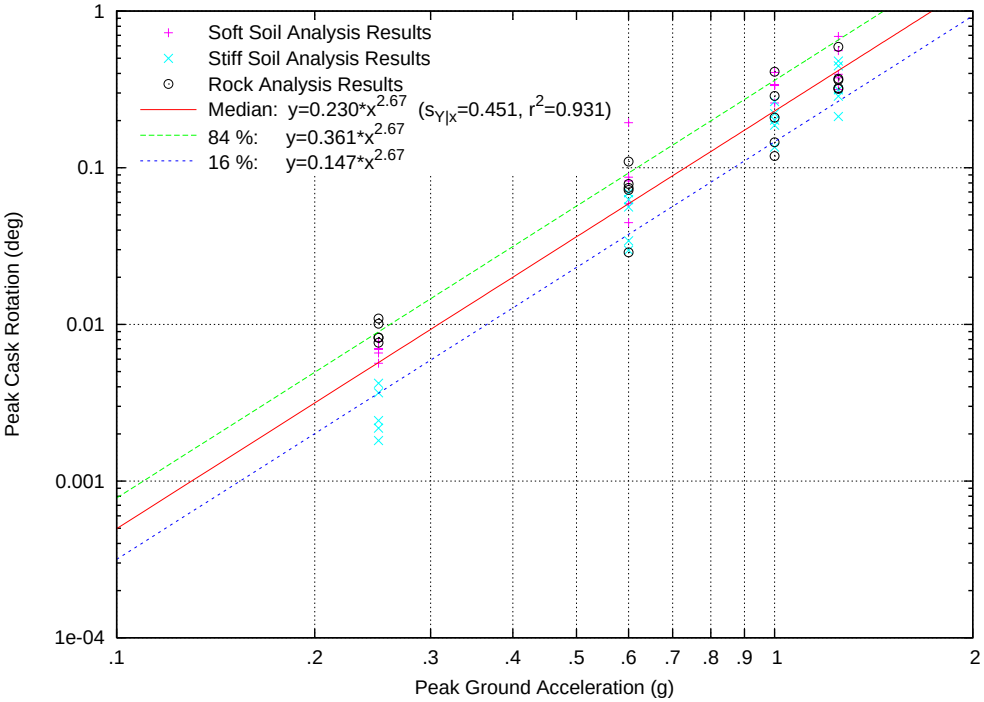

Figure VI.36: Peak Rotation Regression Fit, Rectangular Module, NUREG/CR-6728 Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

VI.2 Nomograms for Combined Spectral Shapes in Terms of 1 Hz PSA

An additional grouping has been performed on the data sets used to generate the regression plots shown in the previous section. The results obtained for all three spectral shapes are grouped together, but instead of using PGA as the ground motion parameter, the PSA at 5% damped 1Hertz (Hz) is used. This parameter is a better indicator of the cask response than the PGA and allows the analysis results from the three spectral shapes to be grouped together. Regression plots are provided for each combination of the two cask designs and three cask/pad friction coefficients. As was done in the previous section, the results for the three soil profiles are grouped together into the same data set. Plots of the peak cask top displacement and peak rotation are provided on both logarithmic and linear scales.

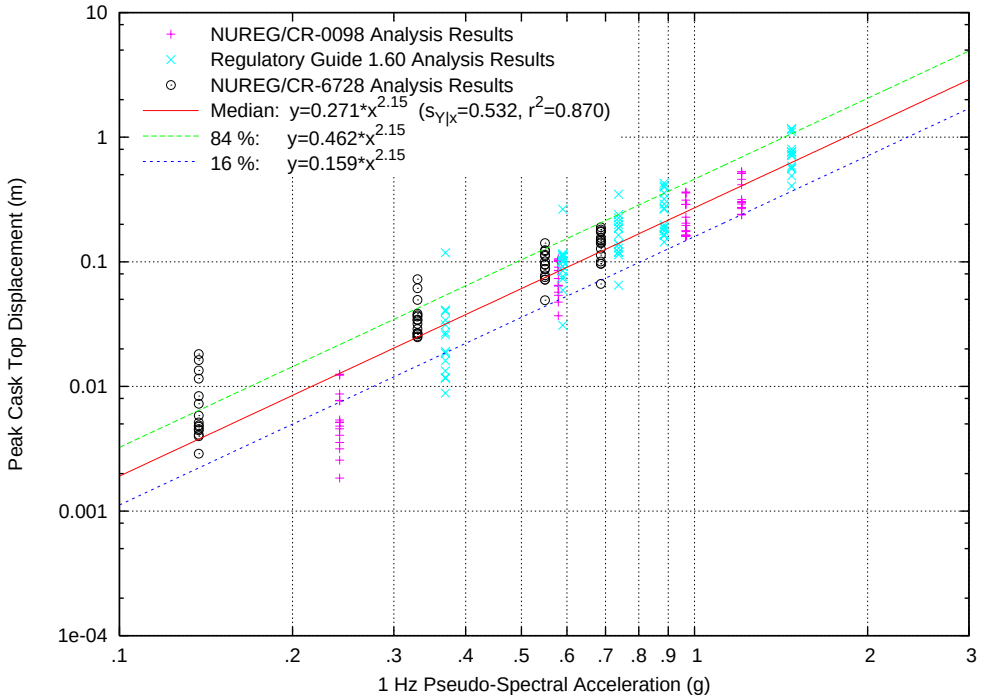

Figure VI.37: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

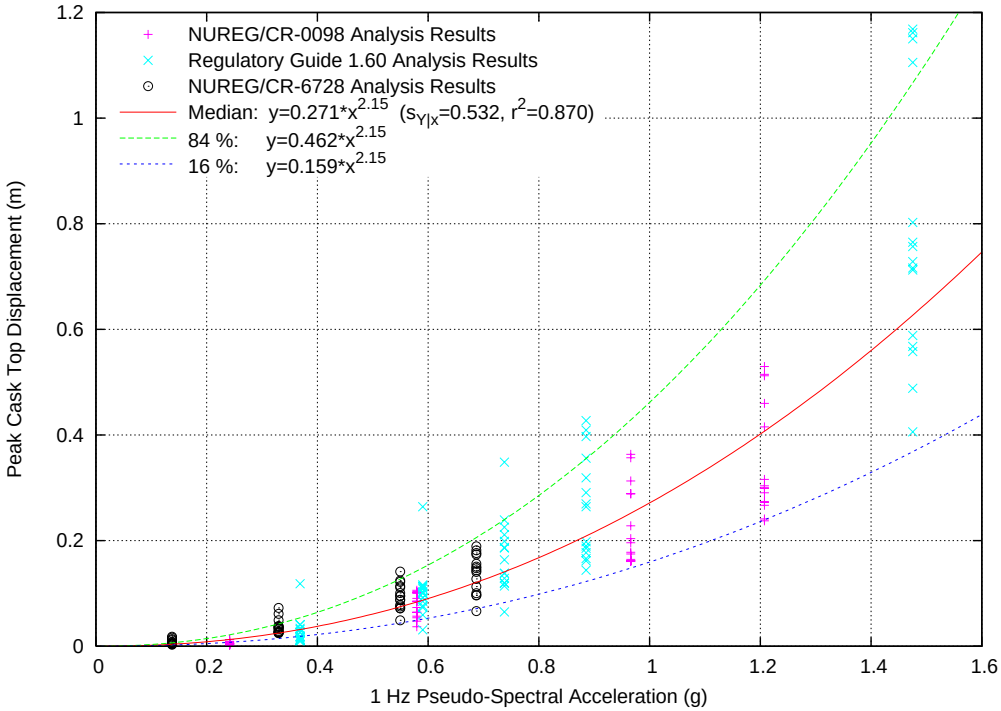

Figure VI.38: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Linear Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

