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Non-linear Seismic Sliding Analysis of an ISFSI Mat Subject to High Ground Motions

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ABSTRACT

NUREG 1536 (Ref. 1) requires demonstration of a factor of safety of 1.1 against sliding for ISFSI mats when sliding stability checks are performed utilizing static equations of equilibrium. This means that the ratio of resisting forces developed at the mat and underlying soil interface divided by the driving inertia forces should exceed 1.1. In seismically active regions, such as the western coastal regions of United States, satisfying this requirement utilizing static checks will prove to be difficult, especially if the design Peak Ground Acceleration (PGA) in the vertical direction is relatively high. High vertical inertia loads associated with vertical accelerations must be subtracted from downward gravity load, resulting in reduced normal forces which when multiplied by the appropriate friction factor, does not provide enough frictional resistive force to resist the applied driving force, which is often a function of PGA in the horizontal direction. Therefore, it is clear that in seismically active regions having PGAs in excess of approximately 0.5g (both horizontally and vertically), demonstration of a safety factor of 1.1 against mat sliding would be challenging.

The Diablo Canyon ISFSI mat faced such a challenge simply because the design ground motions are reasonably high (horizontal PGA = 0.83g and vertical PGA=0.7g). With these high PGA's it is clear that demonstration of a safety factor of 1.1 against sliding utilizing static equilibrium checks is not feasible. However, during the time history simulation, the peak accelerations in horizontal and vertical directions are often of very high frequency and short duration. By performing a non-linear time history sliding analysis of the ISFSI mat, one can demonstrate that even under very high seismic motions, the extent of mat sliding is quite small at representative friction coefficients typical of the interface of the weakest plane. Therefore, as long as the small amount of sliding of the mat does not cause any interferences, it can be determined if it would be acceptable for the mat to slide. Furthermore the effects of changes in the frequency content of the resulting motion into the dry storage modules resting on top of the mat as a result of mat sliding can be examined.

This paper presents the results of a series of non-linear time history analyses of the Diablo Canyon ISFSI mat subject to design basis ground motions. These analyses were performed to determine the extent of mat sliding and the effects of mat sliding on frequency content of the input motion into the storage modules. The results of the study were used to determine whether anchoring the mat to the underlying rock media using rock anchors would be required to prevent sliding, in lieu of the fact that subject to the very high design basis motions, the unanchored mat would slide given the design basis seismic event.

KEY WORDS: Sliding, friction coefficient, friction angle, non-linear, time history analysis, base shear, dry storage cask, ISFSI, mat, response spectra, damping, PGA, ZPA.

INTRODUCTION

Due to high design seismic environment at the Diablo Canyon Power Plant (DCPP) site at coastal region of California, it was decided that the dry storage cask design would be anchored to the supporting concrete mat in order to provide more stability against cask sliding & rocking in a seismic event. Each segment of ISFSI mat at DCPP will support 20 anchored casks. The mat in turn rests on subsurface competent material classified as rock. Figures 1 & 2 show the horizontal & vertical control design response spectra for design of ISFSI at DCPP. As seen from these Figures, the design spectra for the ISFSI site have a PGA of 0.83g horizontally and 0.70g vertically. Since the casks are anchored to the mat, the applied inertia forces associated with the cask mass is even at higher horizontal acceleration than the PGA. This would be the corresponding spectral acceleration at the dominant frequencies of the cask. The Stability analysis of the ISFSI mat utilizing traditional static methods showed that the factor of safety of 1.1 against sliding, as required by NUREG 1536 (Ref. 1), could not be achieved simply because the magnitude of the ground PGA at this site is reasonably high. This is demonstrated below assuming the entire

mat and casks are represented by 1 DOF problem of total mass (m), using the 100%-40%-40% rule for combining seismic inertia forces, assuming that this mass is excited at PGA levels (in reality the cask mass is excited at slightly higher than PGA acceleration levels), and using a friction coefficient of 0.73:

Net vertical inertia load acting upwards	= 0.4x0.7g (m) = 0.28g(m)
Net normal load acting downwards	= (1-0.28) g (m) = 0.72g(m)
Net frictional resisting forces	= 0.73x0.72g(m) = 0.53g(m)
Net driving force	= $[(0.4x0.83g)^2 + (0.83g)^2]^{0.5}$(m) = 0.89g(m)
Factor of safety against sliding using static methods	= 0.53/0.89 = 0.6<1.1

As seen from the above simple illustration, the factor of safety of 1.1 against sliding cannot be achieved once the control design accelerations begin to exceed approximately 0.5g. Therefore the alternatives were to either anchor the mat to the underlying rock media using rock anchors, or to evaluate the extent and consequence of potential sliding of the mat under defined seismic scenario at the site. The latter was decided as the first option if it could be demonstrated that: 1) as a result of mat sliding, potential changes to the design control motion used in cask design are manageable, and 2) if the amount of sliding was sufficiently small that it would not cause any interferences. If these 2 acceptance criteria were to be met, then mat sliding would be acceptable.

This paper documents the results of a series of non-linear time history analyses of a finite element representation of the cask/mat set-up at Diablo Canyon ISFSI. The purpose of the analyses were threefold:

a. To determine the extend of sliding that occurs at the mat/rock interface subject to ISFSI control motion.
b. To determine whether as a result of mat sliding, the cask design shears and moments, are altered and if so by how much.
c. To evaluate changes in control motion as a result of mat sliding

These analyses were performed as non-linear time history analysis of the cask/mat structure allowing for any sliding potential at the rock/mat interface. The only source of non-linear behavior is the friction characteristics at the mat rock interface. In order to properly capture an average of the non-linear response, as per guidelines of reference 2, sliding analyses were performed for 5 sets of time histories each developed to match the ISFSI control motion spectra. The best estimate of maximum sliding was predicted assuming two interface sliding friction coefficients of $\mu = 1.19$ corresponding to a friction angle of 50°, and $\mu = 0.73$ corresponding to a friction angle of 36°. This represented the range of the sliding friction coefficient expected at this interface.

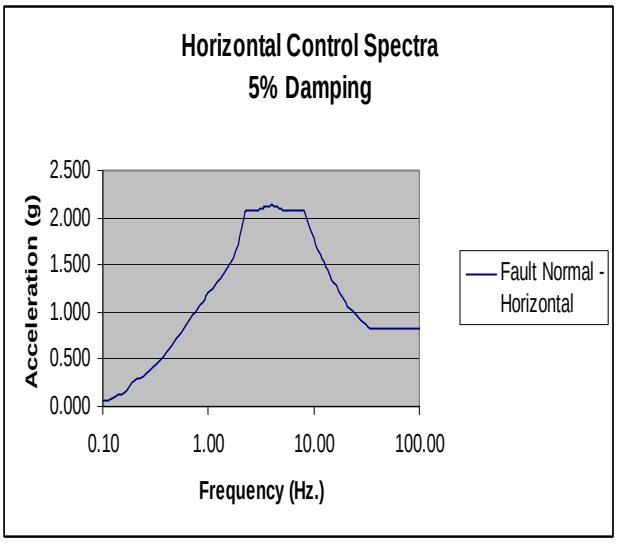

Figure 1

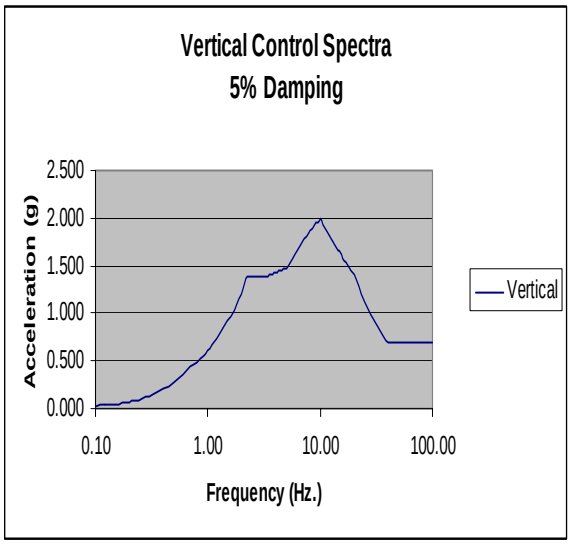

Figure 2

MODELING

A simple non-linear stick model was developed for the purposes of these analyses. The set of 20 casks on a segment of ISFSI mat were represented by a lollypop stick model representing the cask dynamic characteristics. The mat was represented by its mass only. The interface between the rock and the mat surface was modeled using special non-linear interface element with appropriate friction properties. This non-linear interface element was a biaxial friction element that had coupled friction properties for the two shear deformations, post-slip stiffness in the shear directions, gap behavior in the axial direction, and linear stiffness properties for the three rotational degrees of freedom.

