SEISMIC STABILITY ANALYSIS OF A CASK TRANSPORTER ON SLOPED SURFACES

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ABSTRACT

Many commercial nuclear plants are currently in the process of storing excess spent fuel in various dry cask storage facilities on-site. This on-site storage requires loading of the spent fuel from the fuel pool onto a cask and then transporting the cask using a heavy duty transporter to the location of the on-site Independent Spent Fuel Storage Facility (ISFSI). Whilst on the transporter, the cask and the transporter must remain physically stable under postulated seismic loads. Physical stability is defined by evaluating the amount of potential sliding on the road surface as well potential for rocking and in the worst case tip-over of the transporter carrying the cask. Because of the low ratio of the CG height to width of the transporter, typically rocking and tip-over is not a concern, even under the most extreme of the seismic environments. However, sliding of the transporter on the road will occur once the ratio of lateral to normal load exceeds the dynamic friction coefficient that is representative of the interface characteristics between the transporter tracks and the road. For sites located in high seismic environment such as the Diablo Canyon Power Plant (DCPP), this is almost certain, given the high value of the design seismic input.

Therefore as a prudent part of the design process, the sliding of the transporter carrying the cask is calculated under the design seismic scenario. This process requires performing non-linear sliding analysis, where appropriate consideration has to be given at any instant of time during the seismic excitation to the friction resistance being overcome, thus resulting in some level of sliding. Once this sliding displacement is calculated, appropriate measures can be provided in order to make sure that the transporter has enough clearance as it travels the intended path, and that it will not bump into any restraints which may result in unwanted impact loads.

This process is reasonably straight forward as long as the road surface is a flat one. However, the road from the Fuel Building to the ISFSI at DCPP is sloped at certain locations along the travel path. Thus, the determination of sliding levels under a seismic scenario on a sloped road becomes more complicated, as gravity now plays an additional role in that there will be a component of the gravity that would tend to assist sliding down-slope and would prevent sliding up-slope of the road. In addition, the normal component of the applied load (gravity plus seismic) resisting frictional forces, is also slightly less because of the slope between the road and the horizontal plane. These added complications must be properly accounted for in performing such a stability analysis on a sloped road.

This paper summarizes the methodology and the results for performing such analysis for the DCPP Dry Cask transporter on a sloped road. The road has slopes both longitudinally and transversely which had to be accounted for in performing these seismic stability analyses.

Keywords: Dry Cask Storage, Load path, Road Slope, Longitudinal Slope, Transverse Slope, Sliding, Overturning, Transporter, Transporter Stability, Coefficient of Dynamic Friction.

INTRODUCTION

A heavy duty transporter carries the dry cask containing spent fuel from the fuel building of Diablo Canyon Power Plant (DCPP) up a sloped road to the location of the ISFSI. This road has various slopes along the travel path, the highest of which is 8.5% longitudinally. For most of the road, the longitudinal slope is 6%, however at a few areas the slope gets as high as 8.5%. Transversely, the road has a 2% slope to allow for drainage. As the transporter travels this path, a design basis seismic scenario is conservatively postulated, even though the total duration of the transporter being on this road is very small compared to the life of the plant.

The objective of the seismic scenario postulation is to ensure that the transporter remains stable under severe rocking conditions, and to calculate the anticipated sliding distance both along the longitudinal and transverse directions of the road. The slope of the road tends to help the sliding down-slope and resist it up-slope. This is because of the gravity component and the fact that on a sloped surface, this component of force would not be normal to the road surface, not only resulting in a lower normal force, but also resulting in a component of the weight parallel to the down-slope of the road, thus assisting the inertia forces acting down-slope and resisting then acting up-slope.

Non-linear sliding analyses were performed for 3 conditions of:

- Flat surface
- Inclined surface with 6% longitudinal slope and 2% transverse slope
- Inclined surface with 8.5% longitudinal slope and 2% transverse slope

The focus of this paper is to study the effects of road slope on sliding displacements both down-slope and up-slope, compared to flat surface conditions.

ANALYSIS METHODOLOGY

Previous stability analysis of the transporter had concluded that the transporter is not susceptible to instability as a result of rigid body rocking under postulated seismic scenario. Therefore, the scope of this paper is limited to the study of sliding behavior of the transporter both on flat surface and on sloped surface.

