Seismic considerations for spent nuclear fuel storage in dry casks

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Abstract: To aid the United States Nuclear Regulatory Commission, Sandia National Laboratories (SNL) was contracted to investigate the seismic behavior of typical dry cask storage systems. Parametric evaluations characterized the sensitivity of calculated cask response characteristics to input parameters. The parametric evaluation investigated two generic cask designs (cylindrical and rectangular), three different foundation types (soft soil, hard soil, and rock), and three different casks to pad coefficients of friction (0.2, 0.55, 0.8) for earthquakes with peak ground accelerations of 0.25g, 0.6g, 1.0g and 1.25g. A total of 1165 analyses were completed, with regression analyses being performed on the resulting cask response data to determine relationships relating the mean (16% and 84% confidence intervals on the mean) to peak ground acceleration, peak ground velocity, and pseudo-spectral acceleration at 1 Hz and 5% damping. In general, the cylindrical casks experienced significantly larger responses in comparison to the rectangular cask. The cylindrical cask experienced larger top of cask displacements, larger cask rotations (rocking), and more occurrences of cask toppling (the rectangular cask never toppled over). The cylindrical cask was also susceptible to rolling once rocking had been initiated, a behavior not observed in the rectangular cask. Cask response was not overly sensitive to foundation type, but was significantly dependent on the response spectrum employed.

Key words: dry cask storage; spent nuclear fuel; seismic analysis

1 Introduction

As of 2010 there were over 1400 spent nuclear fuel dry storage casks in use in the United States (U.S.). These casks are located at 63 independent spent fuel storage installations (ISFSI) in 33 states[1]. With 104 operating nuclear power plants in the U.S.[1] and defunding of high level waste storage repository at Yucca Mountain in 2011[2], the use of dry cask storage is likely to increase in years to come. The events that occurred at Fukushima Daiichi nuclear power plant following the Tōhoku earthquake and tsunami of March 11, 2011 highlight the need to be vigilant in assessing the potential risks that seismic events pose to nuclear power installations[3]. Dry cask storage is no exception. Because storage of spent nuclear fuel in dry storage casks at ISFSIs typically consists of arrays of unanchored freestanding casks on relatively thin (0.6–0.9 m) concrete pads (Fig.1), there are safety concerns related to the performance of casks and cask internals in the event of earthquake induced ground shaking. In their standard ISFSI configurations, casks are susceptible to rocking, sliding, toppling, and/or cask-to-cask pounding during an earthquake. For this reason, the U.S. Nuclear Regulatory Commission (NRC) requires that seismic response be considered when applicable and assessment details included in any ISFSI licensing application[4].

Fig.1 Above ground dry storage cask arrays[5,4]
To aid the U.S. NRC in reviewing storage cask licensing applications, Sandia National Laboratories (SNL) was contracted by the U.S. NRC Office of Nuclear Regulatory Research to investigate seismic behavior of dry cask storage systems. The research effort carried out by SNL was performed in several phases. The first phase included three site-specific/cask-specific analyses in which cask rocking, sliding, and toppling were quantified. The first investigation involved three-module rectangular Transnuclear West module/cask \(^7\); the second investigation involved HI-STORM 100 casks at Hatch Nuclear Power Station \(^8\); the third investigation involved HI-STORM 100 casks at the Private Fuel Storage Facility \(^9\). In an effort to characterize the sensitivity of calculated cask response characteristics to input parameters, a parametric evaluation was performed on work to the three site specific analyses. The parametric evaluation investigated the sensitivity of basic cask design, earthquake ground motion, foundation soil characteristics, and cask-to-pad coefficients of friction on the calculated seismic response of the cask \(^10\). This paper summarizes this parametric evaluation.

