SEISMIC ANALYSIS OF FREE-STANDING DRY STORAGE CASK FOR SPENT FUEL

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ABSTRACT

For most dry storage facilities for spent fuel, storage casks are freestanding on a concrete pad. Thus, relative motion between the cask and the pad may be induced during earthquakes, leading to stability concerns. In this study, the seismic stability conditions of a freestanding cask were examined quasi-statically, and the borderline value friction coefficient which differentiates the dominant motion type between sliding and rocking was obtained. Then, a finite element (FE) cask-pad model considering the frictional contact at their interface was established, and a dynamic analysis simulating a scaled cask shaking table test was conducted. Through appropriate settings, the nonlinear dynamic analysis can reasonably reproduce the test results. The influence of the friction coefficient of the cask/pad interface on the cask response was further investigated using this FE model. For the case with lower friction coefficient, the sliding response dominated the seismic motion of the cask; while apparent rocking of the cask was caused at a higher friction coefficient. Thus, the results of the FE analysis are conformable to the quasi-static analysis. In addition, the nutation motion of the vertical cylindrical cask (VCC) which follows the rocking response was also discussed, which may possibly cause considerable horizontal displacement and is therefore unfavorable to the seismic stability of the VCC.

INTRODUCTION

The management and storage of high level nuclear waste, such as spent fuel and damaged control rods, is a critical issue in the operation of nuclear power plants. In most countries, the final disposal strategy for the high level nuclear waste is to install long-term storage facilities so that its radioactivity may decay with time. However, because of the extremely strict requirements of geological and hydrological conditions for the assurance of absolute safety, the selection of a suitable site is very difficult. Therefore, appropriate planning for temporary storage of spent are necessary prior to the operation of the final disposal, and usually two steps are included: (1) short-term storage, in which spent fuel is stored in pools to be cooled down; (2) interim storage, in which spent fuel is stored in dry storage facilities installed at the site of the nuclear power plant. Dry storage means the decay heat of spent fuel is removed by natural air convection instead of by coolant fluid such as water. In Taiwan, the available space of spent fuel pools at Chinsan Nuclear Power Plant (NPP) is now running out, and the site for final disposal has not been decided yet. Therefore, Taiwan Power Company (TPC) is planning to install a dry storage facility at the Chinsan NPP for the interim storage of spent fuel.

For most dry storage facilities for spent fuel, storage casks are freestanding on a concrete pad, rather than anchored like typical civil structures. Physically disconnecting the cask and the pad can reduce installation and future decommissioning costs. However, this will lead to seismic stability concerns of the cask in terms of sliding, rocking, and even nutation (for vertical cylindrical casks) during earthquakes. If the collision between casks or the tipping over of the cask is induced, the cask could be damaged and radioactive leaks might be caused. Since Taiwan is located in a seismic active area, it is necessary to investigate the seismic behavior of a free-standing dry storage cask.
In this paper, the seismic stability conditions of a freestanding cask will be examined by quasi-static analysis, and the borderline value of the friction coefficient at the cask/pad interface which differentiates the motion type at the onset of cask motion between sliding and rocking can be obtained. Then, a finite element (FE) cask-pad model considering the nonlinear frictional contact at the cask/pad interface will be established, and a dynamic analysis will be performed to simulate a shaking table test on a 1/3 scale model cask conducted by Central Research Institute of Electric Power Industry (CRIEPI) (Shirai et al., 2003) to check the validity of this FE model. In addition, the influence of the friction coefficient of the cask/pad interface on the cask response will be investigated using this FE model to verify the results of the quasi-static analysis, and the unfavorable nutation response which might cause considerable horizontal displacement of the vertical cylindrical cask (VCC) will be discussed.

THE EVALUATION FOR THE SEISMIC RESPONSE OF FREESTANDING CASK

Since the storage casks in the spent fuel dry storage facility are unanchored structures freestanding on a concrete pad, the modeling of the highly nonlinear frictional contact behavior at the cask/pad interface will be the main concern in the evaluation for the seismic response of the cask. Several representative numerical analysis models and shaking table tests will be introduced as follows.