A non-linear rigid body model of the transporter was developed. The model is capable of capturing geometric non-linearity at the interface of transporter base and ground. This interface is modeled using friction element along the two local horizontal surfaces, and using a compression-only contact element vertically. Laterally, friction is the only means of resisting lateral motion induced by seismic inertia of the transporter. Once friction is overcome the transporter will begin to slide relative to top of the road surface. This non-linear behavior is modeled using friction elements at the base. For all sliding analyses, a dynamic Coefficient of Friction (COF) of 0.4 was used in all analyses. Vertically, the transporter is free to separate from the road surface in the "up" direction due to potential rocking and free-flight modes of response. However in the "down" direction, the road surface and the supporting soil or rock media will act as a restraint to the transporter. This geometric non-linear behavior is modeled using gap/contact elements at the base. In addition, vertical dashpots are placed under the gap element to absorb the energy dissipated due to the impact nature of contact of the transporter on the road surface as a result of separation. Also vertical springs are placed under the gap element to represent the vertical stiffness of the underlying media and transporter tracks combined.

On a sloped surface, this model is simply rotated by angles (α) and (β) which represent the longitudinal and transverse slopes of the road surface. Figure 1 shows the model on sloped surface. All analyses were performed using the SAP2000 Non-linear computer program. Also, since element non-linearity is involved, all analyses were non-linear time history analysis. All non-linear time history analyses were performed using the Fast Nonlinear Analysis (FNA) Approach (See Ref. 2 for details of the methodology). To comply with SRP 3.7.1 (Ref. 1) for performing non-linear analysis, 5 sets of analyses were performed subject to the 5 sets of time histories representing the rock ground motion at DCPP. To account for potential amplification of ground motion due to presence of soil deposits along the roadway all input motions were conservatively amplified by a uniform factor of 2. Table 1 summarizes the PGA of the 5 sets of time histories used for these analyses after being scaled up by a factor of 2.

Figures 2 through 4 show the site design ground spectra for the 2 horizontal directions of fault parallel, fault normal, and vertical, scaled up by factor of 2. All time histories were developed to envelop the same ground design response spectra for the site. These spectra correspond to ground motions amplified by a uniform scale factor of 2 to represent a hypothetical seismic event allowing for potential soil amplification. It is noted that this approach is a very conservative estimation of potential ground motion amplification associated with presence of soil strata.

Sliding of the transporter on a sloped road surface was studied for conditions of having different grades longitudinally and transversely. For analyses cases on sloped surface, two models are developed. One has a 6% grade along the longitudinal direction and 2% grade along the transverse direction of the road. The second model has an 8.5% grade longitudinally and 2% grade in the transverse direction. These 2 separate slopes constitute various portions of the road that the transporter will travel on. For the 6% grade model, 10 analyses cases were run, 5 sets with fault parallel component of motion aligned longitudinally, and the other 5 sets the fault normal component of motion aligned with the longitudinal direction of the transporter. For the 8.5% model, only two analyses cases were run. These would correspond to the two cases from the 6% model, which resulted in highest sliding displacement along the longitudinal and the transverse directions respectively.

In order to simulate the effect of gravity, a ramp function was defined where the load is ramped up to unity at 5 seconds and held constant for another 5 seconds. This ramp function uses the static gravity load case as a multiplier, hence simulating the gravity condition in a time-history analysis environment. The gravity time history analysis case is defined as a pre-condition to the various seismic time history analyses cases, thus simulating presence of gravity conditions before and during application of dynamic loads.