2 Parametric evaluation

In order to quantify response characteristics of dry storage casks to earthquake ground motions, a series of simple finite element models were constructed in which freestanding cask, underlying concrete pad, and supporting and surrounding soil column were each explicitly modeled. The transient dynamic finite element code ABAQUS was used to perform the analysis \(^11\). In order to effectively handle the significant nonlinearity expected in each solution run, an explicit time integration scheme was employed. Models were kept as simple as possible so as to both maximize the critical time step required by explicit time integration solution method and to minimize computational resources required to perform the large numbers of runs required for a parametric evaluation. Two basic cask designs were investigated; cylindrical and rectangular (Fig. 2 for an example of two such designs).

2.1 Finite element model description

2.1.1 Mesh

Each finite element model is comprised of distinct representations of the cask, underlying concrete pad, and supporting and surrounding soil column (Fig. 3). For both cask types, the cask was represented using 8-node reduced integration hexahedral elements. Elastic material properties intended to represent the gross structural response characteristics of each cask were assigned to the cask elements. The mass was assigned in such a way as to achieve the correct total cask mass and the desired aspect ratio (one half the cask’s least horizontal dimension, which is the diameter for the cylindrical cask and the width for the rectangular cask, divided by the height to center of mass) for each cask. The cylindrical cask had a total mass of 161 950 kg (representing a fully loaded cask) total height of 5.87 m, base radius of 1.68 m, and a height to its center of gravity of 3 m. This gave the cylindrical cask an aspect ratio of 0.56. The rectangular cask had a total mass of 170 100 kg (representing a fully loaded cask), a total height of 4.57 m, a base width of 2.95 m, a base length of depth (including non-integral shield walls) of 6.4 m, and center of gravity height of 2.54 m. This gave the rectangular cask an aspect ratio of 0.58. To accurately capture the circular geometry of the cylindrical cask, a relatively greater number of elements were used to represent the cylindrical cask than the rectangular
cask. This resulted in element sizes in the cylindrical cask that ended up setting a critical time step for the cylindrical cask analyses that was too small. To get around this problem, the cylindrical cask was made analytically rigid, eliminating the models ability to capture the elastic response of the cask. It was felt that this limitation of the model was relatively unimportant for parametric study being undertaken.

The concrete pad underlying each cask was modeled using continuum shell elements. These special purpose elements behave like shell elements in bending modes but have 8 nodes enabling them to capture through thickness deformations unlike shell elements. A single layer of continuum shell elements were used to model each concrete pad. Elastic material properties intended to represent the gross structural response characteristics of pad were assigned to concrete pad elements. For cylindrical cask model, pad thickness, length, and width were 0.61 m, 10.0 m and 10.0 m, respectively, whereas for rectangular cask pad thickness, length, and width were 0.91 m, 12.5 m and 9.0 m, respectively. For cylindrical cask, the cask was situated within one quadrant of the pad to replicate a typical cask array layout and rectangular cask was situated at the center of the pad.

The supporting soil column was modeled as a cylinder comprised of horizontal layers of elements. Three generic soil profiles were used in the analyses, one representing a soft soil profile, one representing a stiff soil profile, and one representing a rock profile (Table 1, Table 2 and Table 3, respectively). For each soil profile, different sets of material properties were assigned to each layer of elements within the soil column. Identical foundation mesh configurations were used to represent the soft and hard soil profiles, whereas a different mesh configuration was used to represent the rock profile. The outside diameter of the cylindrical foundation models was 167.5 m and the overall depth was 42.7 m.

<table>
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<th>Layer thickness/m</th>
<th>Elastic modulus/MPa</th>
<th>Poisson’s ratio</th>
<th>Density/kg·m⁻³</th>
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2.1.2 Boundary conditions

Ground shaking was introduced to the model at the soil column base at two orthogonal horizontal components and one vertical component. In an idealized, infinitely wide stratified soil mass subjected to earthquake motions applied at its base, the displacements at any two points within a horizontal plane should be equal at any given time (consistent with a one-dimensional soil column assumption). In the immediate region of a structure situated on the surface of such a semi-infinite soil mass there will be disturbances in this uniform displacement field due to interactions between the soil and structure. These effects tend to dissipate away from the structure due to damping in the soil mass. The boundary conditions chosen for the finite element model need to recreate this behavior within the soil column. To achieve this, multi-point constraints (MPC) were applied to the nodes encircling each horizontal plane at the interface of each soil layer, as shown in Fig.3, with one node acting as the master node and all other nodes being constrained to have the same displacement as the master node. This allows the soil column to deform through shear deformation in each soil layer, but prevents bending deformation and radial expansion or contraction of the soil column. To minimize some of the effect of waves reflected off of the soil column boundaries, the soil column horizontal dimension was made large in comparison to the concrete pad.