Numerical Analysis Model

A seismic evaluation of cylindrical casks was performed by Moore et al. (2000) with soil-structure interaction (SSI) effects considered using the code SASSI (Lysmer et al., 1981) to demonstrate the importance of including the out-of-plane flexibility of the pad, which was modeled by plate elements. The casks were modeled by beam elements, and the contact at the cask/pad interface was simulated by beam elements along with spring elements. Singh et al. (2001) generated a model for the storage cask using the code DYNAMO (Holtec, 1991). The frictional interaction between the cask and the pad was modeled by vertical compression-only gap elements and horizontal piecewise linear friction elements.

In order to take the SSI effects and the frictional contact at the cask/pad interface into consideration simultaneously, a three-dimensional fully coupled cask-pad-ground model was established by Luk et al. (2005) using the FE code ABAQUS/Explicit Version 6.4 (ABAQUS, Inc., 2003) to perform parametric evaluations of seismic behavior of freestanding casks. An explicit time integration scheme was adopted because no iteration is needed in solving nonlinear dynamic problems. Coulomb’s friction law was utilized to simulate the friction behavior at the interfaces, and penalty contact constraint algorithm was used to prevent penetration between the three bodies.

Following the idea of Luk et al. (2005), Ko et al. (2009) also adopted the code ABAQUS/Explicit to generate a cask-pad-ground model to evaluate the responses of the ground and the cask of a planned dry storage facility under the design based earthquake. With appropriate parameter settings, a Rayleigh damping model was utilized to approximate the hysteretic damping model for the simulation of the inherent energy dissipation mechanisms of soil material and frictional contact interface.

Shaking Table Test

Since the highly nonlinear nature of frictional contact at the cask/pad interface, one of the best ways to investigate its behavior is to conduct earthquake simulation tests. A series of shaking table tests on a 1/3 scale model cask using the two-dimensional (horizontal and vertical) shaking table were performed by Central Research Institute of Electric Power Industry (CRIEPI) in Japan (Shirai et al., 2003). The frictional coefficients at the cask/pad interface and the seismic response of the freestanding cask under actual strong earthquake motions were investigated. CRIEPI once again conducted shaking table tests on a full scale cask model using three-dimensional input motions at the E-Defense in Hyogo, Japan for a real assessment of the frictional coefficients between the concrete pad and the cask pedestals made of different materials and the seismic response of the full scale dry storage cask (Shirai et al., 2007).
QUASI-STATIC ANALYSIS OF FREESTANDING CASK

A preliminary examination of the seismic stability conditions of a freestanding cask will be made quasi-statically here. Figure 1 shows the free body diagram of the cask. The height of the center of gravity is denoted as $h_{cg}$, and the shortest horizontal distance from the center of gravity to the edge of the cask is denoted as $r$, which is half of the lateral dimension of the cask. The loads applied to the cask include the gravity force, $mg$, the horizontal seismic inertia force, $ma_h$, and the vertical seismic inertia force, $ma_v$, where $m$ is the mass of the cask, $g$ is the acceleration of gravity, $a_h$ is the magnitude of the horizontal ground acceleration vector during a seismic event, and $a_v$ is the vertical ground acceleration at that same time. Only the less stable case in which $a_v$ is upward will be discussed here, and thus the compressive normal force acting on the base of the cask is $(mg - ma_v)$.

![Figure 1. Free body diagram of a freestanding cask.](image)

The cask and the pad are regarded as rigid bodies, and the cask/pad interface is assumed to follow the Coulomb’s law of friction, that is,

$$f_s = \mu_s N \tag{1}$$

where $\mu_s$ denotes the coefficient of static friction, $N$ is the compressive normal force at the interface, and $f_s$ denotes the maximum static friction force at the interface. Slippage between the bottom of the cask and the surface of the pad will occur only when the lateral force acting to the cask, in this case, the horizontal seismic inertia force, is greater than $f_s$:

$$\mu_s (mg - ma_v) < ma_h \Rightarrow \mu_s < \frac{a_h}{g - a_v} \tag{2}$$

On the other hand, the tipping of the cask will be initiated when the driving moment generated by the horizontal seismic inertia force exceeds the stabilizing moment generated by the normal force at the cask/pad interface:

$$(mg - ma_v) r < ma_h h_{cg} \Rightarrow r < \frac{a_h}{h_{cg}} \frac{r}{g - a_v} \tag{3}$$
By combining Eq. (2) and Eq. (3), it is concluded that tipping of the cask will occur prior to slippage if \( \mu_s > (r/h_{cg}) \), and thus rocking will be its prevailing seismic response. In contrast, if \( \mu_s < (r/h_{cg}) \), sliding of the cask will be induced and tipping over will not occur because a fixed fulcrum which provides a reaction force with the same magnitude as the horizontal seismic inertia force is necessary for tipping over to be caused (see Figure 1). However, if slippage occurs firstly, the fulcrum will be moving and the reaction provided cannot exceed the kinematic friction force at the interface. That is, \( (r/h_{cg}) \) can be regarded as the borderline value of the friction coefficient which differentiates the motion type at the onset of cask motion between slippage and tipping, or, differentiates the dominant seismic response type of the cask between sliding and rocking.

**DYNAMIC ANALYSIS FOR THE SEISMIC RESPONSE OF FREESTANDING CASK**

Although the quasi-static analysis helps to check the stability conditions of a freestanding cask under a given earthquake acceleration, it can only give information about the occurrence of sliding and tipping. In order to clarify whether or not the sliding distance of the cask will exceed the allowable limit to prevent collision between casks and the tipping over will be induced, a dynamic analysis is necessary.

**Modeling of Cask Freestanding on Pad**

As mentioned previously, the modeling of the highly nonlinear frictional behavior at the cask/pad interface is the main concern in the seismic analysis of a freestanding cask. Simplified methods such as Moore et al. (2000) and Singh et al. (2001) can reduce the analysis cost, yet may not give a fair assessment of the complex responses of the cask, such as the nutation of vertical cylindrical cask, and the coupled rocking-sliding motion in which the contact area at the cask/pad interface keeps changing.

Therefore, following the idea of Luk et al. (2005) and Ko et al. (2009), the FE code ABAQUS/Explicit Version 6.11 (Dassault Systèmes, 2011), which has ISO 9001 and ANSI/ASME NQA-1 (nuclear quality assurance) certifications, is adopted in this study. Thus, the geometry of the cask can be well captured by the flexibility of the finite element method, the efficiency of analysis can be kept by the explicit time integration scheme, and the highly nonlinear frictional contact at the cask/pad interface can be appropriately simulated by the “contact pair” algorithm of ABAQUS.

The “contact pair” algorithm provided in the ABAQUS code uses the master/slave concept for contact interactions. That is, one of the two surfaces forming a contact pair is assigned as the master surface, and the other as the slave one. The nodes on the master surface can penetrate the slave surface, while the slave nodes are constrained not to penetrate the master surface. For the contact constraint in this study, the penalty contact algorithm is used, which is similar to introducing stiff springs between the two surfaces to keep them from penetration. Thus, the high frequency chatter at the interface can be reduced.

Regarding the modeling of friction, the Coulomb’s friction law is adopted, as depicted in Eq. (1). Once the shear force at the interface exceeds this maximum static friction, the surfaces can slide.

**Simulation of CRIEPI Shaking Table Test on 1/3 Scale Model Cask**

1. **Introduction of CRIEPI Shaking Table Test on 1/3 Scale Model Cask**

   The shaking table test on a 1/3 scale model cask conducted by CRIEPI (Shirai et al., 2003) is adopted here as the case study of the dynamic analysis for the cask response. The layout of this test and the dimensions of the cask are as shown in Figure 2. A 1/3 scale specimen of a vertical cylindrical cask (VCC) with an outer diameter of 1,230 mm (1,313 mm for the pedestal), a height of 1,921 mm, and a total weight of 8.3 MT was used to simulate a concrete cask with an outer diameter of 3,940 mm, a height of 5,787 mm, and a total weight of 147 MT. The cask pedestal was made of concrete, and the cask body was made of steel and the cross section was adjusted to fit the inertia properties to be simulated. In addition, a scale canister specimen was installed inside the cask to simulate the canister loaded with spent fuel.
The cask specimen was freestanding on a 2,600mm×2,600mm×300mm concrete pad. Two-dimensional (horizontal and vertical) shaking table was used with artificial earthquakes and actual earthquakes (including the record of JMA Kobe station in 1995 Hyogoken-Nanbu Earthquake) as input motions. Furthermore, a 5Hz sinusoidal wave excitation test on the concrete cask pedestal was performed for the friction coefficient between the concrete cask and the concrete pad. Results showed no significant difference between the static friction coefficient, $\mu_s$, and the kinematic one, $\mu_k$, and the concrete-to-concrete friction coefficient can be regarded to be constant and is about 0.7 (Shirai et al., 2003).