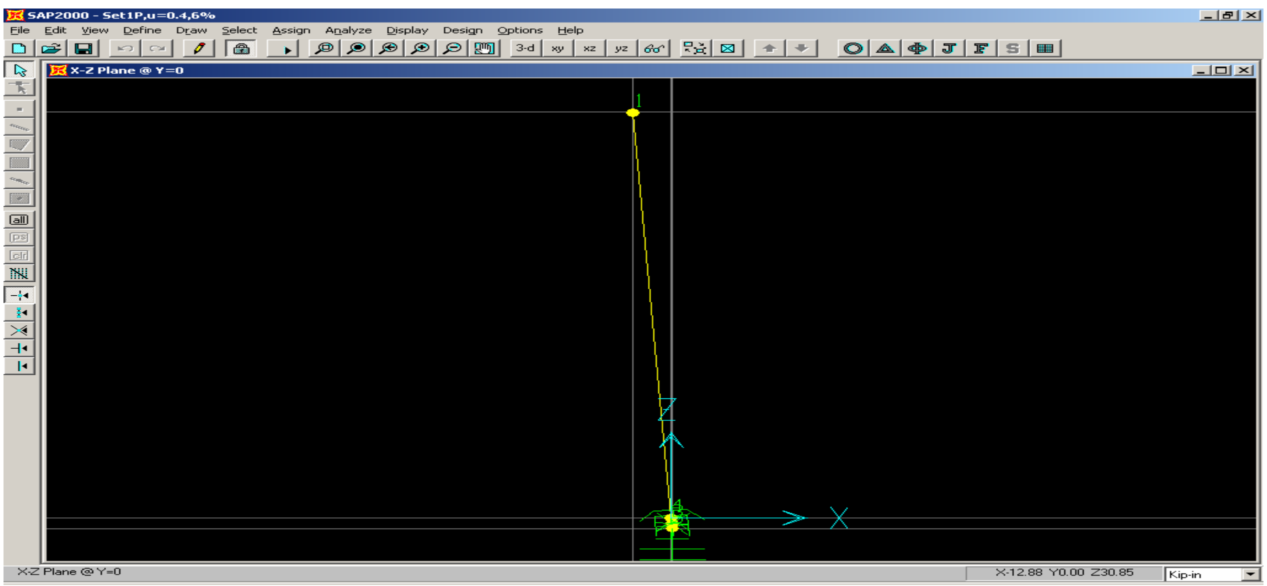

Figure 1: 6% Grade Model

	Peak Ground Acceleration (PGA, g), Scaled by factor of 2		
Time History Set	**Fault Normal**	**Fault Parallel**	**Vertical**
1	1.85	1.80	1.39
2a	1.85	1.73	1.47
3	1.75	1.77	1.39
5	1.75	1.85	1.48
6	1.76	1.77	1.47
Average	1.79	1.78	1.44