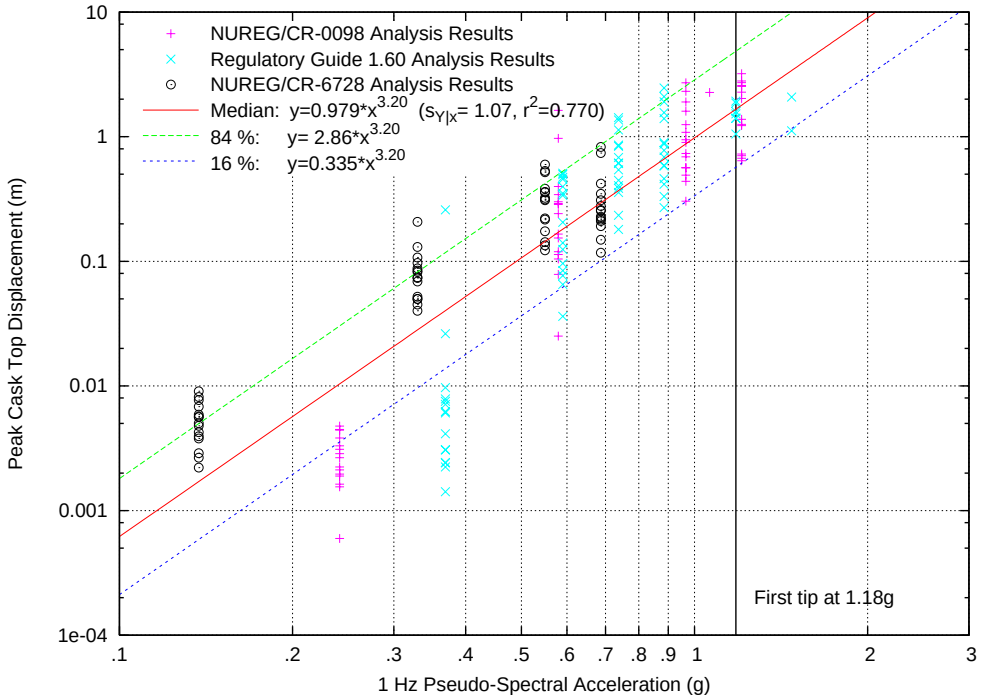

Figure VI.39: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

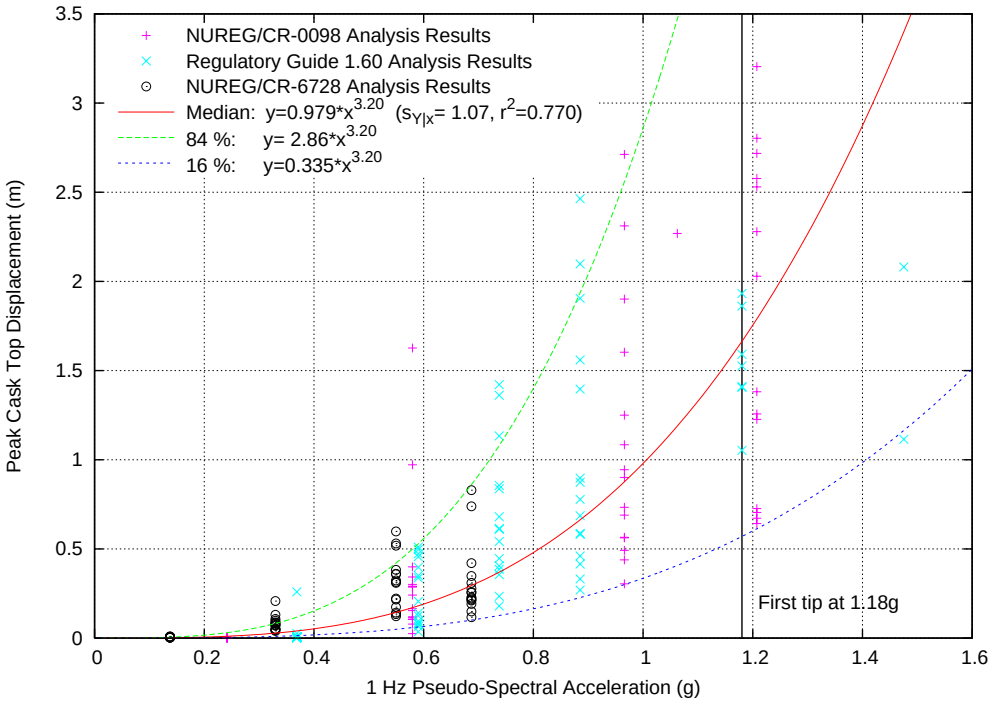

Figure VI.40: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Linear Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

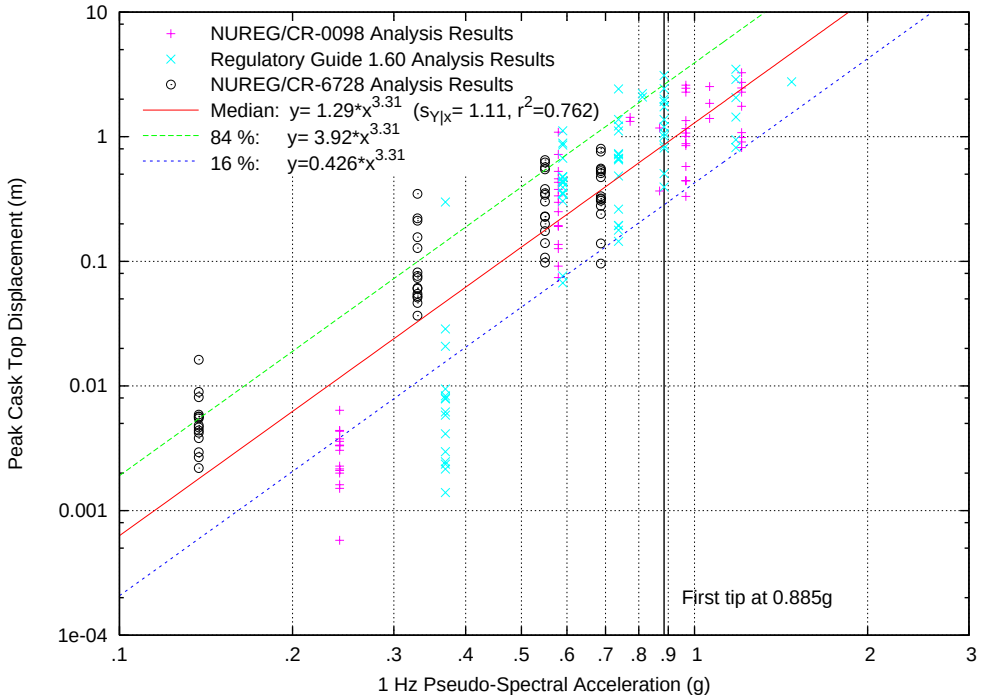

Figure VI.41: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

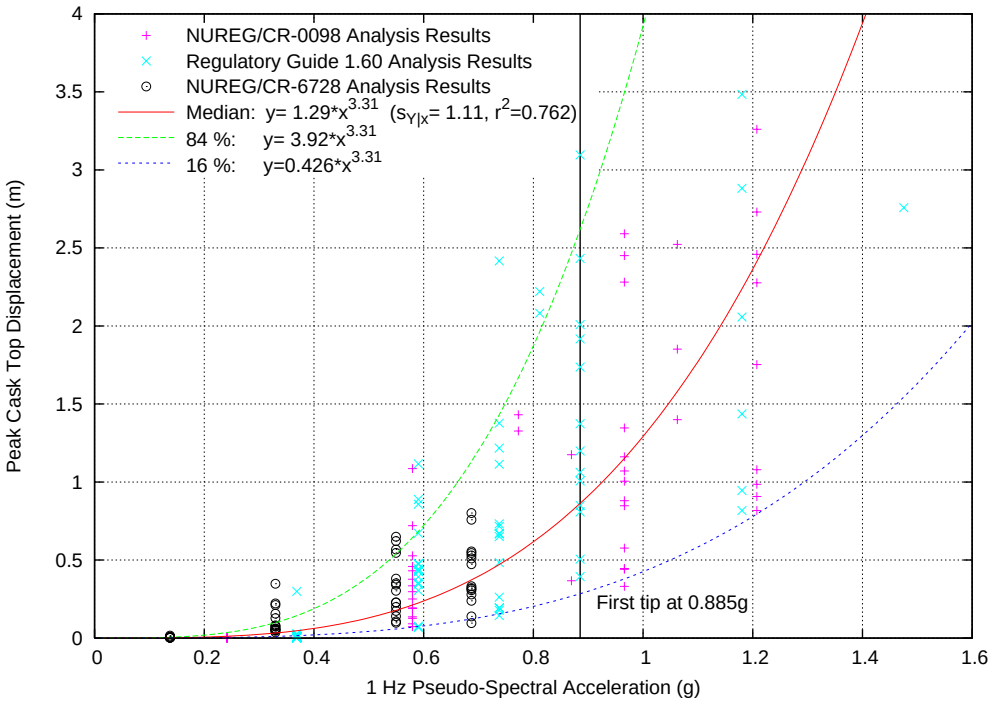

Figure VI.42: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Linear Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