The cask superstructure stick was modeled such that it represented the dynamic properties of the anchored cask. The fundamental frequencies of the cask superstructure model in these analyses were based on best estimate of the rocking frequency of the anchored cask allowing for proper anchorage stiffness. The model of the cask superstructure alone was called the "fixed base" model. The same model when mounted on the friction element coupled with representation of the mass of ISFSI mat was called the "sliding" model. The relative ratio of peak response between the sliding model and the fixed base model would determine whether as a result of mat sliding, the design shears & moments used for design of cask would be affected. This approach ensured that any potential increases in design peak responses due to sliding were properly carried through the design. In addition to the ratio of peak design responses at the base of the cask, response spectra were extracted at top of the mat and compared to input control motion to determine the impact on spectral shape as a result of mat sliding.

For the vertical direction, the tensile component of base reaction was studied as this component was judged as the important parameter resulting in lower normal resisting force at the interface thus higher sliding displacement under a seismic event.

The fixed base model was modeled with a rocking frequency of 15.9 Hz and a vertical frequency of 29.3 Hz., representing the dynamic characteristics of the cask superstructure. In order to properly capture the sliding behavior, all analyses were performed based on non-linear time-history analysis methodology. Gravity loading was present prior and during the seismic excitation so that the effects of normal weight downward was properly allowed for in doing sliding calculations at each time step. Computer code SAP2000N (3) was used to perform all analyses cases.

NON-LINEAR SEISMIC SLIDING ANALYSIS RESULTS

Table 1 summarizes the sliding displacement at the base of the model. These numbers represent the sliding of the mat under the postulated seismic events. The net vector horizontal sliding is obtained using the SRSS of the maximum of the 2 individual sliding components along X or Y directions. This combination assumes that the 2 sliding displacements along X & Y directions reach their peak at the same time. This is conservative, however judging from the time-history plot of the sliding displacements, it is seen that peak sliding generally occurs at (or very close to) the same time for X & Y directions. This is expected since sliding is often as a result of vector driving forces (shears) exceeding the sliding resistance.

Table 1: Summary of Max. Mat Sliding Displacements

Case No.	Seismic Event	Friction Coefficient (μ)	Max. mat Sliding X (inch)	Max. mat sliding Y (inch)	Net Horizontal Sliding (inch)
1	TH1	1.19	+1.12	-1.11	1.58
2	TH2	1.19	-0.02	+0.01	0.02
3	TH3	1.19	+0.11	+0.07	0.13
4	TH4	1.19	-0.07	+0.14	0.16
5	TH5	1.19	-0.12	+0.13	0.18
	Avg. 5 cases	1.19			0.41
6	TH1	0.73	+2.34	-2.00	3.08
7	TH2	0.73	-0.27	+0.25	0.37
8	TH3	0.73	+0.83	+0.45	0.94
9	TH4	0.73	+0.37	+0.98	1.05
10	TH5	0.73	+0.26	+0.55	0.61
	Avg. 5 cases	0.73			1.21

The approach used to arrive at the best estimate of the mat sliding was as follows. The average of response due to the 5 Time History cases was obtained as per SRP guidelines (Ref. 2), since the average of these 5 sets was used to match the target spectrum. The average of the 5 TH cases resulted in a best estimate of max. sliding of 0.41" for a friction coefficient of 1.19. Corresponding best estimate of mat sliding for a friction coefficient of 0.73 is 1.21". Note that the highest absolute max. mat sliding for any one of the 5 analyses cases was 1.58" (for a friction coefficient of 1.19) and 3.07" (for a friction coefficient of 0.73), both of which correspond to the TH Set 1 case. These numbers are also reported here, however per SRP guidelines, the best estimate of max. sliding of the mat subject to multiple time histories whose average envelope the same design spectrum can be taken as the average of all the individual cases. This averaging is allowed for different time histories whose average match a target spectrum (Ref. 2).