Contact between the cask and concrete pad, and between the concrete pad and supporting soil was modeled using a finite sliding penalty method based formulation. A simple Coulomb friction model was used to represent frictional component of interaction between contacting bodies. For this model, no differentiation was made between the static and kinetic coefficients of friction; both values were set equal to each other. The coefficient of friction between concrete pad and supporting soil was set to 1.0. This relatively large coefficient of friction was selected to represent the frequently encountered situation in which the concrete pad is set down within the soil column, thus creating a situation in which significant resistance to lateral movement of the concrete pad with respect to supporting soil is provided by soil surrounding the pad. The coefficient of friction between the cask and pad varied as discussed later.

2.1.3 Damping

Because the elements within the model are represented as purely linear-elastic, there is no inherent mechanism in the model to represent structural damping. This is of the largest concern for the soil column since damping mechanism in soil can be significant. For this reason, mass proportional Rayleigh damping was imposed upon the soil column elements. Mass proportional damping has the greatest effect on the lower frequency modes of the structure, whereas stiffness proportional damping has the greatest effect on higher frequency modes. Stiffness proportional damping was not utilized because it was found that its use had only a small impact on the calculated response characteristics, and had a large negative impact on

### Table 2 Stiff soil foundation material properties

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### Table 3 Rock foundation material properties

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the explicit integration solution scheme critical time step for the analysis. Rayleigh damping was not utilized for either concrete pad or cask. Target percentages of critical damping for various soil foundation layers were computed so as to generate values compatible with the strains that occur with an earthquake conforming to NUREG/CR-0098\(^{19}\) spectral curve shape with a peak ground acceleration of 0.25g. The specific values utilized are listed in Table 1, Table 2, and Table 3 for the soft soil, stiff soil, and rock foundation profiles, respectively.

2.1.4 Ground motion determination

In an effort to include ground shaking representative of what could be encountered throughout the U.S., input ground motions for use in this project were created that correspond to response spectrum curves for eastern and central U.S., as well as for the western U.S. Procedures outlined in NUREG/CR-0098 \(^{19}\) and Regulatory Guide 1.60 \(^{19}\) were used to generate response spectra (both vertical and horizontal components calculated separately) representative of western U.S. earthquakes, and procedure outlined in NUREG/CR-6728 \(^{19}\) was utilized to generate a spectrum (both vertical and horizontal components calculated separately) representative of central and eastern U.S. earthquakes. Fig.4 illustrates the calculated spectra used in analyses. Specific ground motions for use in the cask analyses were then generated through a period-dependent scaling of several recorded ground motions against these calculated spectra. The five selected earthquake records representative of western U.S. earthquakes, scaled against NUREG/CR-0098 and Regulatory Guide 1.60 response spectra, are: a. 1978 Iran Tabas; b. 1999 Taiwan Chi-Chi; c. 1992 Landers; d. 1994 Northridge; e. 1979 Imperial Valley.

The five selected earthquake records representative of central and eastern U.S. earthquakes, scaled against NUREG/CR-6728 response spectra are: a. 1985 Nahanni; b. 1988 Saguenay; c. 1979 Imperial Valley; d. 1989 Loma Prieta; e. 1994 Northridge. After period-dependent scaling, each of scaled ground motion were linearly scaled (equally across all frequencies) to produce input ground motions with peak ground accelerations (PGA) ranging from 0.25g to 1.25g. The ground motions generated by method outlined above are for motions at the ground surface. In order to calculate the appropriate input values for introduction of the ground motions at the base of soil column, the equivalent linear seismic response software SHAKE91 \(^{19}\) was used to perform a de-convolution analysis and determine the base input motions for each earthquake motion and each foundation soil type.