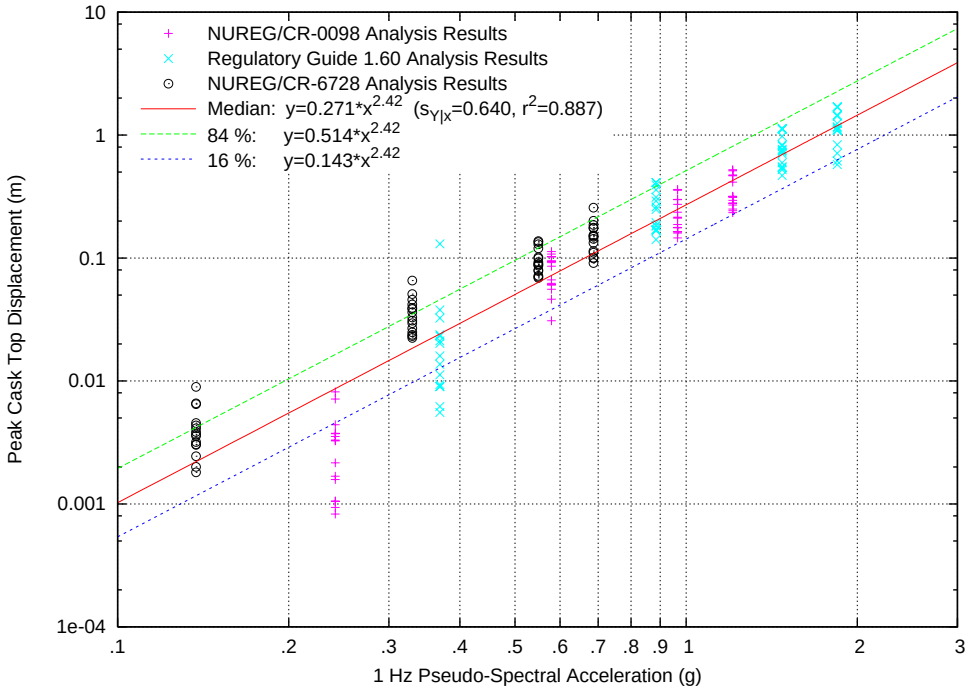

Figure VI.43: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

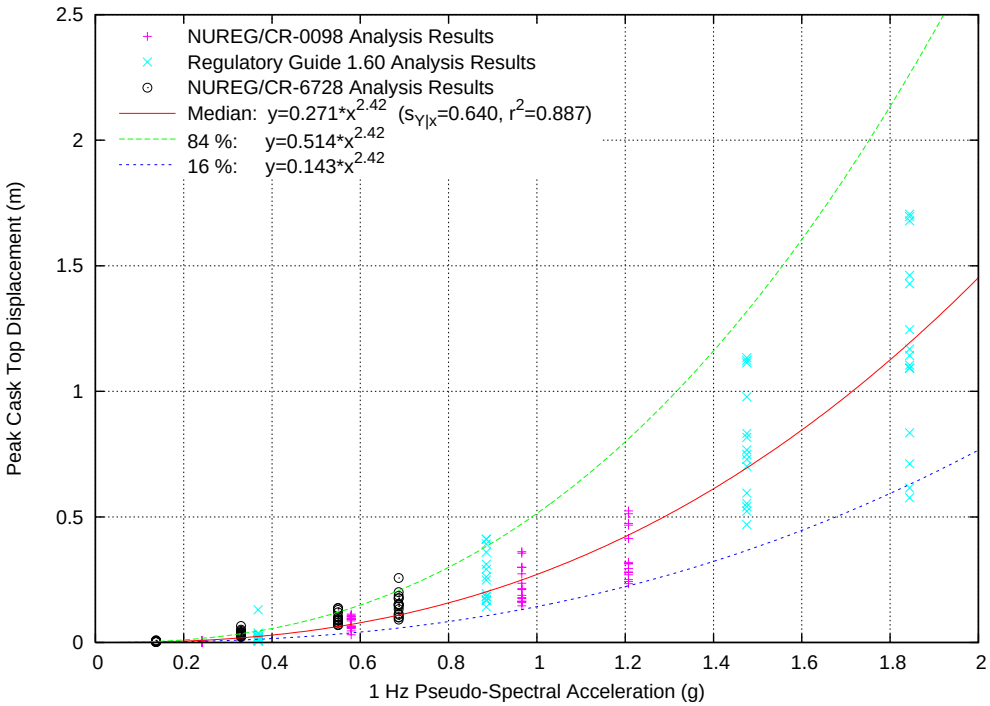

Figure VI.44: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Linear Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

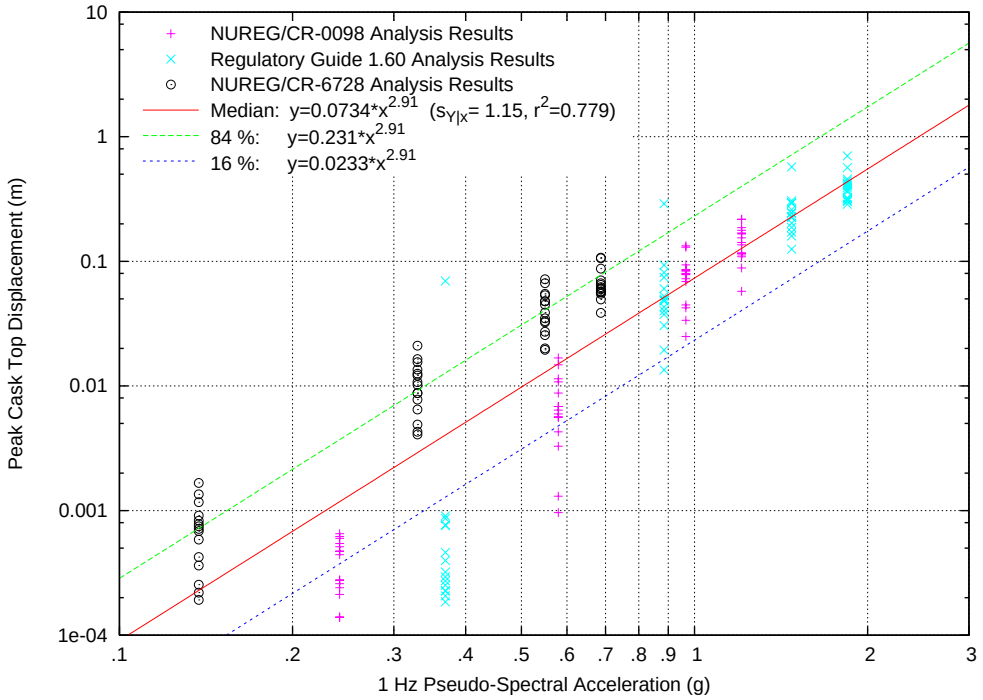

Figure VI.45: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

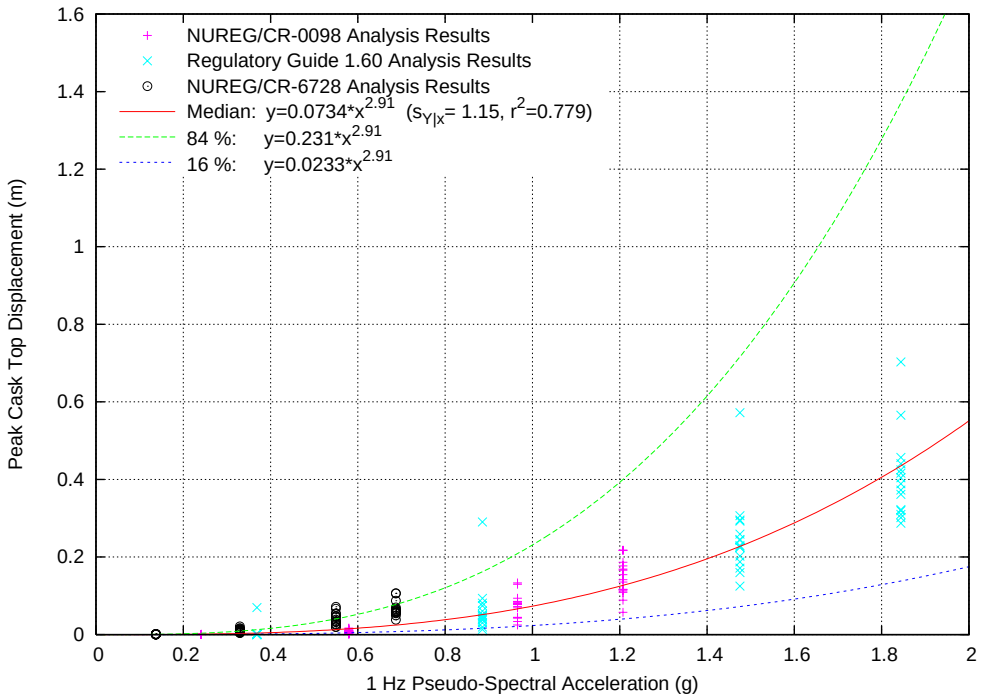

Figure VI.46: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Linear Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