Table 2 below summarizes the ratio of maximum net base shear per cask from these non-linear analyses after allowing for mat to slide compared to maximum net base shears obtained from fixed base analysis which is not subject to sliding. Net shear were computed based on SRSS of X & Y shears in the time domain and extracting the highest value. Same approach as sliding displacement was used here to come up with the best estimate of net shear, i.e. the average of the 5 TH cases was used as the best estimate of sliding shear when compared to fixed based shear.

Table 2: Summary of Ratio of Max. Shear & Tension Response (Sliding Vs. Fixed Base)

Case No.	Seismic Event	Friction Coefficient (μ)	Ratio of Sliding/Fixed Base Net Shear	Ratio of Sliding/Fixed Base Net Tension
1	TH1	1.19	0.97	1.01
2	TH2	1.19	0.98	1.00
3	TH3	1.19	0.82	1.01
4	TH4	1.19	1.00	1.00
5	TH5	1.19	1.01	1.01
	Avg. 5 cases	1.19	0.95	1.005
6	TH1	0.73	0.88	1.01
7	TH2	0.73	1.03	1.00
8	TH3	0.73	0.76	1.01
9	TH4	0.73	0.88	1.00
10	TH5	0.73	0.99	1.01
	Avg. 5 cases	0.73	0.90	1.005

The relative ratios of sliding/fixed base reported in Table 2 for net shear were used to predict the effect of mat sliding on the design shear. For this purpose, the average shear response of the 5 TH cases was calculated for both the sliding and the fixed base results. This ratio of the average shear for sliding (for each friction coefficient) versus the fixed base average shear indicated the ratio that should be applied to the design bases shear to account for the effect of mat sliding. Since this ratio was found to be less than unity, conservatively a ratio of unity was applied. As seen from Table 2 above, the average ratio of sliding shear to fixed base shear was calculated as 0.95 for u=1.19 and 0.90 for u=0.73. This trend is expected, as the lower the friction coefficient, the more the mat slides, thus resulting in more earthquake energy dissipation and therefore lower shear forces at the cask/mat interface. Even though the fixed base shears were not adjusted in design, in reality, these analyses predicted that the peak net shear after allowing for effects of mat sliding would actually reduce by 5% & 10% respectively for the 2 friction coefficient studied.

Table 2 also summarizes the ratio of maximum base tension per cask from these non-linear analyses after allowing for mat to slide compared to maximum base tension obtained from fixed base analysis, which is not subject to sliding. As seen from the results, the net tension hardly changes. The average of the five TH cases resulted in a net tension increase of 0.5%, which is negligible. Therefore it was concluded that the peak tension load essentially does not change as a result of mat sliding.

Figures 3 and 4 show the base sliding plots at the mat/rock interface for X & Y directions for TH case 1, for μ=1.19. Figures 5 and 6 show similar plots for TH case 1 for μ=0.73 case. Figures 7 and 8 show the comparison of

response spectra at rock versus mat after sliding for both horizontal directions. These spectra serve to determine if the input motion is significantly altered as a result of mat sliding. Spectra comparisons vertically were not investigated as no separation took place vertically, therefore vertical motion did not change as a result of mat sliding. Similarly Figures 9 and 10 show similar plots for TH case 1 for μ=0.73 case. The results for other 4 TH cases are not reported here, but follow similar pattern.

The spectra comparison plots for all 10 cases revealed that the motion at the cask/mat interface does get somewhat altered, but typically at frequencies of approximately 16 to 20 Hz. or higher. These high frequency spikes are considered real and as a result of the sliding. However, since the cask dominant frequency was shown to be around 15.9 Hz., it was expected that the peak response would not get altered. This was verified since the base shear after sliding was not increased versus the design shear as a result of mat sliding. Therefore it was concluded that the discrepancies in the cask/mat interface motion after sliding takes place were of no engineering consequence for the design of the cask embedment, and thus the mat. Cask internals are designed to much higher "g" loads and therefore were not affected by these relatively minor spectral acceleration increases primarily in the high frequency range.

