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Analysis for seismic response of a free-standing vertical cylindrical cask for spent fuel

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ABSTRACT

The management and storage of the high radioactive waste has always been an important issue for the safe and continuous operation of nuclear power plants. In Taiwan, the available space of spent fuel pools for short term storage is going to be exhausted in a few years, and the location of the final disposal facility is still to be decided. Therefore, the installation of dry storage facilities for interim storage is necessary.

In this study, the seismic behavior of the free-standing vertical cylindrical cask (VCC), which is widely used in existing dry storage facilities, are investigated. A quasi-static equilibrium analysis of the cask is firstly performed to examine the basic physics of a free-standing VCC. Then, the ANSYS/LS-DYNA code is adopted to analyze the seismic response of the dry storage facility with free-standing casks. A 3D finite element model consisting of a freely-standing VCC and a concrete pad will be established with the simulation of the nonlinear frictional contact at their interface. Analyses for the seismic responses of the cask at various values of the friction coefficient were performed. The results show that the free-standing cask will sliding and rocking, but not tip over, during strong earthquakes. A borderline value of the friction coefficient which differentiates the motion type of the cask at the onset of motion between sliding and rocking was deduced, and can be related to the radius/height ratio of the cask.

INTRODUCTION

The management and storage of highly radioactive waste has always been an important issue in the safe and continuous operation of nuclear power plants. In Taiwan, the available space in spent fuel pools for short-term storage of such waste will be exhausted in a few years, and the location of a final disposal facility is yet to be decided. Therefore, the installation of dry storage facilities for interim storage is vital. In dry storage facilities, the spent fuel is stored in dry-type storage casks or modules, and these casks/modules are usually free-standing on a concrete pad rather than anchored like other civil structures. This leads to stability concerns in terms of sliding and rocking in the event of an earthquake. The main considerations for the seismic safety of free-standing casks/modules are the possible collision between casks/modules due to their horizontal displacement and tipping-over due to the rocking response during earthquakes.

Many studies have been conducted on the motion of a single body freely standing on the floor. Ishiyama [1] categorized the fundamental response modes as sliding, bouncing, and rocking. Accordingly, through the combination of these three modes, any motion of a rigid body in a plane can be classified into six different situations: (1) rest; (2) rotation; (3) sliding; (4) sliding and rotation; (5) sliding and bouncing; and (6) rotation, sliding and bouncing. The coefficient of friction must be greater than the breadth–height ratio of the body in order to initiate rocking motions. Scalia and Sumbatyan [2] showed that a rigid block resting on a floor subjected to a strong horizontal ground motion will not jump, if the friction coefficient at the interface is small enough. Lin and Shi [3] illustrated a strong dependence between the stability and the aspect ratio (h/r) and size (R). Cylinders of smaller aspect ratio and larger size are more stable. Koh and Mustafa [4] investigated the dynamic response of a free-standing vertical cylinder on a shaking rigid foundation using a simplified three-dimensional (3D) model. Three types of response were observed, including rocking, nutation, and toppling.

Many experimental studies on the friction coefficient at the steel/concrete interface have been made. Rabbat et al. [5] performed fifteen tests on the coefficient of static friction between a rolled steel plate and cast-in-place concrete or grout. The average effective coefficient of static friction ranged between 0.57 and 0.70. Baltay et al. [6] showed that the friction coefficient between concrete and mild steel is between 0.2 and 0.6. These experimental studies also indicate that the friction coefficient can be influenced by the presence of mill scale on the steel surface, as well as by the normal pressure applied to the interface. In a study on the seismic response of free-standing storage casks, Shirai et al. [7] performed several excitation tests on a 1/3-scale model cask using a shaking table. The friction behavior between the pad surface and cask pedestal under sinusoidal excitation and the seismic response of a free-standing vertical cylindrical cask (VCC) under strong earthquake motions were investigated.

Ko et al. [8] used the ABAQUS/Explicit code to establish a fully coupled cask–pad–ground finite element (FE) model to analyze the seismic response of the dry storage facility. The differential settlement of the foundation pad due to the self-weight of the casks increases the sliding potential of the casks during earthquakes.

According to previous studies, the friction coefficient at the interface between the cask and the pad is crucial to the seismic response of the free-standing VCC. However, the friction coefficient can differ greatly between different materials. In this paper, the seismic behavior of the free-standing VCC, which has been widely used in practice, will be investigated for various friction coefficients. Firstly, a quasi-static equilibrium analysis of the cask is performed to examine the basic physics of a free-standing cask. Then, the ANSYS LS-DYNA code is adopted to analyze the seismic response of the dry storage facility with free-standing casks. A 3D FE model consisting of a free-standing VCC and a concrete pad will be established with the simulation of the nonlinear frictional contact at their interface. Artificial earthquake motions, which are compatible to the design spectra, will be adopted as input motions. Analyses will be performed for various values of friction coefficient. The characteristics of the seismic response of a free-standing VCC and the influence of the friction coefficient at the cask/pad interface will be presented and discussed herein..