2.2 Scope of evaluation

A comprehensive series of parametric analyses were conducted. Table 4 summarizes the specific input parameters that varied. While the scope of investigation is by no means exhaustive, it does span a realistic range of parameters that might be encountered in the field. In total, 1 165 analyses were completed.

3 Analysis results

Three main response parameters were used to characterize behavior of analytical cask models: a. lateral displacement of the cask at its base relative to the concrete pad (as a measure of cask sliding); b. angular rotation of the cask centerline with respect to the vertical coordinate axis (as a measure of cask tipping angle); c. lateral displacement of the top of the cask relative to the concrete pad (as a combined measure of cask tipping and sliding, Fig.5).

In total, 1 165 analyses were performed. As expected, the cask response tends to increase as the ground motion intensity increases. While the earthquake magnitudes were scaled linearly, the cask response does not increase linearly as a function of the ground motion magnitude. In fact, in some instances, the cask response under a given set of input parameters was lower with a higher level of ground shaking. This is because the cask response is very sensitive to the phasing of ground motion pulses with respect to the cask response. Because the cask response is highly nonlinear, changing the scaling of a ground
and $x$ is the independent variable) to the cask response data to determine a series of relationships relating peak cask top displacement and peak cask rotation to PGA. This was done for each cask type, spectral response curve, coefficient of friction between the cask and pad, and foundation soil type. In addition, for each relationship, 16% and 84% confidence intervals were also calculated ($\pm \sigma$, or one standard deviation). Fig. 6 illustrates one such set of curves in which the peak top displacement of a cylindrical cask is plotted against PGA for NUREG/CR-0098 earthquakes with pad-to-cask coefficient of friction of 0.55 and soft soil foundation profile. It is clear from this one example that there was a large amount of scatter in cask response data. This is not entirely unexpected since cask response once sliding or rocking has been initiated will be highly nonlinear and sensitive to characteristics of earthquake shaking as well as details of the response of cask/pad system.

Fig. 7 shows the set of curves for peak top displacement of a cylindrical cask plotted against PGA for NUREG/CR-0098 earthquakes with pad-to-cask coefficient of friction of 0.55 and soft soil, and a rock foundation profile, respectively (plotted on log-log scales). A general observation made from an analysis of parametric study results, which is also illustrated by the cask response data in Fig. 7, is that the foundation soil type did not have a large impact on the cask response quantities. For this reason, results from different foundation types were grouped before performing the final regression analyses. The quality of fit of these grouped curves was generally good. In some cases however, the goodness of fit was worse. This was largely in situations where magnitude of response parameter was relatively small, such as the case for cask rotation when the response was dominated by

<table>
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<td>PGA</td>
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Fig. 5 Illustration of key cask response quantities

motion can affect this phasing in such a way that the overall magnitude of the response is significantly decreased. For this reason it is important that any cask response analysis consider a number of different earthquakes when determining expected cask response to ground shaking.

Despite the trend discussed above, the mean response across the earthquakes and conditions considered always tend to increase monotonically. Based on this observation, regression analyses were performed to fit an exponential equation of the form $y = Ax^c$ (in which $A$ and $B$ are regression determined constants.
sliding instead of rocking or tipping (low pad-to-cask friction coefficient and high PGA).

Fig. 7 Peak top displacement, cylindrical cask, NUREG/CR-0098 earthquakes, cask-to-pad $\mu =0.55$, soft soil and rock profiles $^{[10]}$