Figure 2. Layout of the CRIEPI shaking table test on a 1/3 scale model cask (Shirai et al., 2003)

2. FE Model for Simulation

The FE model for the simulation of the CRIEPI shaking table test on a 1/3 scale model cask is as shown in Figure 3. The eight-node continuum elements C3D8R of ABAQUS were used. The concrete cask and the canister were modeled as separate bodies yet were full-bounded for the sake of simplicity because the main concern was the overall seismic response of the cask rather than internal stability. In addition, since the complex details of each component also had little influence on the cask response, the material parameters were averaged in each component to obtain a representative approximation of the overall inertia and stiffness properties of the cask. The pad was also modeled by C3D8R elements and its flexural flexibility was neglected for better efficiency. The frictional contact at the cask/pad interface was modeled by the “contact pair” algorithm of ABAQUS, and the friction coefficient ($\mu$) was set to be 0.7 according to the sinusoidal wave excitation test on the concrete cask pedestal (Shirai et al., 2003).

Figure 3. FE model of the CRIEPI shaking table test on a 1/3 scale model cask
3. Results of Simulation

The test case of CRIEPI shaking table test on 1/3 scale model cask with concrete pedestal using the JMA Kobe input motion was adopted for simulation. The peak ground acceleration was 818 gal, and the time increment of the input motion was 1/1.73 of the actual record because of similarity law.

The comparison between the test result and the analysis result is given in Figure 4. It should be mentioned that a 2-D test with excitations input in the horizontal Y direction and the vertical Z direction was simulated here (definitions of the directions as shown in Figure 3), and therefore the displacement at the bottom of the cask in Figure 4 is along the Y axis and the rocking angle is around the X axis. It is shown that the maximum displacement and its occurrence moment (about 18mm at 5.9 sec.) can be fairly captured by the analysis; the back and forth displacement response at the middle stage of the test can be approximately reproduced; a residual displacement close to the test result, about 5 mm, can also be obtained. As for the rocking response, the maximum rocking angle and its occurrence moment (about 0.042 rad. at 5.8 sec.) can also be accurately acquired, and the predominant frequency and the magnitude of the analyzed rocking response were close to the test result before 8 sec. However, a smaller rocking angle and a higher rocking frequency than the test result were obtained when the excitation gradually decayed (after 8 sec.). In general, the analysis procedure used here gives a good assessment of the seismic behavior of the freestanding cask, especially the rocking response.

Figure 4. Cask responses from CRIEPI shaking table test on 1/3 scale model cask with concrete pedestal (Shirai et al., 2003) and from FE analysis

It is noted that the displacement at the bottom of the cask showed a back and forth trend and the predominant frequency was closed to that of the rocking response, implying that this displacement response was closely related to the rocking response. That is, the dominant motion type of the scale cask was the rocking response in this CRIEPI shaking table test. Moreover, a top-spinning behavior of the cask was observed in this test (Shirai et al., 2003). Therefore, in order to exhibit the characteristics of the cask response, the lateral displacement locus of the top and the bottom of the cask is drawn in Figure 5. It can be seen that, following the rocking response, a rolling motion of the cask along its circular edge of the
A pedestal was observed, leading to the spinning behavior of its top and bottom. This phenomenon is similar to the nutation of the gyroscopic motion and was discussed in detail by Mustafa (1987). The nutation of the cask under earthquake excitation may cause a large lateral displacement, is not easy to attenuate, and is highly nonlinear so that it is difficult to be accurately simulated numerically. Consequently, nutation is unfavorable to the seismic stability of the widely used vertical cylindrical cask.