QUASI-STATIC EQUILIBRIUM ANALYSIS OF FREE-STANDING CASK

The quasi-static equilibrium analysis of a dry storage cask was performed first to examine the basic physics before proceeding with the dynamic analysis for its seismic response. It is assumed that the cask and the pad are both rigid bodies, and the interface between the cask and the pad follows Coulomb's law of friction. That is, slippage occurs between two surfaces only when the lateral force acting to cause sliding is greater than the product of the friction coefficient (μ) and the compressive normal force on these surfaces; in other words, the maximum static friction force at the interface.

Fig. 1 shows the free body diagram of a cylindrical cask. The height from the cask base to the center of gravity (CG) is denoted as h_{cg}, and the radius of the cask is denoted as r. The forces applied to the cask include the gravitational force, mg, the horizontal seismic inertial force, ma_h, and the vertical seismic inertial force, ma_v; where m denotes the mass of the cask, g is the acceleration due to gravity, a_h is the horizontal ground acceleration, and a_v is the vertical ground acceleration. The more conservative case of an upward a_v is considered here, and the effective compressive normal force acting on the cask base is $m(g - a_v)$.

When the horizontal seismic inertial force on the cask exceeds the maximum static frictional force at the cask/pad interface, the cask will slide relative to the pad, i.e.,

$$ma_h \geq \mu(mg - ma_v) \;\Rightarrow \mu \leq \frac{a_h}{g - a_v} = a_c \tag{1}$$

When the overturning moment generated by the horizontal seismic inertial force on the cask exceeds the stabilizing moment provided by the effective weight of the cask, one side of the cask will be lifted (rocking) against the contact point between the two bodies, i.e.,

$$ma_h h_{cg} \geq (mg - ma_v)r \quad \Rightarrow \frac{r}{h_{cg}} \leq \frac{a_h}{g - a_v} = a_c \tag{2}$$

For cases with $\mu > (r/h_{cg})$, the rocking motion of the cask will be induced whenever $a_c > (r/h_{cg})$. For the VCC model selected, since r=2.125 m and h_{cg}=2.975 m, the ratio of r/h_{cg} is 0.714 in this case. According to the quasi-static equilibrium analysis, this can be regarded as a borderline value of the frictional coefficient, differentiating the motion type of the cask between sliding and rocking. Therefore, the response of the cask is pure sliding without any tip-over for cases with μ = 0.2, 0.4 and 0.6, while it is dominated by a rocking type motion at μ = 0.8. This can be verified via the dynamic analysis.

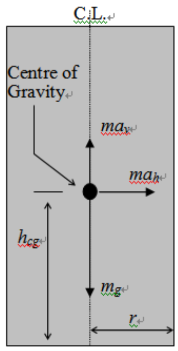


Fig. 1 Free body diagram of a free-standing cask.

NUMERICAL ANALYSIS MODEL OF FREE-STANDING CASK

The finite element code ANSYS/LS-DYNA is adopted in this study in order to examine the influence of friction coefficients on the seismic response of an elastic storage cask. LS-DYNA is a general purpose explicit finite element code capable of highly nonlinear dynamic analysis for 3-dimensional structures. It is an ANSI/ASME NQA-1 (nuclear quality assurance) certificated code and is widely used in the nuclear power industry, usually for the analyses of the seismic response, tip-over, and drop of spent fuel dry storage casks, as well as the investigation of the impact of airplanes or other projectiles on the containment structures.

Validation of the finite element code

A simulation for the shaking table test of a 1/3 scale model cask performed by Central Research Institute of Electric Power Industry (CRIEPI) in Japan [7] was conducted using the LS-DYNA code. In this test, 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 metric tons 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 metric tons. The cask specimen was freestanding on a 2,600mm×2,600mm×300mm concrete pad. The scale model cask for the shaking table test and its FE model are shown in Fig. 2. The record of JMA Kobe station in the 1995 Kobe earthquake was used as input motions. The concrete-to-concrete friction coefficient at the cask/pad interface can be considered constant and is about 0.7 according to the sinusoidal excitation test of the bottom part of the cask [7]. During the shaking table test, the dominant motion type of the scale cask was the rocking response. Moreover, a top-spinning behavior of the cask was observed, which means a nutation motion was induced.