Fig.8 shows the set of curves for peak top displacement of a cylindrical cask plotted against PGA, with a pad-to-cask coefficient of friction of 0.55 and all foundation soil profiles for NUREG/CR-0098, Regulatory Guide 1.60 and NUREG/CR-6728 earthquakes. A general observation made from analysis of the parametric study results, which is also illustrated by the cask response data in Fig.8, is that the specific response spectrum used to adjust the recorded ground motions had a significant impact on the magnitude of the cask response. In general, NUREG/CR-0098 or Regulatory Guide 1.60 earthquake resulted in the most extreme responses, with NUREG/CR-6728 earthquake responses being noticeably below the other two spectra earthquakes. Fig.4 illustrates that the frequency content of NUREG/CR-6728 response spectrum is heavily weighted towards higher frequencies (say for periods < 0.25 s) and has significantly less energy at lower frequencies (longer periods) when compared against the other two spectra. This suggests that the response of cask is more strongly associated with the longer period (lower frequency) content of the ground shaking. A method to characterize rocking frequency of the cask as a function of the tipping angle was proposed by Housner $^{[15]}$, which indicates that the rocking period is zero at a tipping angle of zero, and that the period asymptotically approaches infinity as the tipping angle approaches a configuration in which the center of gravity of the cask is over its corner. For a non-sliding or rocking cask, the frequency of the cask-pad-soil system is determined by the resonant frequency for the system (estimated to be equal to 8–14 Hz for the soft soil and rock foundations, respectively), whereas once the cask starts to rock the response frequency drops and the cask’s response becomes more heavily dominated by the lower frequency components of the ground shaking.

Fig.8 Peak top displacement, cylindrical cask, cask-to-pad $\mu =0.55$, all foundation profiles $^{[10]}$
Regression analyses of the results against several other earthquake magnitude measures were also performed. For these regression analyses all response spectra earthquakes for a given cask response parameter (e.g., peak cask top displacement), cask type (e.g., cylindrical), and cask-to-pad coefficient of friction were lumped together. Two alternate measures were investigated, peak ground velocity (PGV) and PSA at 1 Hz and 5% structural damping. It was discovered that the quality of fit PSA curves were consistently higher than those for PGV curves. For this reason, the use of PSA curves is recommended. The complete set of PSA response curves can be found in Ref. [10].

3.1 Cylindrical cask select results

In Fig. 9–Fig. 11, the magnitude of cylindrical cask top and bottom lateral displacements versus time are plotted for each of NUREG/CR-0098 ground motions with PGA of 1.0g, a stiff soil foundation type, and pad-to-cask coefficients of friction of 0.2, 0.55 and 0.8, respectively. The tendency for cylindrical cask to undergo rocking when coefficient of friction

![Fig. 9 Top and bottom displacement versus time, cylindrical cask, cask-to-pad $\mu = 0.20$, NUREG/CR-0098 earthquakes, PGA=1.0g, stiff soil foundation](image)

![Fig. 10 Top and bottom displacement versus time, cylindrical cask, cask-to-pad $\mu = 0.55$, NUREG/CR-0098 earthquakes, PGA=1.0g, stiff soil foundation](image)

![Fig. 11 Top and bottom displacement versus time, cylindrical cask, cask-to-pad $\mu = 0.80$, NUREG/CR-0098 earthquakes, PGA=1.0g, stiff soil foundation](image)
between the cask and pad is sufficiently high is clearly demonstrated in the figures (in Fig.10 and Fig.11, the top and bottom displacements do not exactly track each other). When the coefficient of friction between cask and concrete pad is lower (say equal to 0.2), the cask tends to slide and not rock (in Fig.9, top and bottom displacements diverge from each other). In cases where rocking was induced without significant sliding of the cask on the concrete pad, the cask had a strong tendency to roll. In general, at high levels of ground motion, rocking/rolling motions dominated the cylindrical cask response, with no marked difference between the responses at pad-to-cask coefficients of friction above 0.55. In multiple cases the cask tipped over (Fig.11). For the NUREG/CR-6728 ground motions, the cask never tipped over, whereas overturning was observed for both the NUREG/CR-0098 and Regulatory Guide 1.60 ground motions at PGAs as low as 0.6g.