![Figure 5. Lateral displacement locus of the cask from FE analysis (with concrete pedestal, $\mu = 0.7$)](image)

4. Influence of Friction Coefficient on the Seismic Response of the Cask

The simulation in the previous section was for the cask with concrete pedestal. However, a steel base plate is usually installed at the bottom of the cask in practice to enhance its capability against impact. Hence, the seismic responses for the cask with concrete pedestal and for that with steel base plate are to be compared in this section in order to investigate the influence of the friction coefficient at the cask/pad interface on the seismic behavior of the cask. The friction coefficient ($\mu$) is 0.7 for the concrete pedestal case, and is considered 0.5 for the steel base plate case according to the sinusoidal wave excitation test on the concrete-filled steel pedestal (Shirai et al., 2007). The JMA Kobe input motion is also used here.

The analyzed seismic response of the cask for $\mu = 0.7$ and $\mu = 0.5$ are given in Figure 6. It can be seen that a more apparent displacement response is observed for $\mu = 0.5$ than $\mu = 0.7$, and it is more likely to be induced by the sliding motion according to its tendency. On the other hand, almost no rocking behavior occurs for $\mu = 0.5$. It is concluded that the dominant motion type of the cask for $\mu = 0.5$ is the sliding response, instead of the rocking response for $\mu = 0.7$.

It should be mentioned that the $(r/h_{og})$ value of this 1/3 scale model cask can be calculated to be 0.683 based on its design. According to the quasi-static analysis, the dominant seismic response type of the cask will be sliding when $\mu = 0.5 < 0.683$, and will be rocking when $\mu = 0.7 > 0.683$, which is conformable to the dynamic analysis.

In addition, the displacement locus of the top and the bottom of the cask for $\mu = 0.5$ is given in Figure 7. It is shown that the displacements of the top and the bottom of the cask are synchronized and are merely along the excitation direction (Y direction), which means that no rocking and nutation will be induced when sliding is the dominant seismic response type of the cask. Thus, the seismic behavior of the cask will be easier to predict.
Figure 6. Comparison of cask responses from FE analysis for $\mu = 0.7$ and $\mu = 0.5$

Although in this case the maximum and residual displacements are larger for $\mu = 0.5$ than $\mu = 0.7$, a large friction coefficient at the cask/pad interface is still not preferable because the possible nutation behavior is not easy to attenuate and may cause a considerable lateral displacement if the cask rolls along its circular edge of the pedestal to a specific direction, and also because the rocking behavior will make the cask pedestal keep impacting the pad, which is unfavorable for its structural integrity. Accordingly, a higher seismic stability may be achieved by setting the friction coefficient at cask/pad interface to be a few lower than the $(r/h_{cg})$ value of the cask.

Figure 7. Lateral displacement locus of the cask from FE analysis (with steel base plate, $\mu = 0.5$)
CONCLUSION

1. According to the quasi-static analysis and the dynamic analysis presented, the relative motion between the cask and the pad is greatly influenced by the frictional behavior at their interface. If the friction coefficient is lower than the \((\frac{r}{h_{cg}})\) value of the cask, the cask response will be dominated by sliding; on the other hand, the dominant response will be rocking if the friction coefficient is larger than \((\frac{r}{h_{cg}})\).

2. The dynamic analysis procedure adopted in this study to solve the highly nonlinear contact problem of a freestanding cask under earthquake excitation gives a good assessment of its seismic response, including the displacement and the rocking angle.

3. In addition to the frictional behavior at the cask/pad interface, the geometry of the cask is also crucial to the seismic response of the cask. This is because the rocking response of a vertical cylindrical cask is usually followed by the nutation motion, which may induce considerable displacement and is difficult to be accurately analyzed.

4. The rocking and nutation behavior of a vertical cylindrical cask is unfavorable since the former will make the cask pedestal keep impacting the pad and the latter may cause a considerable lateral displacement. Accordingly, a higher seismic stability may be achieved by setting the friction coefficient at cask/pad interface to be a few lower than the \((\frac{r}{h_{cg}})\) value of the cask.

REFERENCES

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