Table 1: Summary of PGAs for the 5 Sets of Input TH Sets, Scaled by factor of 2

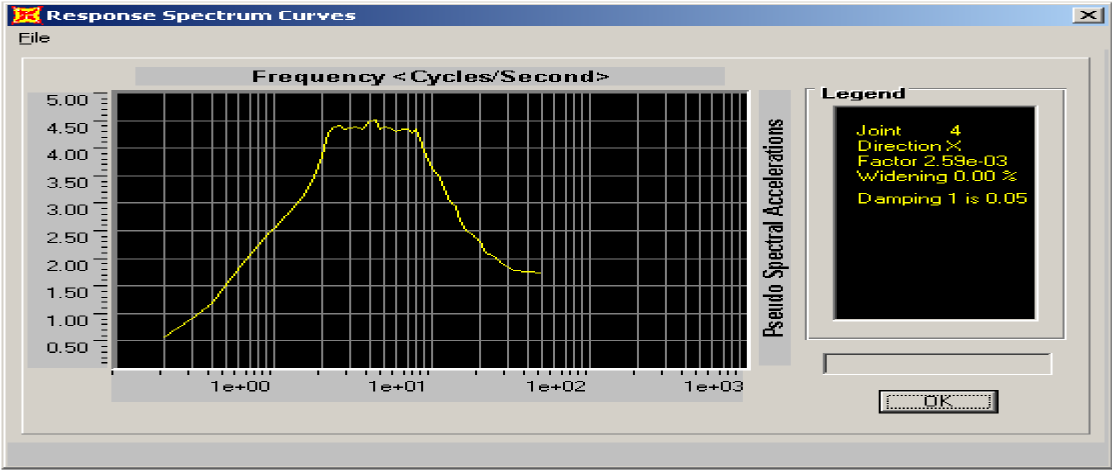

Figure 2: Set 6 Spectra (Fault Normal), 5% damping, Scaled by factor of 2

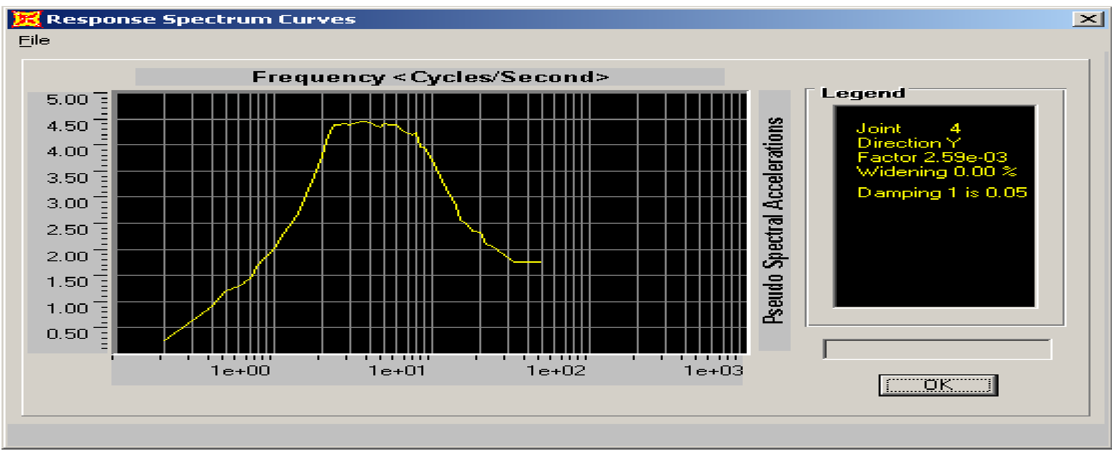

Figure 3: Set 6 Spectra (Fault Parallel), 5% damping, Scaled by factor of 2

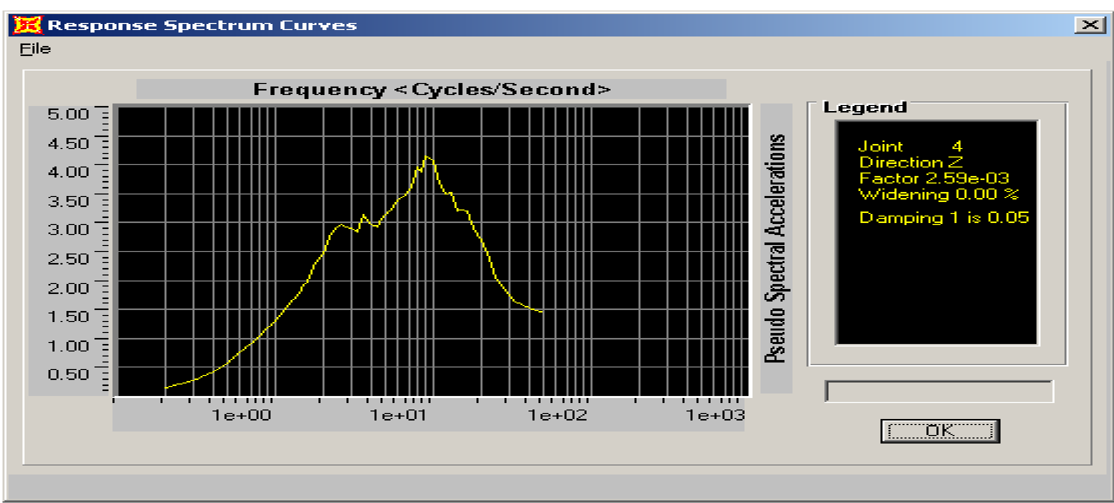

Figure 4: Set 6 Spectra (Vertical), 5% damping, Scaled by factor of 2

RESULTS

Table 2 below provides a summary of maximum sliding displacements for the 2 orthogonal directions (longitudinal and transverse), as well as uplift displacement for all the flat surface analyses cases (1 through 6).

Analysis Case	T/H Set	COF	Peak Longitudinal Displacement (in)	Peak Transverse Displacement (in)	Peak Uplift Displacement (in)
1	1	0.4	49.6	40.0	0.47
2	2a	0.4	30.5	27.3	0.53
3	3	0.4	27.3	53.2	0.20
4	5	0.4	37.1	65.3	0.24
5	6	0.4	48.4	54.1	0.45
Average for 5 sets at COF=0.4			**38.5**	**48.0**	**0.38**

Table 2: Summary of Maximum Sliding & Uplift Displacements for Flat Surface Cases

The best estimate of sliding and uplift displacements are obtained by averaging these 5 cases. This averaging is allowed as per SRP Guidelines, Section 3.7.1 (Ref. 1) since the average of the 5 sets of time histories were used to match the target spectrum.