3.2 Rectangular cask select results

Fig.12 shows a comparison of the top and bottom lateral displacement trajectories for cylindrical and rectangular casks for NUREG/CR-0098 earthquake, with a PGA or 1.0g, a stiff soil foundation, and coefficient of friction between the cask and pad of 0.55. Two things are immediately obvious; the cylindrical cask experiences significantly larger displacements than the rectangular cask, and the cylindrical cask experiences rocking and/or rolling motion whereas the rectangular cask does not. These observations are generally true for rectangular cask for the range of earthquakes investigated. This behavior is largely the result of rectangular cask's non-circular base which encourages preferential rocking (about the cask long dimension axis) and eliminates the possibility of cask rolling about its base once a rocking motion has been initiated.

![Fig.12 Top and bottom displacement trajectories, cask-to-pad \( \mu = 0.55 \), NUREG/CR-0098 earthquakes, PGA=1.0g, stiff soil foundation](image)

In Fig.13-Fig.15, the magnitude of rectangular cask top and bottom lateral displacements versus time are plotted for each of NUREG/CR-0098 ground motions with PGA of 1.0g, stiff soil foundation type, and pad-to-cask coefficients of friction of 0.2, 0.55, and 0.8, respectively. The tendency of rectangular cask to slide without rocking when the coefficient of friction between cask and concrete pad is low is clearly demonstrated in the figures (Fig.13, top and bottom displacements exactly track each other with permanent lateral displacements existing at the end of shaking). When the coefficient of friction between the cask and concrete pad is higher (say equal to 0.8), the cask tends to rock as well as slide (Fig.15, top and bottom displacements diverge from each other). In no instances investigated did a rectangular module tip over. The largest observed peak top of cask displacement for NUREG/CR-6728 earthquakes was 0.26 m at PGA=1.25g, whereas the largest displacements for NUREG/CR-0098 and Regulatory Guide 1.60 earthquakes at the same PGA were 0.52 m and 1.70 m, respectively. The cask top displacement was generally higher for lower cask-to-pad coefficients of friction. Because coefficient of friction of 0.2 is sufficiently low, neither of cask designs investigated exhibit any significant tipping, and as a result the response of the rectangular cask was very close to that of the cylindrical cask for coefficient friction of 0.2.
Conclusion

Storage of spent nuclear fuel in dry storage casks at independent spent fuel storage installations typically consist of arrays of un-anchored freestanding casks on concrete pads. In this configuration the casks are susceptible to rocking, sliding, toppling, and/or cask-to-cask pounding during an earthquake. To aid the U.S. NRC in their assessment of licensing applications for dry cask storage systems and storage installations, SNL was contracted to investigate seismic behavior of typical dry cask storage systems. The research effort carried out by SNL was performed in several phases; with the final phase consisting of a parametric evaluation utilizing the explicit transient dynamics finite element code ABAQUS to characterize the sensitivity of calculated cask response characteristics to input parameters. The evaluation investigated two generic cask designs (cylindrical and rectangular), three different foundation types (soft soil, hard soil, and rock), and three different casks to pad coefficients of friction (0.2, 0.55, 0.8) for earthquakes with peak ground accelerations of 0.25g, 0.6g, 1.0g, and 1.25g conforming to three different
response spectra representative of earthquakes that could occur throughout the United States. Three main response parameters were used to characterize the behavior of analytical cask models: a. lateral displacement of cask at its base relative to concrete pad (as a measure of cask sliding); b. angular rotation of cask centerline with respect to vertical coordinate axis (as a measure of cask tipping angle); c. lateral displacement of the top of cask relative to concrete pad (as a combined measure of cask tipping and sliding).

A total of 165 analyses were completed, with regression analyses being performed on the resulting cask response data to determine relationships relating the mean (16 % and 84 % confidence intervals on the mean) to peak ground acceleration, peak ground velocity, and pseudo-spectral acceleration at 1 Hz and 5 % damping. In general, it was found that cylindrical casks experienced significantly larger responses in comparison to rectangular cask. The cylindrical cask experienced larger top of cask displacements, larger cask rotations (rocking), and more occurrences of cask toppling (the rectangular cask never toppled over). The cylindrical cask was also susceptible to rolling once rocking had been initiated, a behavior not observed in the rectangular cask. Cask response was not overlying sensitive to foundation type, but was significantly dependent on the response spectrum employed.

References

Author
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