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Seismic Instability Analysis of Overpacks on A Concrete Aging Pad at Yucca Mountain Nuclear Waste Repository

Kyu H. Hwang and Frederic F. Grant
Simpson Gumpertz & Heger
KHwang@sgh.com
FFGrant@sgh.com

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1. Introduction

10 Code of Federal Regulations (CFR) 63.21 [1] requires that a preclosure safety analysis (PCSA) be performed to ensure specified preclosure performance objectives have been met. The purpose of the PCSA is to identify the potential seismically initiated event sequences associated with preclosure operations of the repository and assign appropriate design bases to provide assurance of achieving the performance objectives specified in the 10 CFR Part 63 [1] for radiological consequences.

A seismic fragility analysis of the Yucca Mountain repository was performed as part of the PCSA in support of the License Application for the Yucca Mountain Project (YMP). This paper presents a case study of a seismic response analysis of unanchored dry storage casks mounted on a concrete aging pad over a soil media at the Yucca Mountain repository. The storage casks are cylindrical, have an aspect ratio of about two, and are modelled as unanchored rigid bodies free to rock and slide.

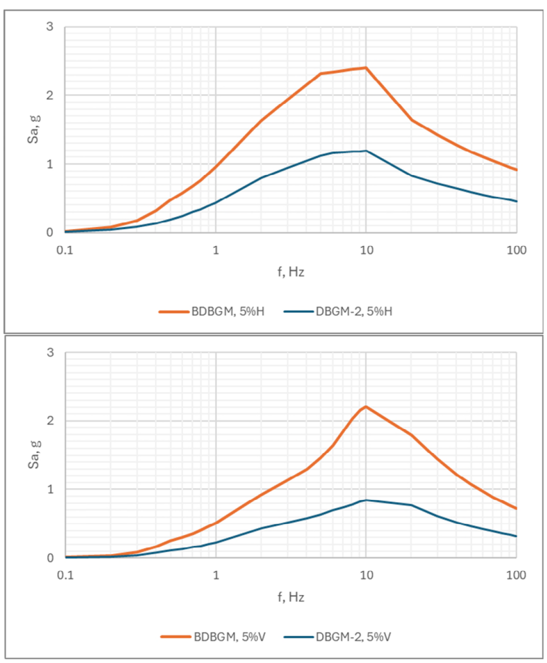

Fig. 1. BDBGM vs DBGM-2 [2]

The whole structural system must be designed to 5E-4 annual probability of exceedance (APE) design basis ground motion (DBGM-2) and be capable of withstanding beyond design basis ground motion (BDBGM), whose APE is 1E-4 [2]. Figure 1 compares the DGBM-2 to BDBGM for horizonal and vertical directions at 5% damping. The peak ground accelerations (PGAs) of the DBGM-2 and BDBGM are 0.45g and 0.91g, respectively.

According to NUREG/CR-6865 [3], a cylindrical cask has a strong tendency to undergo a rolling motion in preference to a rocking motion if the ground motion is sufficiently high to put the cask into motion and the coefficient of friction is sufficiently high to prevent sliding. The dry casks or overpacks are an unanchored cylindrical rigid body with a circular base such that they are prone to rocking and then rolling in a seismic event. Such instability of the overpacks can be assessed by dynamic analyses following the procedure delineated in ASCE 4-16 [4]. Dynamic analysis of unanchored components may be carried out using simplified nonlinear analysis method or detailed nonlinear response-history analysis method. Simplified method is based on conservatively biased approximation that accounts for the uplift nonlinearity, while nonlinear response history analysis method involves the number of time history analyses to simulate rocking of the object. It should be noted that rocking followed by rolling of a cylindrical object is sensitive to phasing of earthquake components and thus application of the simplified method requires a large margin of a factor of 10 for design.

In this study, seismic demands on the overpack are obtained by considering soil-structure interaction effect and then instability of the overpack is assessed by simplified method separately.

2. Soil-Structure Interaction Analyses

2.1. Analysis Model

The concrete aging pad is 718 ft long (X direction), 114 ft wide (Y direction), and 3 ft thick (Z direction) and supports 9 piles of 4 by 4 overpacks. Each of the overpacks is a 22 ft high and 12 ft diameter cylinder and weighs 500 kips. The concrete aging pad is modeled using 6-ft by 6-ft shell elements and the overpacks are modeled using beam elements in the computer software SAP2000 [5]. This structure model is presented in Figure 2.