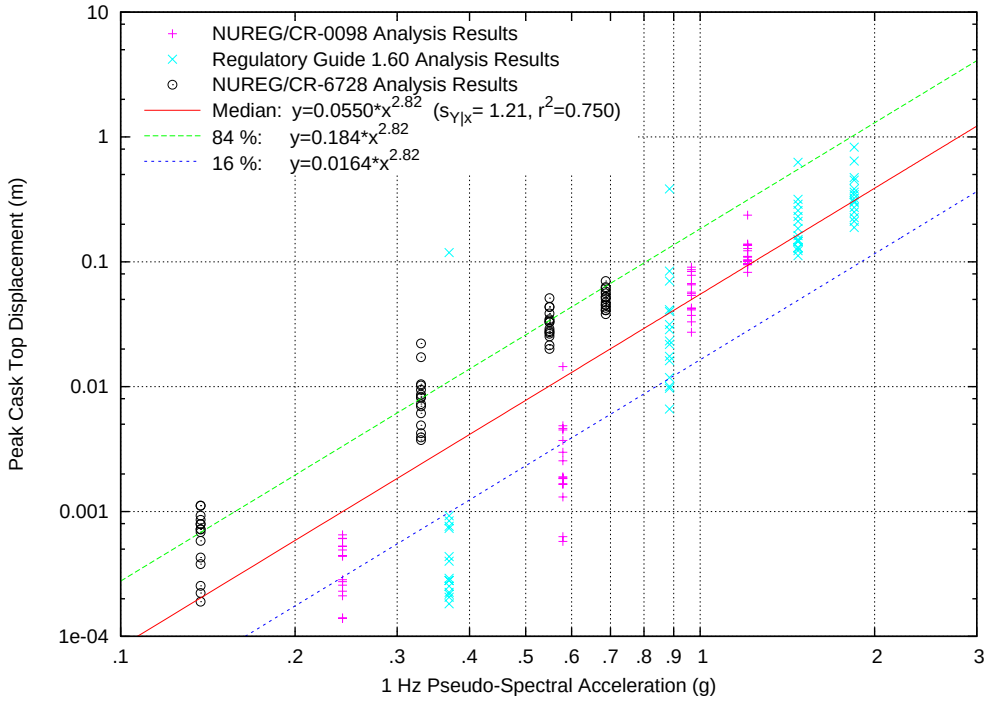

Figure VI.47: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

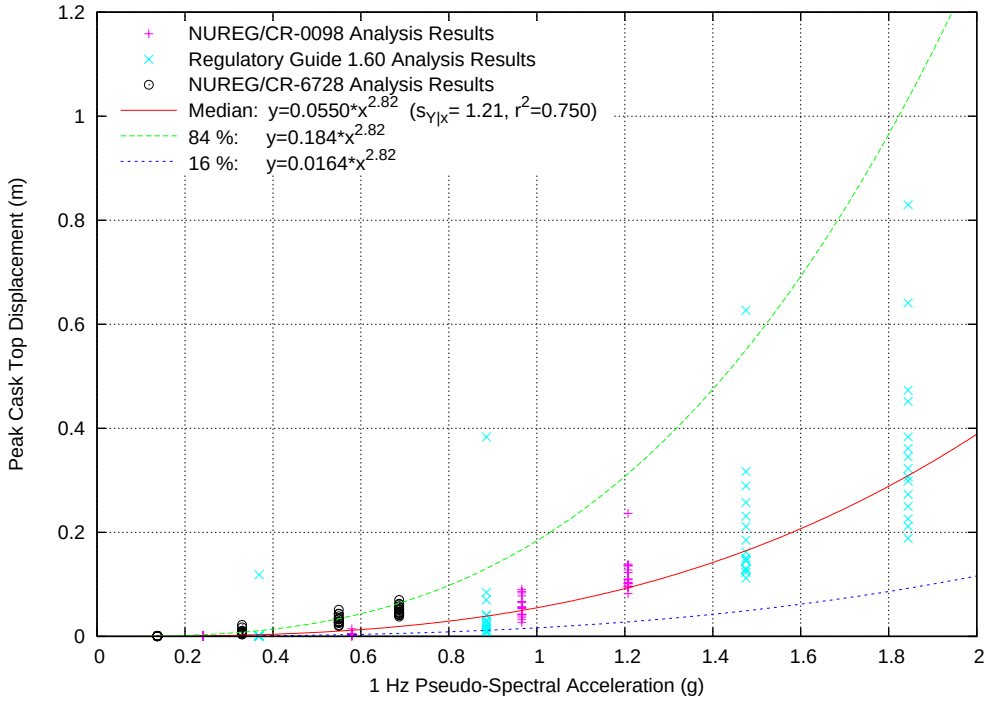

Figure VI.48: Peak Top Displacement Regression Fit in Terms of 1 Hz PSA, Linear Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

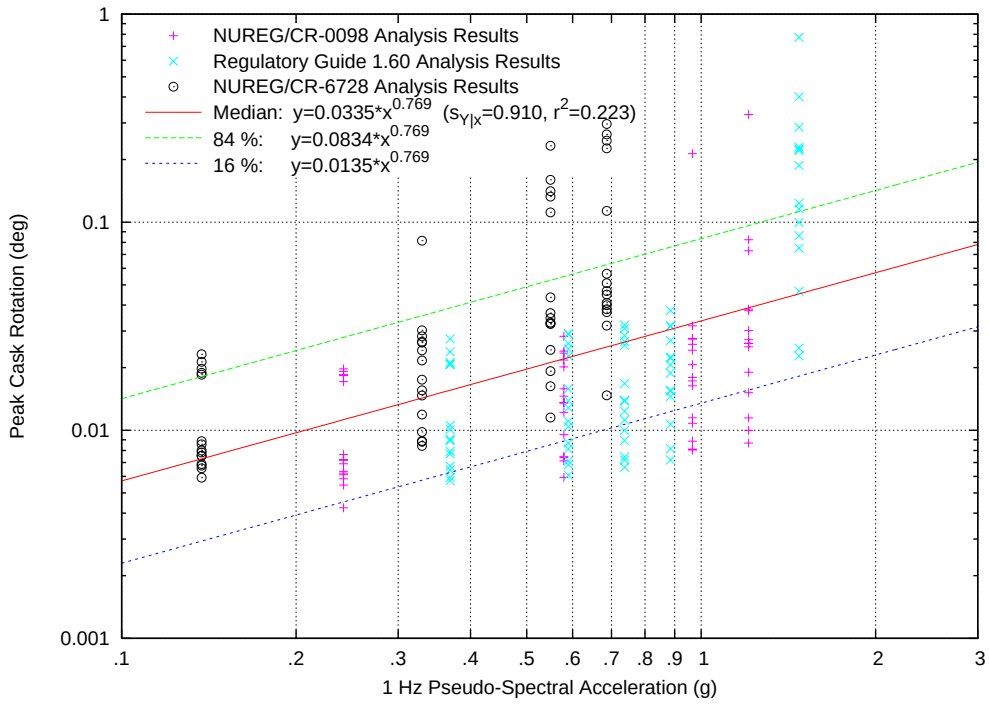

Figure VI.49: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

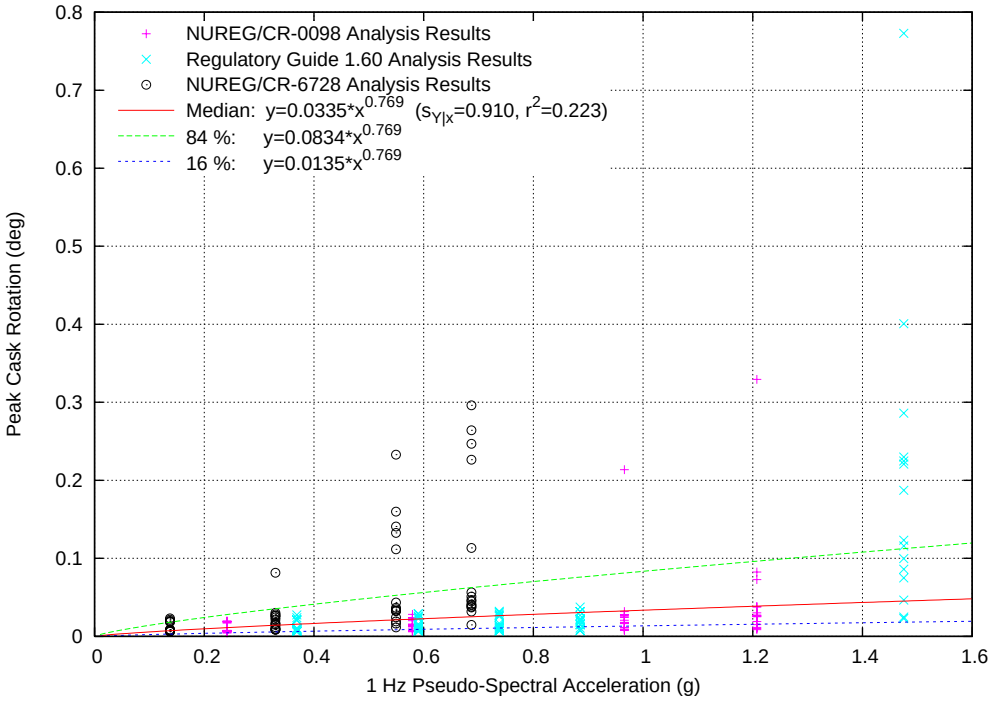

Figure VI.50: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Linear Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