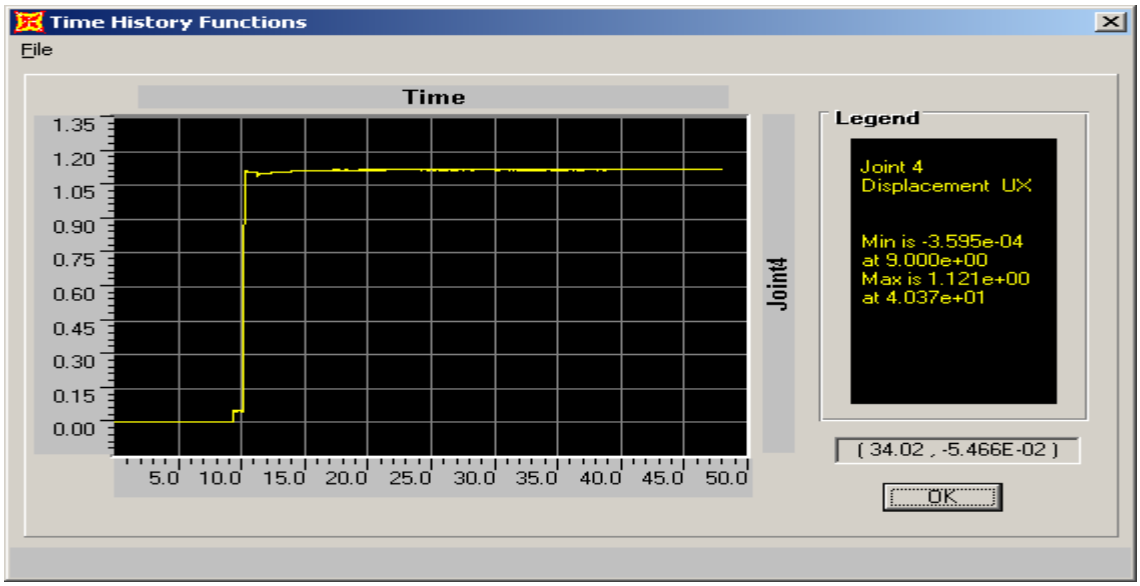

Figure 3: Sliding Displacement X (in) for TH Set 1, μ = 1.19

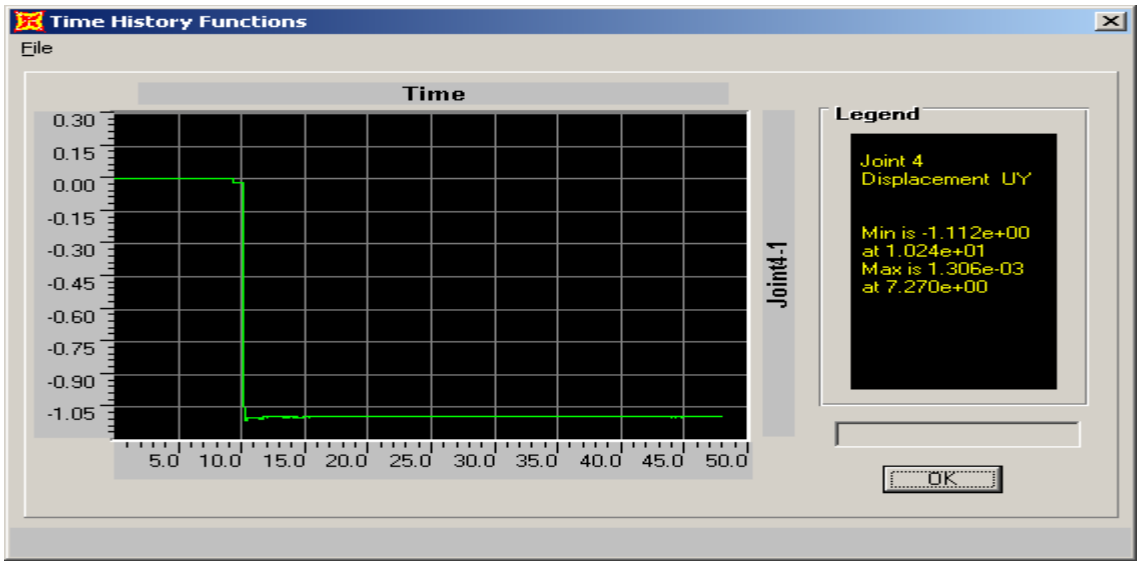

Figure 4: Sliding Displacement Y (in) for TH Set 1, μ = 1.19

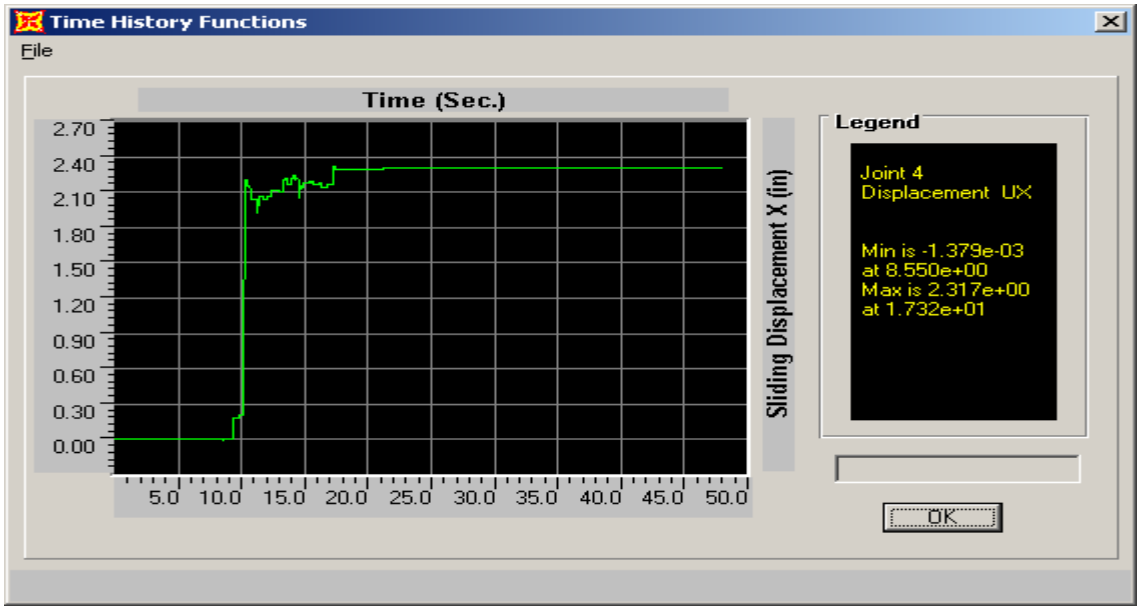

Figure 5: Sliding Displacement X (in) for TH Set 1, μ = 0.73

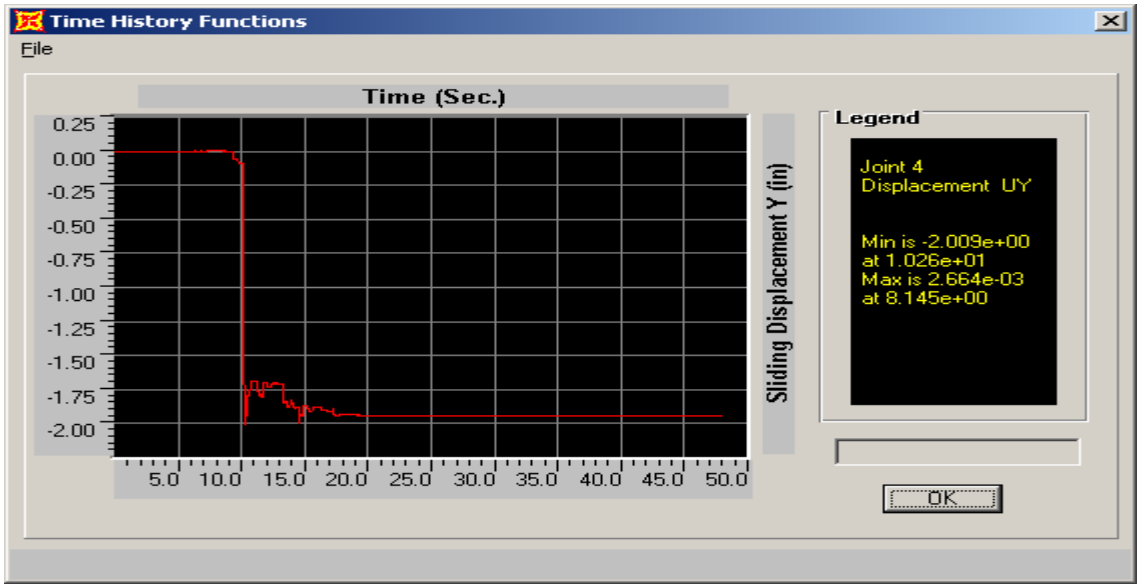

Figure 6: Sliding Displacement Y (in) for TH Set 1, μ = 0.73

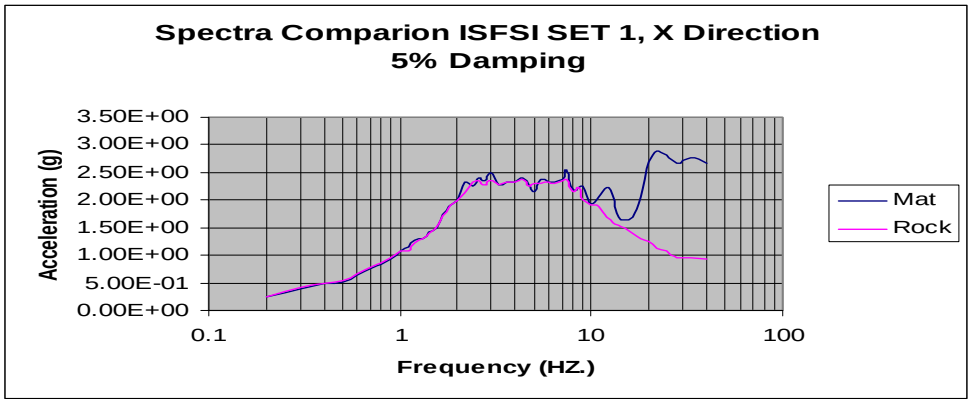

Figure 7: Spectra Comparison, X, TH Set 1, 5% Damped, μ = 1.19

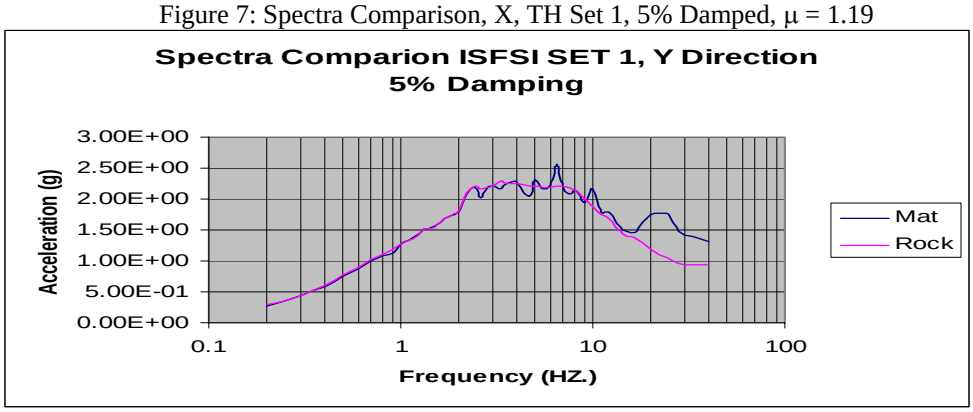

Figure 8: Spectra Comparison, Y, TH Set 1, 5% Damped, μ = 1.19

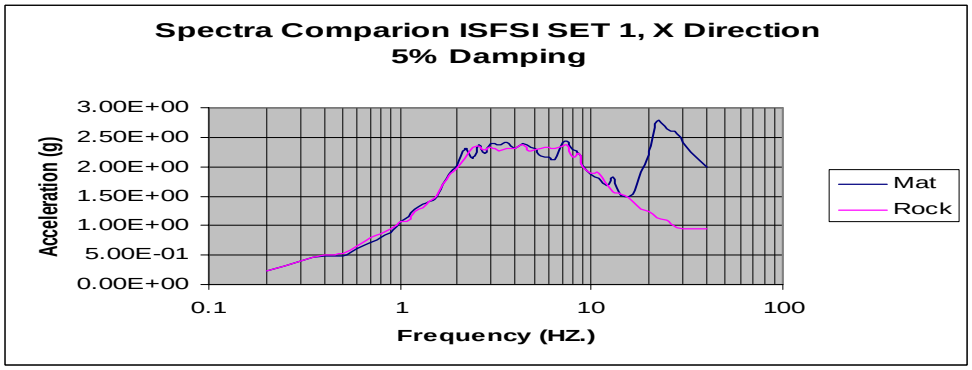

Figure 9: Spectra Comparison, X, ISFSI Set 1, 5% Damped, μ = 0.73

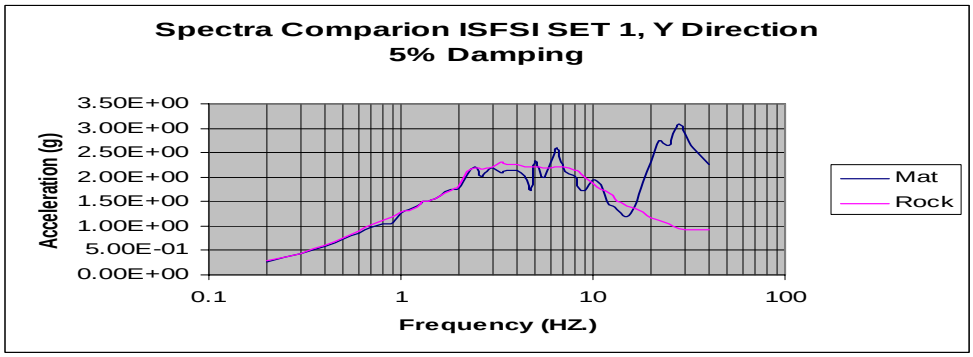