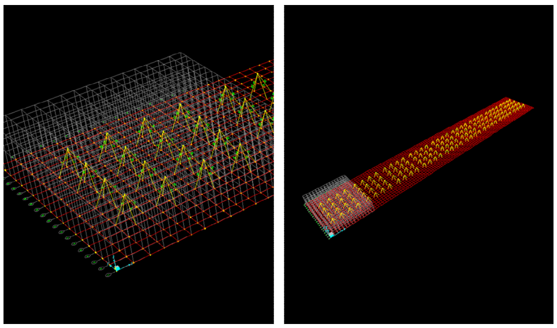

Fig. 2. Structure Model of the Overpacks on Aging Pad

The soil deposit supporting the concrete aging pad and the overpacks is 515 ft deep, whose soil profile as used in the SSI analyses is shown in Figure 3. The average shear wave velocity across the entire soil profile is approximated to be 2,440 fps.

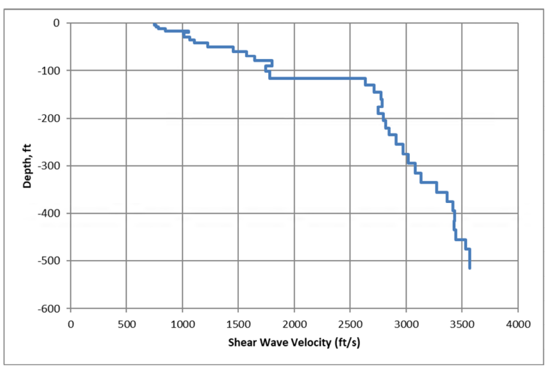

Fig. 3. Soil Profile of the YMP Site

2.2. Seismic Soil-Structure Interaction Analyses

An SSI model is developed using the computer software ACS SASSI [6]. The input time histories compatible with the BDBGM are applied to the SSI model at Elevation (-)515 ft. The response spectra of the input time histories analyzed at 5% damping are presented in Figure 4.

The SSI analysis is performed for each of the three orthogonal directions separately. The response time histories at a node in one direction resuling from the three directional excitations are combined by the square root of sum of the squares. Response spectra at the various nodes on the concrete aging pad are generated and then are averaged over the nodes to obtain best estimate seismic demands on the overpacks.

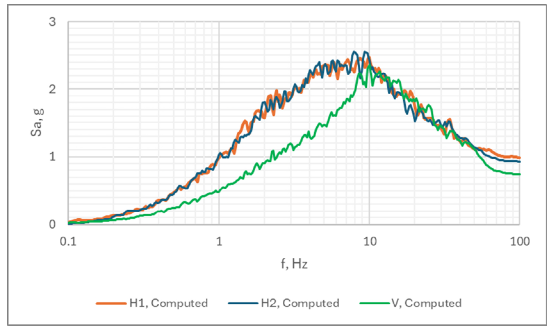

Fig. 4. Response Spectra Compatible with BDBGM

A preliminary study indicates that the overpack is more sensitive to horizontal earthquake excitation for rocking and rolling than the vertical excitation and responds at 13.5% (as confirmed later) of critical damping. Therefore, the 13.5% damped average horizontal response spectrum is selected in use for subsequent analysis to assess instability of the overpacks. In Figure 5, the 13.5% damped response spectrum (solid red curve) is compared to the 5% damped spectrum (dashed red curve) at the top of the aging pad along with the 5% damped horizontal BDBGM spectrum (solid blue curve). This comparison indicates that the SSI system has a little broad-banded spectral peak from 3 to 7 Hz and there is no significant amplification through the soil column below 1 Hz.

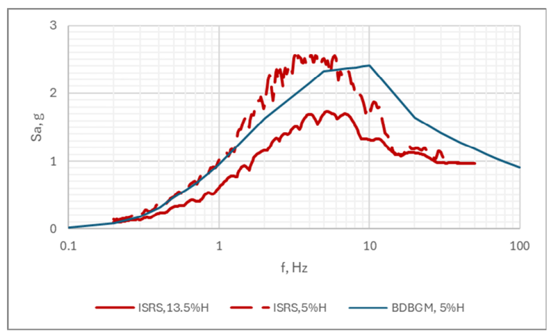

Fig. 5. Average, Horizontal, 5% and 13.5% Response Spectra on Top of Aging Pad

3. Stability Analysis of the Overpack

3.1. Approach

A stability analysis of the overpack is performed following the simplified method delineated in ASCE 4-16 [4]. The ASCE procedure is directly applicable to a rigid body with a rectangular base. In case of the overpack, which is a cylindrical rigid body with circular base, ASCE 4-16 [4] states based on analytical data that the object tends to tip up and roll on its edge at relatively small uplift angles, which is called “the beercan effect” in NUREG CR-6865 [3]. For this reason, the ASCE 4-16 procedure recommends limiting the maximum uplift angle to one-tenth of the instability angle of a rectangular rigid body but does not provide detailed procedure to assess a cylindrical rigid body using the simplified method. In this study, instead of a direct application of the simplified method with the limitation of one-tenth uplift angle, seismic capacity against instability of the overpack is assessed in two steps. In Step 1, an instability curve is developed without consideration of the 10% limitation on the instability angle. In Step 2, instability of the overpack is assessed at one-tenth of the instability angle computed in Step 1, where the overpack in rocking motion starts to roll, like a beercan.