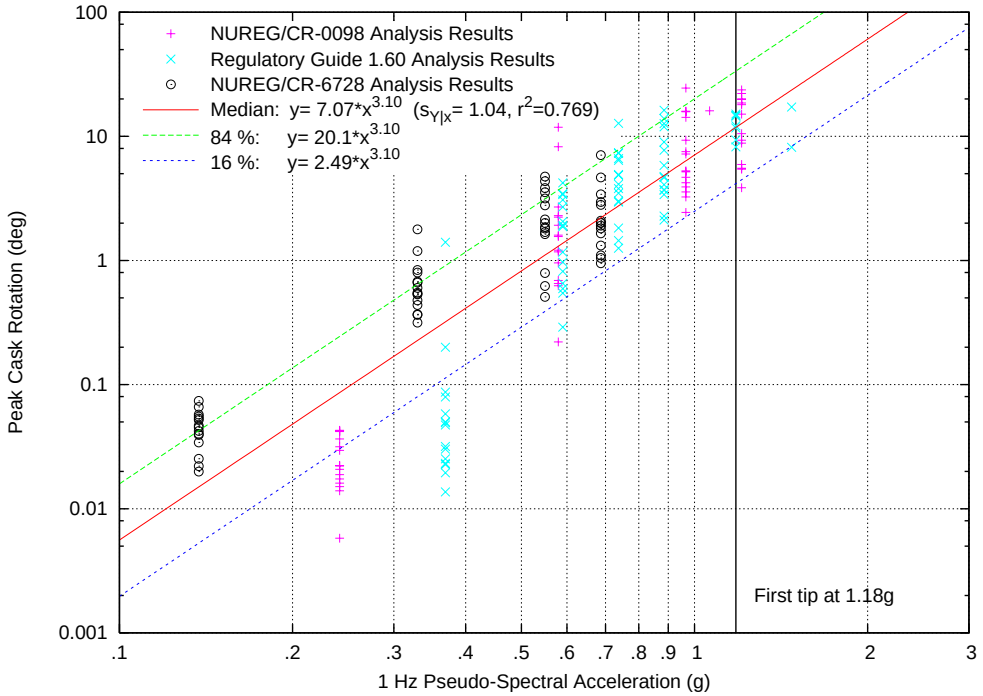

Figure VI.51: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

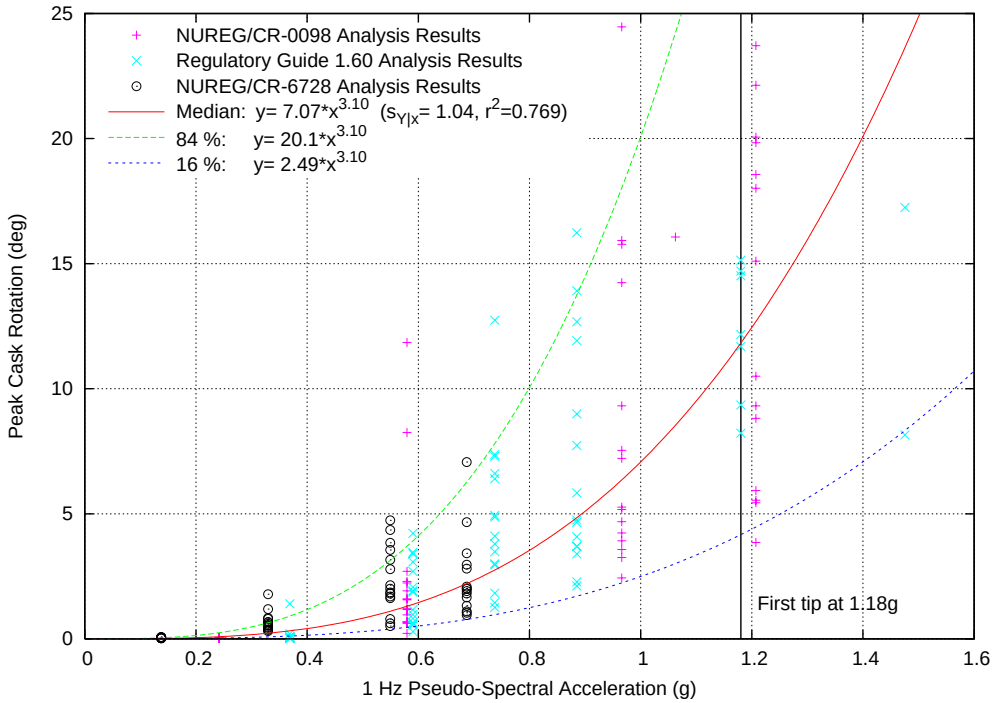

Figure VI.52: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Linear Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

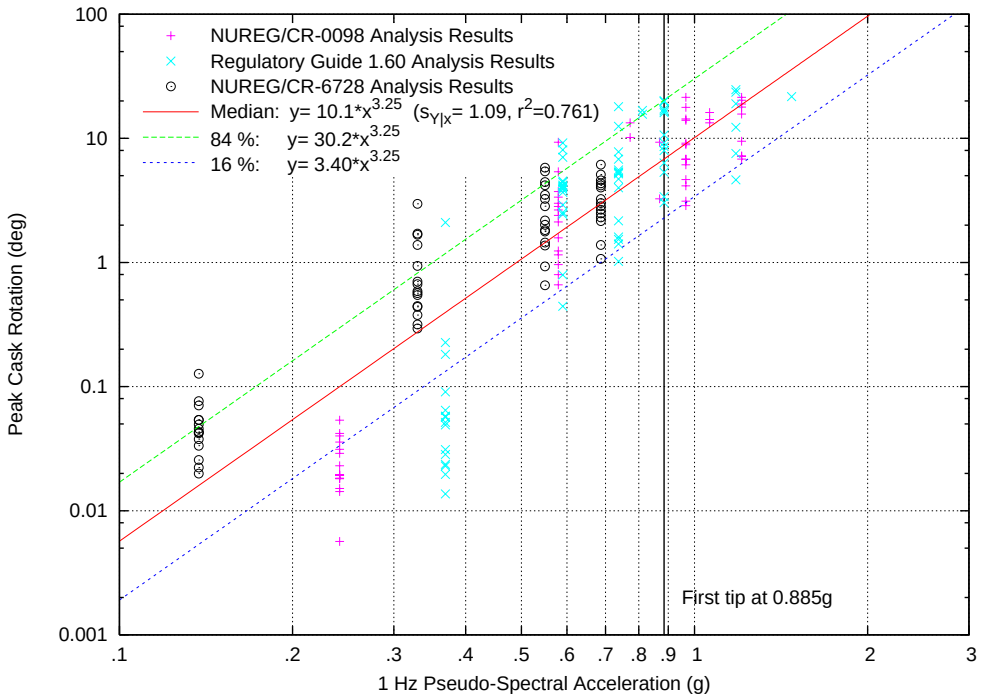

Figure VI.53: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

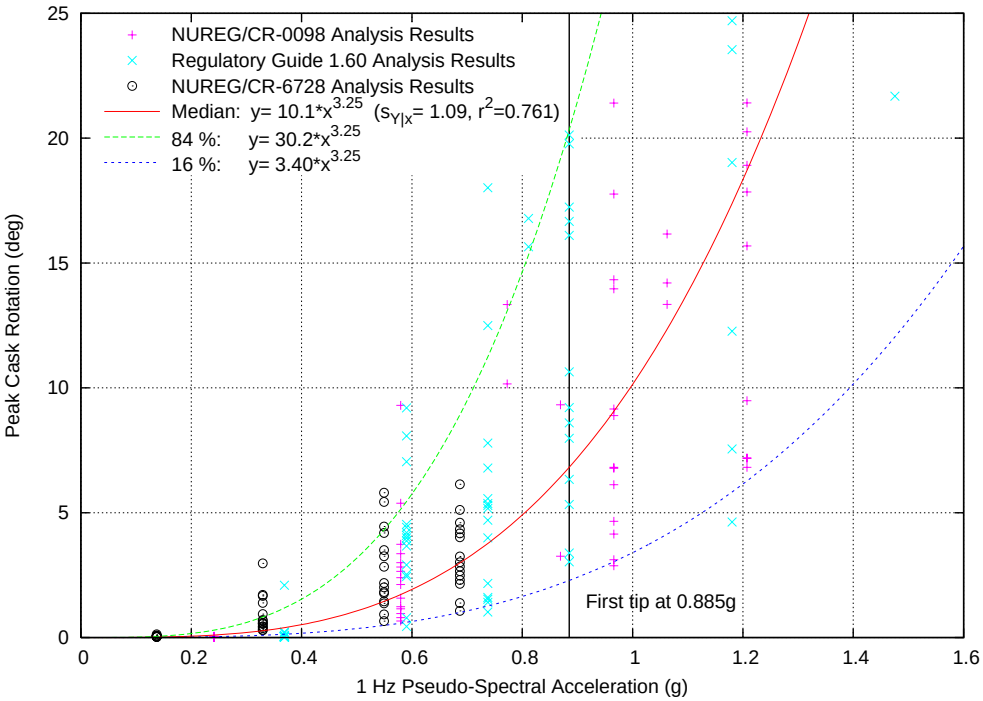

Figure VI.54: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Linear Scale, Cylindrical Cask, All Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