Table 3 below provides a summary of maximum (both positive and negative) sliding displacements for the 2 orthogonal directions (longitudinal and transverse), for all the analyses cases performed on the 6% grade (Analyses cases 7 through 16). The following sign convention applies:

a. Positive longitudinal is max. along upslope for 6% grade
b. Positive transverse is max. along upslope for 2% grade

Analysis Case	T/H Set	COF	Peak Longitudinal Displacement (in)	Peak Transverse Displacement (in)
7	1N	0.4	-50.7/+18.5	-7.1/+35.2
8	2aN	0.4	-78.0/+21.3	-34.5/+0.1
9	3N	0.4	-113.9/+2.8	-35.2/+5.2
10	5N	0.4	-162.7/+7.4	-4.1/+23.2
11	6N	0.4	-83.5/+2.9	-3.0/+45.8
Average "N" Cases			**-97.8/+10.6**	**-16.8/+21.9**
12	1P	0.4	-104.9/+1.7	-53.7/+6.8
13	2aP	0.4	-14.8/+19.7	-25.9/+14.1
14	3P	0.4	-68.9/+14.7	-5.7/+41.7
15	5P	0.4	-106.4/+0.2	-11.8/+56.2
16	6P	0.4	-77.4/+7.7	-4.4/+52.6
Average "P" Cases			**-74.5/+7.7**	**-20.3/+34.3**

Table 3: Summary of Maximum Sliding Displacements for 6% Grade Cases

The average of the each of these 5 cases represent a biased conservative estimate of the mean of the sliding displacements for that particular set (N or P) along either the down-slope for the longitudinal or up-slope along the transverse directions, respectively. To arrive at the biased conservative best estimate of sliding displacements for the case of transporter on 6% grade, the higher of the two sets of best estimates is conservatively taken, rather than average of all 10 cases. This results in 97.8" of sliding displacement down slope of the 6% grade along the longitudinal direction, and +34.3" along the upslope of the 2% transverse grade of the road.

The values reported in Table 3 for up-slope sliding displacements along the longitudinal direction (10.6”) and down-slope sliding displacements along transverse direction (20.3”) are biased unconservative, because of alignment of the signs of the input time histories as discussed earlier. These values are ignored, since sliding displacements in these 2 directions are of no interest.

Based on the 6% grade analysis results, case 5N resulted in highest longitudinal sliding displacement down-slope, whereas case 5P resulted in highest transverse sliding displacement up-slope (see Table 3). These 2 cases were re-run for the 8.5% grade model. Table 4 below summarizes the results:

Analysis Case	T/H Set	COF	Peak Longitudinal Displacement (in)	Peak Transverse Displacement (in)
17	5N	0.4	-208.0/+6.0	-4.0/+25.5
18	5P	0.4	-141.0/+0.1	-11.7/+58.2

Table 4: Summary of Maximum Sliding Displacements for 8.5% Grade Cases

Comparing the results from Table 3 to Table 4, the max. longitudinal sliding displacement increases from 162.7” to 208.0” (28% increase), when the grade of the road is increased from 6% to 8.5%. Max. transverse sliding displacement increases from 56.2” to 58.2” (3.6% increase). This slight change in transverse sliding is expected since the longitudinal sliding changes, because of the larger grade, thus resulting in a different net vector sliding which would slightly affect the transverse sliding, even though the transverse grade is kept constant at 2%. It is noted that the reported sliding displacements for the 2 cases ran are expected to be the max. sliding displacements in the longitudinal and transverse directions. The “best estimate” values are expected to be less if all 5 sets of T/H cases were to be run and results are averaged.

Figure 5 shows the sliding time history trace for analysis case 1 which resulted in highest sliding displacement for analyses cases on flat surface. Figures 6 & 7 show the corresponding sliding time history plots for analysis cases 10 and 17 corresponding to 6% and 8.5% grades. The plots corresponding to highest longitudinal sliding are presented here even though each plot shows the corresponding transverse sliding as well.