3.2. Step 1: Rocking Instability

Table 1 summarizes values of the various parameters related to the overpack in use for instability analysis of the overpack. Equations used in the analysis are taken from ASCE 4-16 [4].

Table 1 – Relevant Parameters of the Overpack

Parameter	Description	Value	Remark
h	Height, ft	11	
d	Diameter, ft	12	
b	d/2, ft	6	
a	Aspect ratio	0.545	
α	Initial instability angle, rad	0.499	
θ_{max}	Max rocking angle, rad	0.749	
F_H	Horiozntal correction factor	1	
F_V	Vertical correction factor	1.064	
I_B	Mass moment of inertia	206.33	
C_I	Coefficient of inertia mass	1.705	
C_R	Coefficient of restitution	0.651	
γ	Logarithmic decrement	0.858	
β_e	Effective damping	0.135	
Sa_{max}	Peak spectral acceleration, g	1.733	Figure 5
f_{em}	Peak frequency, Hz	5.255	Figure 5

Effective damping ratio of the cylindrical overpack in rocking motion is computed by Eq. (1) using the logarithmic decrement value of 0.858 from Table 1. The 13.5% damped, averaged, horizontal response spectrum generated at top of the aging pad is presented in Figure 5.

$$Eq.(1) \quad \beta_e = \frac{\gamma}{\sqrt{4\pi^2 + \gamma^2}} = 13.5\%$$

An instability angle of a rectangular object exists in a certain range of uplift angle computed below. The smallest uplift angle is computed at the frequency where the peak spectral acceleration occurs. This angle is obtained by substituting the aspect ratio of 0.545 and the peak frequency of 5.225 Hz from Table 1 in Eq. (2).

$$Eq.(2) \quad \theta_{om} = \frac{2a}{\frac{C_I h}{g}(2\pi f_{em})^2 + 1} = 0.00171$$

An initial instability angle is determined to be 0.499 radian, by taking the arc tangent of the aspect ratio from Table 1. When the simplified method is used, the computed rocking angle shall be increased by a factor of 1.5 to account for uncertainties per the ASCE [4]. Therefore, this initial instability angle is extended to 0.749 radian, and uplift angles considered in this simulation ranges from 0.00171 to 0.749. Instability analyses are performed at a total of 100 angles. Since the uplift angle exceeds 0.4 radian, the small angle approximation is not applied to the overpack.

Seismic capacities against overpack instability are computed at the 100 uplift angles by Eq. (3).

$$Eq.(3) \quad SAH_{CAP} = \frac{2g(f_1(\theta_o) - 1)}{F_H F_V \theta_o}$$
$$where, \quad f_1(\theta_o) = cos(\theta_o) + a \times sin(\theta_o)$$

Effective rocking frequencies corresponding to the 100 uplift angles are computed by Eq. (4).

$$Eq.(4) \quad f_e = \frac{1}{2\pi}\sqrt{\frac{2g(f_1(\theta_o) - 1)}{C_I {\theta_o}^2 h}}$$

Seismic capacities of the overpack against instability are expressed in term of PGA and are computed by Eq. (5), where SAH_{DEM} are spectral accelerations taken from the 13.5% damped response spectra in Figure 5 at the effective rocking frequencies and are normalized to 1g PGA.

$$Eq.(5) \quad PGA_{CAP} - \frac{SAH_{CAP}}{SAH_{DEM}} PGA_{BDBGM}$$

Table 2 summarizes the uplift angles, effective frequencies, and seismic capacities against instability, expressed in terms of PGA, without consideration of the beercan effect.

An instability curve of the overpack is developed using the data in Table 2 and is presented in Figure 6, which reveals that the instability occurs at 0.226 Hz and the corresponding seismic capacity is 4.703g in PGA. This instability analysis did not consider the beercan effect; the overpack tips up and rolls on its edge with limited energy dissipation.

A reasonable instability level of the cylindrical overpack can be approximated by entering the instability curve in Figure 6 with an instability frequency, which is determined by the same procedure discussed above.