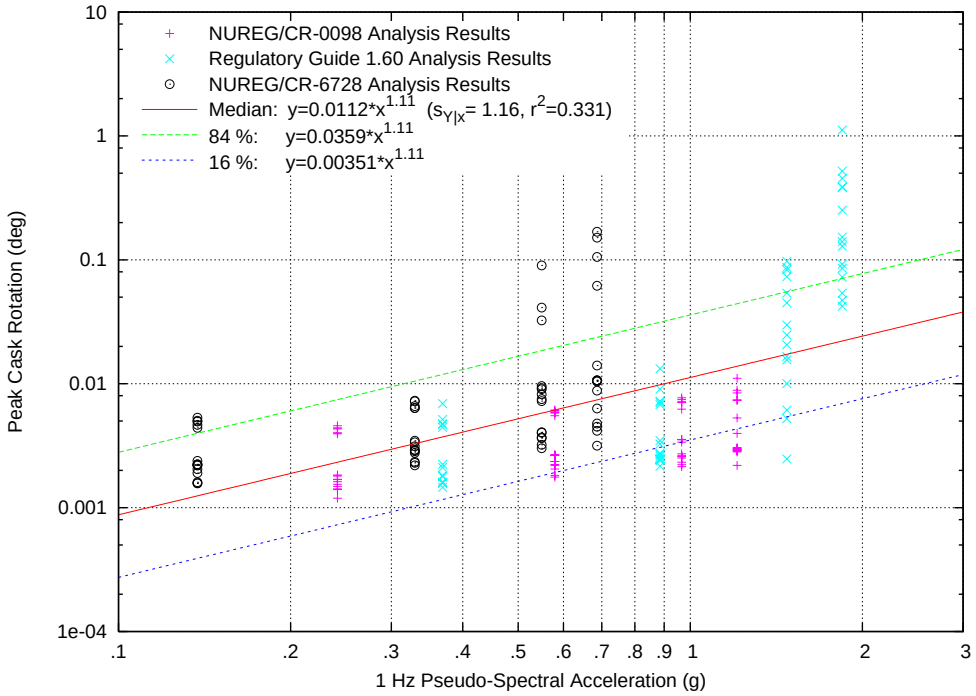

Figure VI.55: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

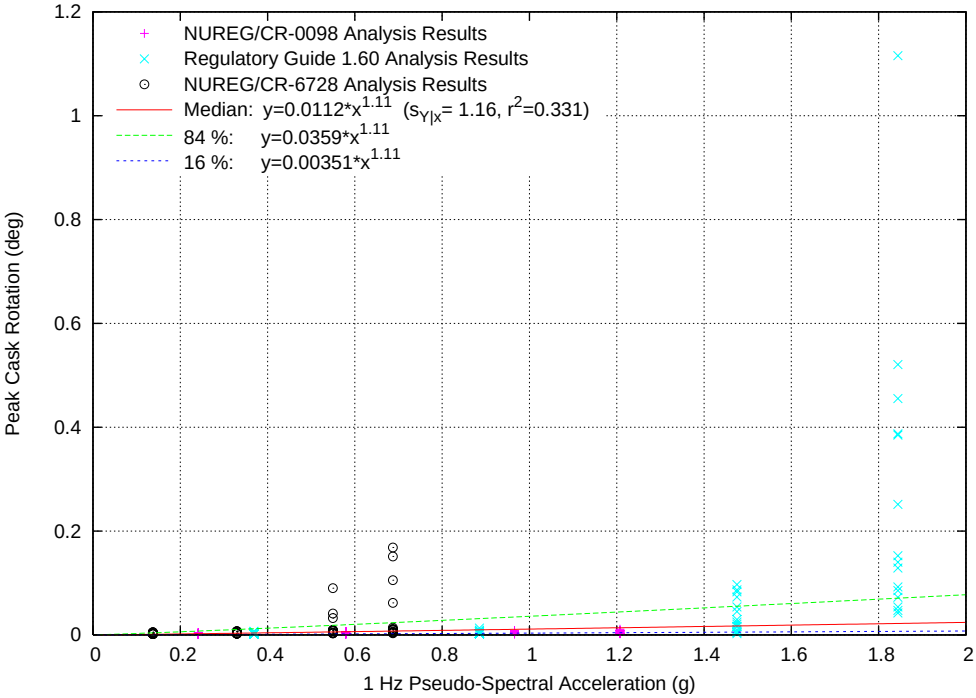

Figure VI.56: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Linear Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.2, All Soil Profiles

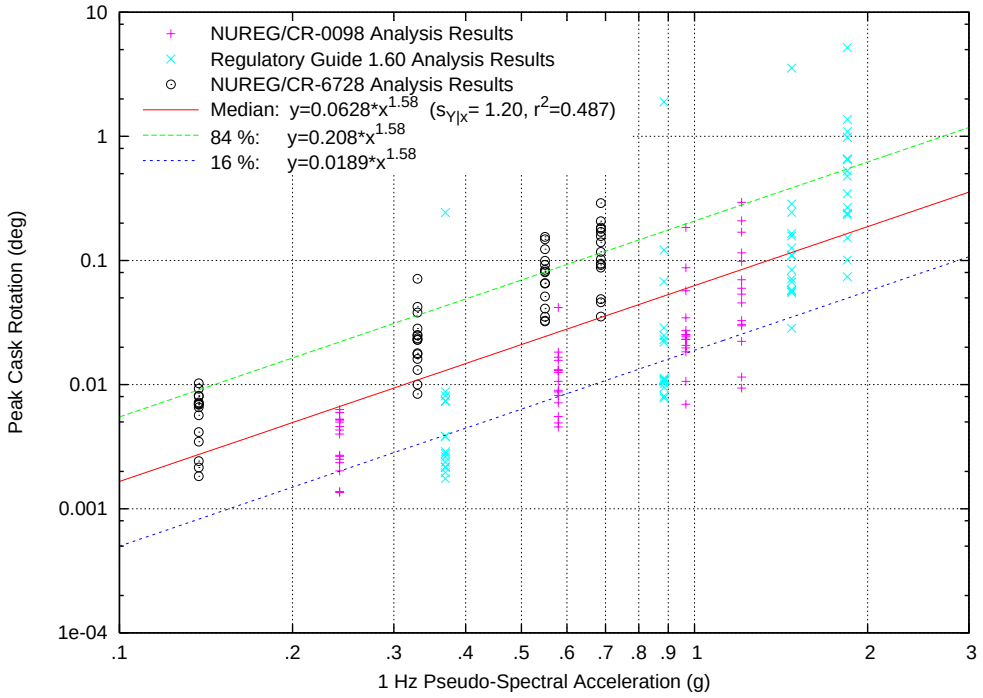

Figure VI.57: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

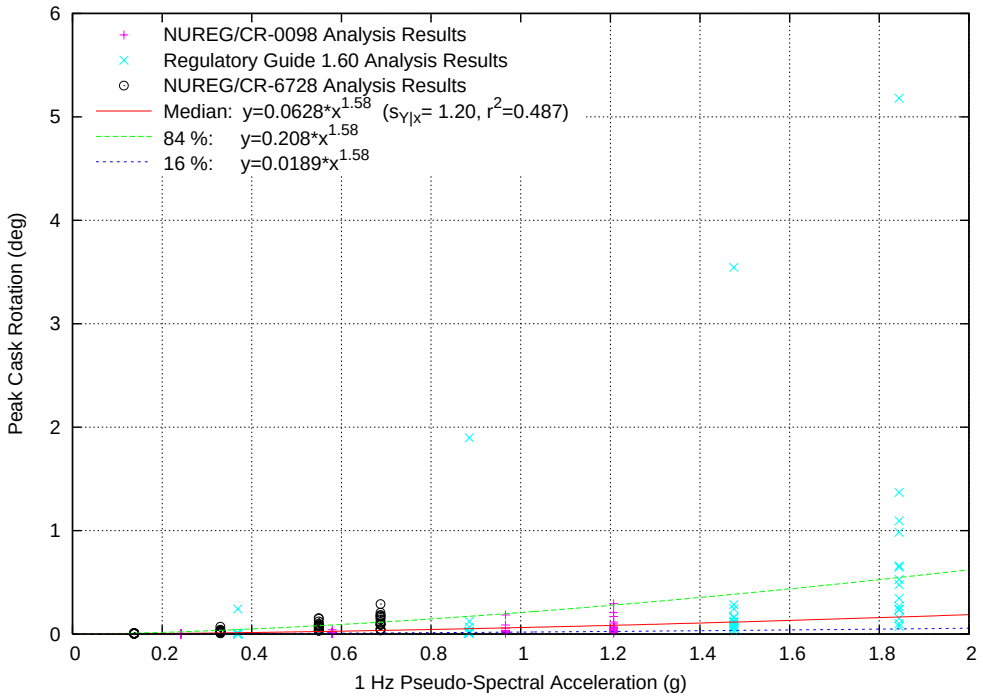

Figure VI.58: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Linear Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.55, All Soil Profiles

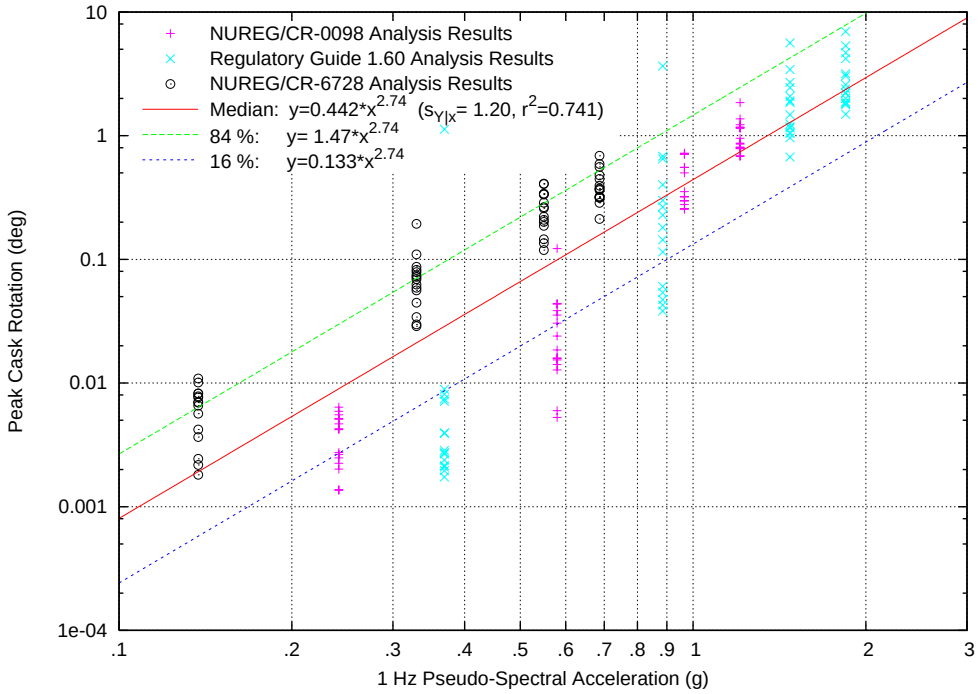

Figure VI.59: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Logarithmic Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