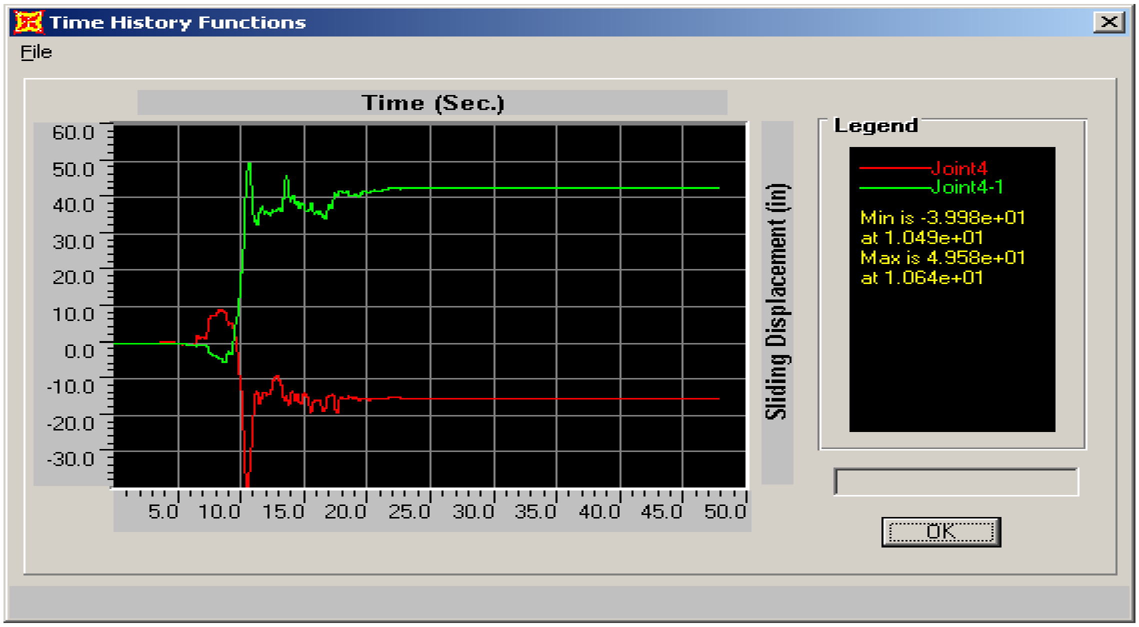

Figure 5: Sliding Displacements for Flat Surface, Set 1, COF=0.4

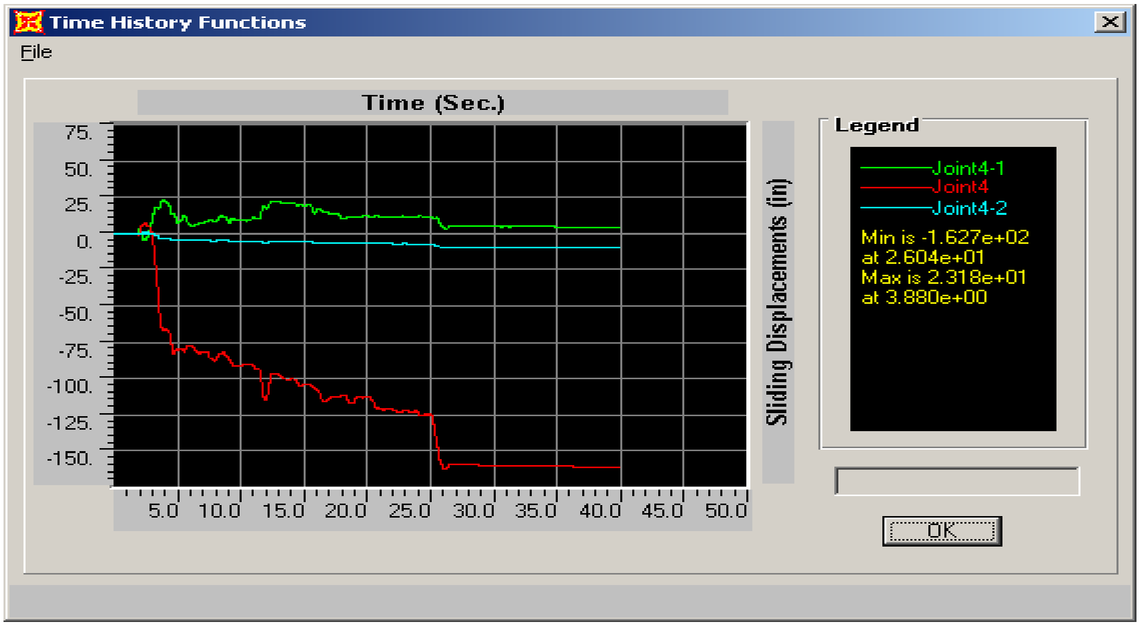

Figure 6: Sliding Displacement(s) for case 5N, COF=0.4, 6% Grade

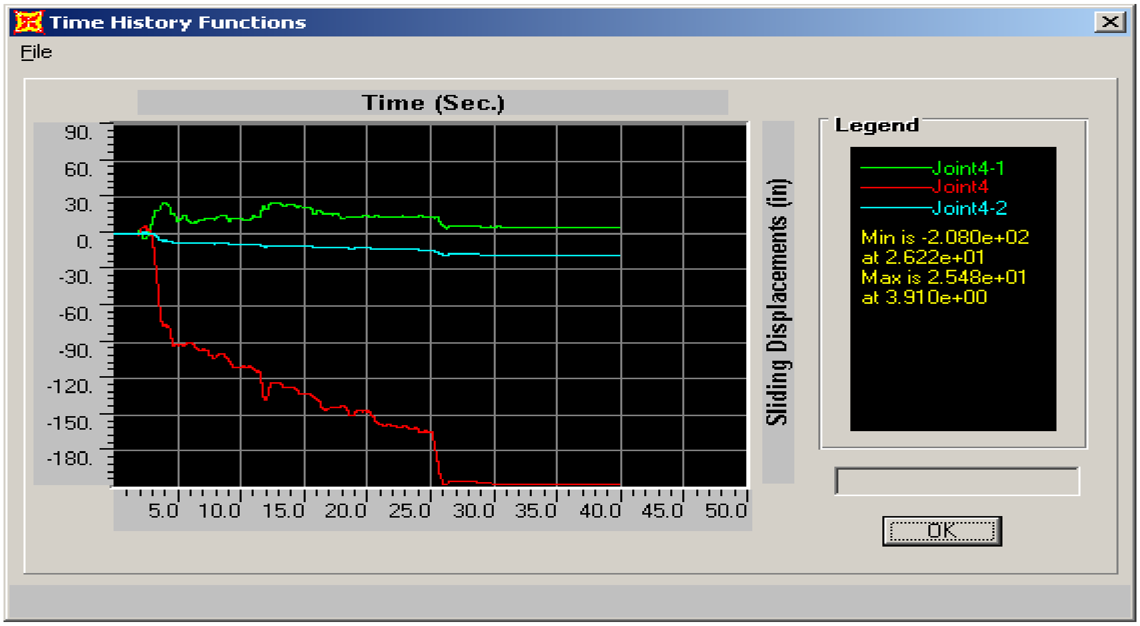

Figure 7: Sliding Displacement(s) for case 5N, COF=0.4, 8.5% Grade

CONCLUSIONS

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

1. The DCPP transporter is not susceptible to rigid body rocking due to its low CG height to width ratio.
2. The best estimate of sliding displacement on flat surface is 48.0”.
3. The conservatively biased best estimate of sliding displacement down-slope on a 6% longitudinal grade is 97.8”, whereas the estimated max. sliding displacement down-slope for one of the individual T/H cases (case 5N) on a 6% grade is 162.7”.

4. The conservatively biased best estimate of sliding displacement upslope of a 2% transverse grade on a 6% grade road is 34.3”, whereas the estimated max. sliding displacement upslope on a 2% grade is 56.2”.
5. The estimated maximum sliding displacement down slope on an 8.5% longitudinal grade is 208.0”.
6. The estimated maximum sliding displacement upslope of a 2% transverse grade on an 8.5% grade road is 58.2”.
7. These estimates of sliding displacements are based on a very conservative estimate of input motion, which is the site spectra (TH) multiplied by uniform factor of 2 across all frequency points to conservatively allow for potential amplifications as a result of potential presence of soil strata along the road surface.

Tables 2, 3, and 4 provide the individual sliding displacements for all analyses cases for the flat road, 6% longitudinal grade, and 8.5% longitudinal grade portions of the road respectively.

REFERENCES

[1] – Standard Review Plan, Section 3.7.2, Rev. 2.
[2] – SAP2000 Integrated Finite Element Analysis and Design of Structures, Computers & Structures, Inc., Berkeley, California.