Figure 10: Spectra Comparison, Y, ISFSI Set 1, 5% Damped, μ = 0.73

CONCLUSIONS

Based on the results of these analyses, the following were concluded:

1. Mat sliding subject to high seismic control motions for the DCPP site were found to be fairly small and not large enough to cause any interference or damage to the mat or the casks. This is expected since even though static methods would predict sliding would happen under high seismic environment, the peak of the control motion is of such a short duration, that actual sliding would be small before reversal in direction of peak acceleration takes place.
2. The acceptance criteria for mat sliding were defined as whether mat sliding would results in increased design shears and moments for the casks and the mat. After mat sliding was considered, it was concluded that design shear and moments for the casks as predicted from fixed base analysis would actually reduce by 5% to 10% for the range of friction coefficients studied. The best estimate of the adjustment factor to account for the effects of mat sliding was calculated as 0.95 for a friction coefficient of 1.19, and 0.90 for a friction coefficient of 0.73.
3. The best estimate of max. axial tension load after sliding remained unchanged.
4. The response spectra comparison plots indicated that the motions generally did not vary up to about 16 Hz, however above this frequency some differences in the motion was seen as a result of mat sliding. This high frequency change in motion was also expected because of onset of sliding phenomenon.

PRACTICAL APPLICATIONS

Demonstration of factor of safety of 1.1 against structural & component sliding is a requirement of many codes. In particular for nuclear power industry, anchorage of temporary structures and equipment maybe required because of this requirement. For regions of high seismicity or for locations high inside a structure where floor ZPAs are high, demonstration of this safety factor using traditional static methods may be difficult resulting in requirement for unnecessary anchorage. Performing non-linear sliding analysis such as that described in this paper is a viable alternative, if it can be shown that the resulting sliding is small and manageable.

REFERENCES

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[2] – Standard Review Plan, Section 3.7.2, Rev. 2.
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