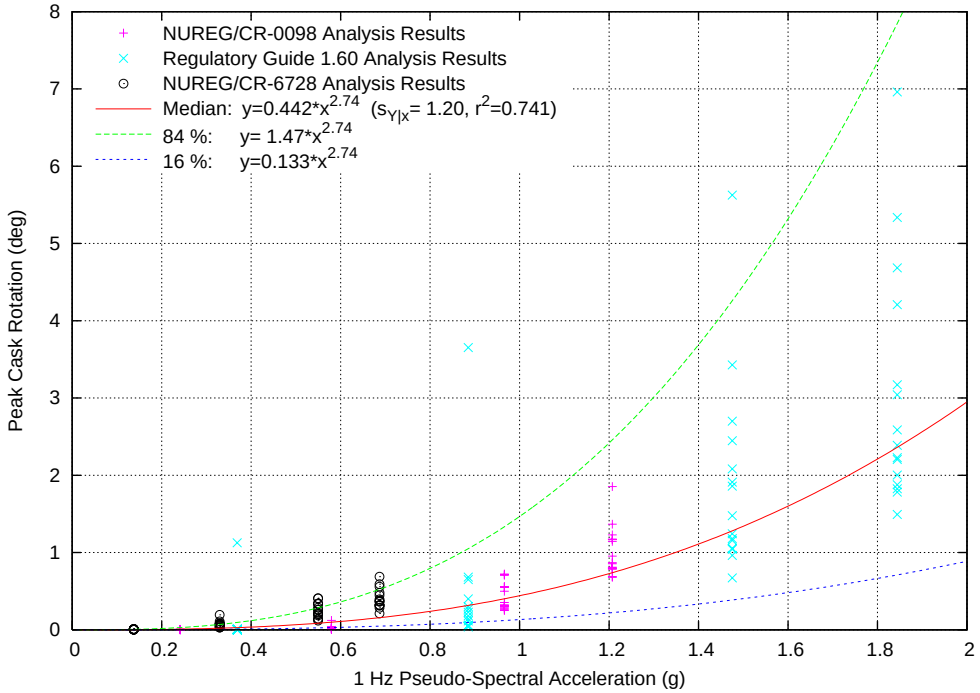

Figure VI.60: Peak Rotation Regression Fit in Terms of 1 Hz PSA, Linear Scale, Rectangular Module, All Earthquakes, Cask/Pad μ=0.8, All Soil Profiles

Appendix VII: Tabulation of Curve Fitting Parameters and Example Calculations

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Appendix VII: Tabulation of Curve Fitting Parameters and Example Calculations

The nomograms for the cask response shown in Appendix VI can be used to estimate the peak cask top displacement and peak cask rotation for specific applications. All of the nomograms were developed using the same power law equation from the procedure outlined in Section 5.5. The power law equation for the cask response y in terms of the ground motion parameter x at a confidence band m standard deviations above the median response was provided in Equation 5.12, and is re-iterated here:

$$y = A x^B \exp\left(m S_{Y|x}\right) \tag{VII.1}$$

In this equation, A and B are the curve fitting coefficients and $S_{Y|x}$ is the conditional standard deviation of the result data after undergoing a logarithmic transformation.

VII.1 Tabulation of Curve Fitting Parameters

The values of A, B , and $S_{Y|x}$ have been provided in the legends of each of the plots in Appendix VI. To facilitate application of these results to site-specific cask response evaluations, these parameters are tabulated below in Tables VII.1 through VII.8. These tables show the parameters for the peak cask top displacement response and the peak cask rotation response. Columns denoted with "disp." contain the parameters for the peak cask top displacement, and those denoted with "rot." have the information for the rotation. Tables are provided for the results from the three individual spectral shapes, as well as for the combined results for all spectral shapes. There are separate tables for the cylindrical cask results and for the rectangular module results. The ground motion parameter, x, for the individual spectral shapes is peak ground acceleration (PGA), while the ground response parameter for the combined spectral shapes is the 5% damped 1 Hz Pseudo-Spectral Acceleration (PSA). When these parameters are used in conjunction with Equation VII.1, the response, y, is in meters for the top displacement and in degrees for the rotation angle.

Table VII.1: Curve Fitting Parameters for Cylindrical Cask, NUREG/CR-0098 Earthquakes, PGA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.216	2.60	0.409	0.0217	0.689	0.718
μ=0.55	0.911	4.06	0.814	6.70	3.94	0.794
μ=0.8	1.150	4.16	0.796	9.01	4.09	0.765

Table VII.2: Curve Fitting Parameters for Cylindrical Cask, Regulatory Guide 1.60 Earthquakes, PGA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.837	2.52	0.465	0.0733	1.71	0.785
μ=0.55	8.96	4.80	1.03	62.5	4.71	0.956
μ=0.8	15.4	5.04	1.13	114	4.94	1.12

Table VII.3: Curve Fitting Parameters for Cylindrical Cask, NUREG/CR-6728 Earthquakes, PGA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.0897	1.88	0.377	0.0456	1.17	0.777
μ=0.55	0.219	2.63	0.543	1.64	2.53	0.583
μ=0.8	0.253	2.71	0.631	2.11	2.68	0.606

Table VII.4: Curve Fitting Parameters for Rectangular Module, NUREG/CR-0098 Earthquakes, PGA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.219	3.08	0.544	0.00386	0.418	0.495
μ=0.55	0.0571	3.78	0.594	0.0304	1.67	0.752
μ=0.8	0.0396	3.70	0.765	0.328	3.58	0.748

Table VII.5: Curve Fitting Parameters for Rectangular Module, Regulatory Guide 1.60 Earthquakes, PGA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.724	2.63	0.519	0.037	2.35	1.17
μ=0.55	0.225	4.16	0.912	0.153	2.70	1.27
μ=0.8	0.172	4.07	0.996	1.36	3.99	1.07

Table VII.6: Curve Fitting Parameters for Rectangular Module, NUREG/CR-6728 Earthquakes, PGA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.0937	2.27	0.335	0.00918	1.02	0.922
μ=0.55	0.0369	2.92	0.477	0.0684	1.89	0.556
μ=0.8	0.0297	2.81	0.417	0.230	2.67	0.451

Table VII.7: Curve Fitting Parameters for Cylindrical Cask, All Spectral Shapes, 1 Hz PSA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.271	2.15	0.532	0.0335	0.769	0.91
μ=0.55	0.979	3.20	1.07	7.07	3.10	1.04
μ=0.8	1.29	3.31	1.11	10.1	3.25	1.09

Table VII.8: Curve Fitting Parameters for Rectangular Module, All Spectral Shapes, 1 Hz PSA

	A (disp.)	B (disp.)	$S_{Y\|x}$ (disp.)	A (rot.)	B (rot.)	$S_{Y\|x}$ (rot.)
μ=0.2	0.271	2.42	0.640	0.0112	1.11	1.16
μ=0.55	0.0734	2.91	1.15	0.0628	1.58	1.20
μ=0.8	0.0550	2.82	1.21	0.442	2.74	1.20

VII.2 Example Calculations

To illustrate the usage of the nomograms, example calculations for two site-specific applications are provided. The two example applications shown here are the Independent Spent Fuel Storage Installation at the Hatch Nuclear Power Station and the proposed Private Fuel Storage (PFS) Facility. Both of these sites use casks with the same characteristics as the cylindrical cask in the parametric study.

VII.2.1 Hatch Example

Figure VII.1 shows a plot of the three horizontal spectral shapes used in this study to develop nomograms, along with the spectral shape of the Hatch site-specific design earthquake. These spectral shapes have all been normalized to the horizontal PGA. The horizontal PGA of the Hatch design earthquake is 0.15 g. From this plot, it can be seen that the Hatch design earthquake has a very similar shape to the NUREG/CR-0098 spectral shape in this study. Because of this close correspondence, it is reasonable to use the nomograms developed from that spectral shape for evaluating this site-specific case. To illustrate the procedure for using the nomograms derived from specific spectra, as well as that for the combined nomograms, both approaches will be illustrated here.

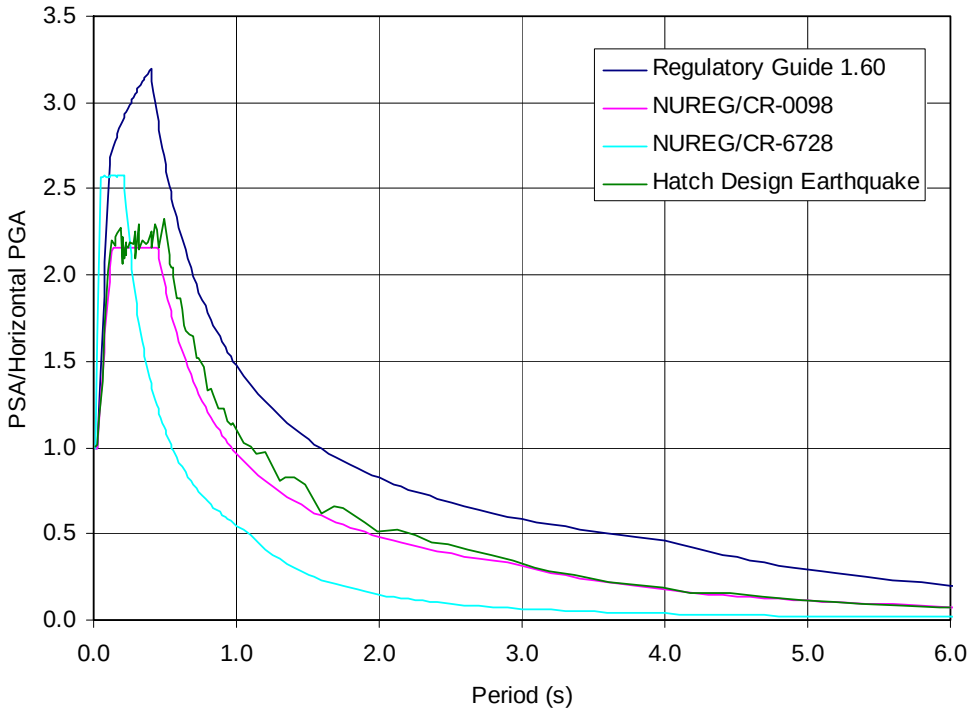

Figure VII.1: Comparison of Hatch Site-Specific Horizontal Spectral Shape with Spectral Shapes Used to Develop Nomograms in the Parametric Study