Table 2 – Instability Capacities from Step 1

No.	θ, rad	fe, Hz	PGA_{CAP}, g
1	0.0017	5.255	0.521
2	0.0018	5.096	0.524
3	0.0019	4.941	0.532
4	0.0021	4.792	0.546
5	0.0022	4.647	0.567
6	0.0023	4.506	0.58
7	0.0025	4.369	0.558
8	0.0026	4.237	0.542
9	0.0028	4.108	0.534
10	0.0030	3.984	0.533
…	…	…	…
90	0.405	0.266	4.173
91	0.431	0.253	4.232
92	0.458	0.239	4.388
93	0.487	0.226	4.703
94	0.518	0.212	4.653
95	0.551	0.198	4.138
96	0.586	0.185	3.814
97	0.623	0.171	3.469
98	0.662	0.157	3.102
99	0.704	0.142	2.711
100	0.749	0.127	2.296

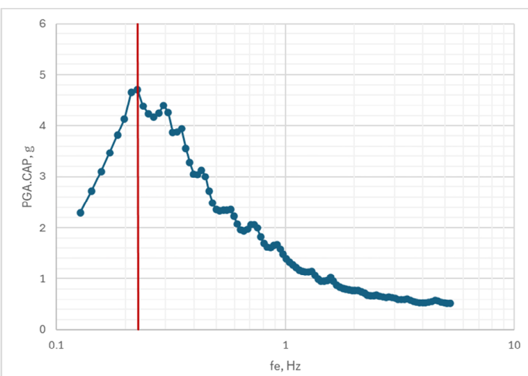

Fig. 6. Instability Curve without Consideration of the Beercan Effect

3.3. Step 2: Rolling Instability (Beercan Effect)

For the overpack with a circular base, a conservative instability angle is set to 10% of the instability angle calculated above, i.e., 0.049 radian. A critical frequency of rocking followed by rolling is computed to be 0.964 Hz by Eq. (4), where seismic demand is 0.585g from Figure 5 when normalized to 1g PGA. The corresponding seismic capacity at 0.964 Hz is computed to be 0.979 g by Eq. (3). Lastly, instability capacity of the overpack is determined by Eq. (5), which is 1.529g. The instability point is marked on the instability curve in Figure 7, which indicates that the overpack may fail at much smaller seismic excitation level when considering the beercan effect.

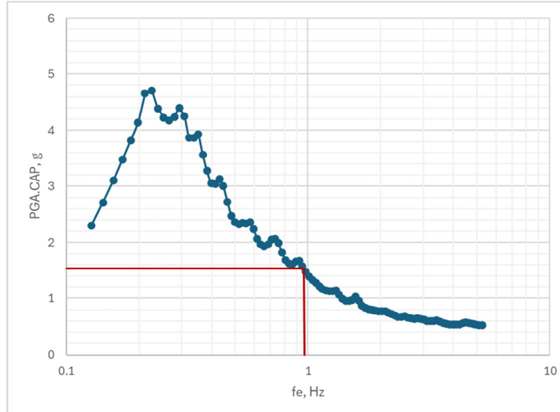

Fig. 7. Seismic Capacity of the Overpack on Instability Curve

4. Conclusions

This paper presents the case study of the seismic assessment of the unanchored dry storage casks mounted on the concrete aging pad over the soil media at the Yucca Mountain repository. The overpack is a cylindrical rigid body with a circular base and is prone to failure due to a combination of rocking and rolling in a seismic event. The instability of the overpack was assessed by the ASCE simplified method in two steps. In the first step, the instability curve was developed without consideration of beercan effect; the overpack will not roll over until it tips over. The resulting critical frequency and seismic capacity at onset of instability are 0.226 Hz and 5.147g, respectively. In the second step, the critical frequency and the corresponding seismic capacity were determined assuming that the overpack becomes unstable at a rocking angle of one-tenth of the instability angle computed in Step 1. The resulting instability frequency is 0.964 Hz, and the instability capacity is 1.673g in PGA, which is about 3 times less than the seismic capacity computed in Step 1. The instability point of the overpack is shown in Figure 7.

In the future, as part of this study, nonlinear time history analyses will be performed to compute response of the same overpack. The seismic capacity in PGA from this study will be compared to capacities from the nonlinear time history analyses. The comparison is performed for three cases: (a) horizontal input in one direction only, (b) concurrent horizontal input in two orthogonal directions, and (c) concurrent input in the two horizontal and one vertical directions. Insights will be derived for possible causes of mismatch between the nonlinear time history and the ASCE 4-16 approach results.

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