To apply the NUREG-CR/0098 spectral shape nomograms to this case, one would use the coefficients provided in Table VII.1, in conjunction with Equation VII.1. To compute the median response, one should set m=0 in that equation. Because exp(0)=1, the entire term related to the confidence band can simply be dropped out of the equation in that case. For the 84% confidence response, one should set m=1. Using the appropriate parameters from Table VII.1, the median cask top displacement with the lower bound μ=0.2 would be computed as:

$$\text{peak top displacement} = 0.216 \cdot 0.15^{2.6} = 0.0016\text{m (0.061 in)}$$

In a similar manner, the 84% cask response for that same case is calculated:

$$\text{peak top displacement} = 0.216 \cdot 0.15^{2.6} \cdot \exp(1.0 \cdot 0.409) = 0.0023\text{m (0.092 in)}$$

The same process is used to compute the peak rotation. The median rotation for that same case would be:

$$\text{peak rotation} = 0.0217 \cdot 0.15^{0.689} = 0.0059\,\text{deg}$$

The 84% rotation would be computed as:

$$\text{peak rotation} = 0.0217 \cdot 0.15^{0.689} \cdot \exp(1.0 \cdot 0.718) = 0.012\,\text{deg}$$

Similar calculations are performed using the appropriate parameters for the other coefficients of friction. A complete set of these computed cask top displacements and rotations using the nomograms for the NUREG/CR-0098 spectral shape is provided in Table VII.9.

TableVII.9: Cask Response Predicted by NUREG/CR-0098 Spectrum Nomograms for Hatch Example

	Median Top Disp. m (in)	**84% Top Disp. m (in)**	**Median Rotation (degrees)**	**84% Rotation (degrees)**
μ=0.2	0.0016 (0.061)	0.0023 (0.092)	0.0059	0.012
μ=0.55	0.00041 (0.016)	0.00093 (0.037)	0.0038	0.0084
μ=0.8	0.00043 (0.017)	0.00095 (0.038)	0.0038	0.0083

The procedure to apply the combined nomograms is very similar to that illustrated above for a specific spectral shape. The major difference is that the 5% damped 1 Hz PSA is used instead of the PGA as the ground motion parameter. The parameters in Table VII.7 should be used to apply the combined nomogram for this application. The design earthquake at this site has a 5% damped 1 Hz PSA of 0.17 g. The median cask top displacement with the lower bound μ=0.2 is computed as:

$$\text{peak top displacement} = 0.271 \cdot 0.17^{2.15} = 0.0060\text{m (0.24 in)}$$

The corresponding 84% cask top displacement is:

$$\text{peak top displacement} = 0.271 \cdot 0.17^{2.15} \cdot \exp(1.0 \cdot 0.532) = 0.010\text{m (0.40 in)}$$

Rotations are computed in a similar manner. The median rotation is:

$$\text{peak rotation} = 0.0335 \cdot 0.17^{0.769} = 0.0086\,\text{deg}$$

Finally, the 84% rotation is computed as:

$$\text{peak rotation} = 0.0335 \cdot 0.17^{0.769} \cdot \exp(1.0 \cdot 0.910) = 0.021\,\text{deg}$$

A table of the complete set of cask top displacements and rotations computed using the combined nomograms is provided in Table VII.10. It can be seen that the combined nomograms indicate somewhat higher responses than the nomograms for the NUREG/CR-0098 spectral shape, but both sets of results are quite small in this case.

TableVII.10: Cask Response Predicted by Combined Nomograms for Hatch Example

	Median Top Disp. m (in)	**84% Top Disp. m (in)**	**Median Rotation (degrees)**	**84% Rotation (degrees)**
μ=0.2	0.0060 (0.24)	0.010 (0.40)	0.0086	0.021
μ=0.55	0.0034 (0.13)	0.0098 (0.39)	0.029	0.082
μ=0.8	0.0037 (0.14)	0.011 (0.44)	0.032	0.095

VII.2.2 Private Fuel Storage Example

Figure VII.2 shows the 5% damped pseudo-spectral acceleration spectrum of the horizontal ground motion records for the PFS design earthquake. As for the Hatch example, the spectra in this plot have all been normalized to the PGA to facilitate comparison of the spectral shapes. The PFS design earthquake has a PGA of 0.74 g, and a 5% damped, 1 Hz PSA of 0.53 g. It can been seen in this plot that the PFS design earthquake does not correspond as closely as the Hatch design earthquake did to any of the spectral shapes used in the parametric study. Because of this, calculations only are provided based on the combined nomograms for this case.

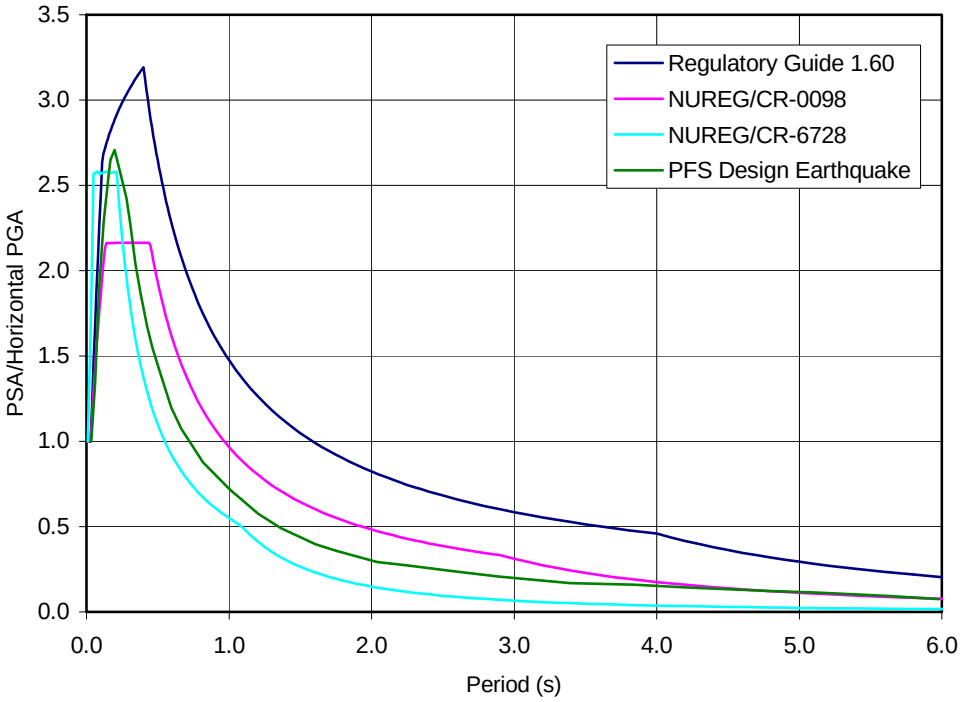

Figure VII.2: Comparison of PFS Site-Specific Horizontal Spectral Shape with Spectral Shapes Used to Develop Nomograms in the Parametric Study

Exactly the same procedure used for the Hatch example using the combined nomograms is used here to compute the cask response. The ground motion parameter used in these calculations is 0.53 g. This has been used in conjunction with the parameters in Table VII.7 and Equation VII.1 to produce the table of cask responses with varying values of μ shown in Table VII.11.

TableVII.11: Cask Response Predicted by Combined Nomograms for PFS Example

	Median Top Disp. m (in)	**84% Top Disp. m (in)**	**Median Rotation (degrees)**	**84% Rotation (degrees)**
μ=0.2	0.069 (2.7)	0.12 (4.6)	0.021	0.051
μ=0.55	0.13 (5.1)	0.37 (15)	0.99	2.8
μ=0.8	0.16 (6.2)	0.48 (19)	1.3	3.8

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10. SUPPLEMENTARY NOTES
Syed K. Shaukat, NRC Project Manager

11. ABSTRACT *(200 words or less)*

Sandia National Laboratories has been contracted by the Office of Nuclear Regulatory Research of the U.S. NRC to conduct a research project to develop a comprehensive methodology for evaluating the nonlinear seismic behavior of freestanding spent fuel dry cask storage systems. The main objective is to perform parametric analyses to characterize the sensitivity of cask response to a number of important input parameters, including two cask designs, three foundation types, three coefficients of friction at cask/pad interface, and five earthquake ground motion records for each of three spectral shapes. The parametric analysis results have been compiled in nomograms to facilitate the safety review of licensing applications by the NMSS staff. This report documents the details of analysis models and all parametric analysis findings.

The ABAQUS/Explicit code is used to investigate the cask response by analyzing three-dimensional coupled models including a freestanding cask, a concrete pad, and a soil/rock foundation interacting with frictional contact at interfaces to provide a realistic simulation of soil-structure interaction effects and the nonlinear cask behavior. The selected earthquake ground motions are fitted to conform to selected spectral shapes, and adjusted using a deconvolution procedure enabling the ground motion to be applied at the foundation model base.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Nonlinear seismic behavior, freestanding spent fuel dry cask storage systems, parametric analyses, nomograms, coupled finite element models, cylindrical cask, rectangular module, soil/rock foundations, coefficients of friction at cask/pad interface, Regulatory Guide 1.60, NUREG/CR-0098, and NUREG/CR-6728 spectral shapes, and earthquake ground motion records.

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