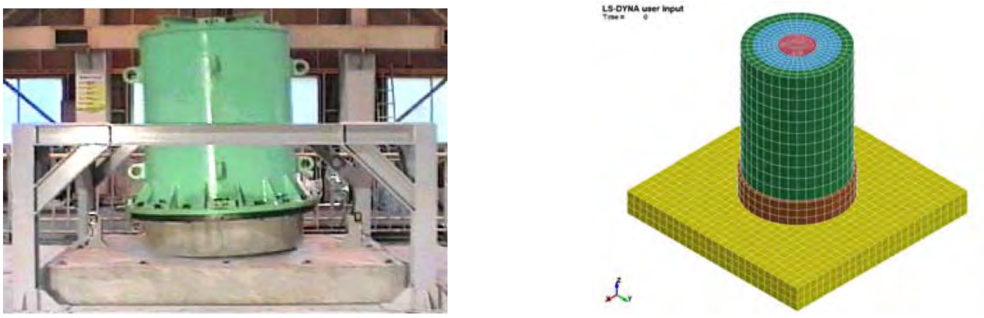


Fig. 2 (a) 1/3 Scale model cask for shaking table test (Shirai et al., 2003) and (b) its FE model.

The comparison of the test results and FE analysis is shown in Fig. 3. The time history of rocking angle of FE analysis was similar to that of the scale model shaking table test. Especially before 8 sec., both the frequency and the magnitude of the rocking response of the FE analysis were quite conformable to the test result. Thus, the LS-DYNA code is verified to be appropriate for simulating the complex coupled motion of rocking and nutation of the vertical cylindrical cask.

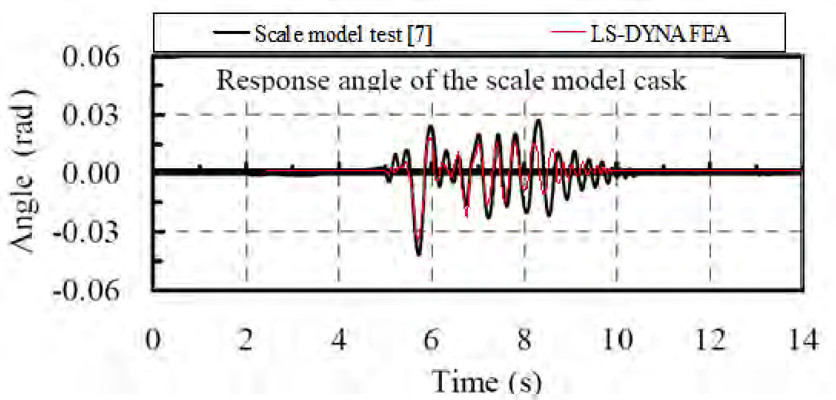


Fig. 3 Cask responses from the scale model shaking table test and from FE analysis.

Numerical Analysis Model

Fig. 4 shows the FE mesh a VCC free-standing on a concrete pad. The VCC and its internal components were represented by a single cylinder; that is, each internal component was not modeled as an independent body. This is because the details of the internal components, such as the cask liner, the canister, and the content inside the canister, are complex yet have little influence on the seismic response of the cask.. Therefore, the mass and stiffness properties of all the components were averaged and were assigned to approximate the overall mass and stiffness properties of the loaded cask. The size of the cask and concrete pad were Φ4.25 m×5.95 m (H) and 8 m (L) ×8 m (W) ×1.2 m (T). Considering the friction behavior between the cask and the pad, the material of the cask was assumed to be rigid in inner cylinder (Φ3.83 m) and elastic in outer, the pad was assumed to be rigid. In this case, r=2.125 m, h_{cg}=2.975 m, and the borderline value of friction coefficient differentiating the initial motion type of this cask, r/h_{cg}, is 0.714 under the material of the cask and pad were both assumed to be rigid.

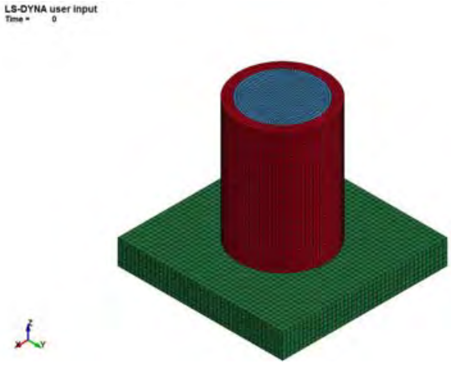


Fig. 4. FE model of the free-standing cask.

Concerning the modeling of the highly nonlinear contact behavior at the interface between the cask and the pad, the "contact_automatic_single_surface" algorithm provided in the ANSYS/LS-DYNA code was used, and the Coulomb's law of friction was adopted for the modeling of friction. The range of friction coefficient between concrete/concrete or concrete/steel interface was 0.2 to 0.7 in previous studies. According to the quasi-static analysis, the friction coefficient will have significant influence on the seismic response of the cask. Consequently, the friction coefficients (μ) 0.2, 0.4, 0.6 and 0.8 were considered for the cask/pad interface in this study. A 40.95-second-duration artificial earthquake with three components of motions (in X, Y, and Z directions) was established and was input on the concrete pad. The peak ground accelerations in X, Y, and Z directions are all scaled to 0.78g.

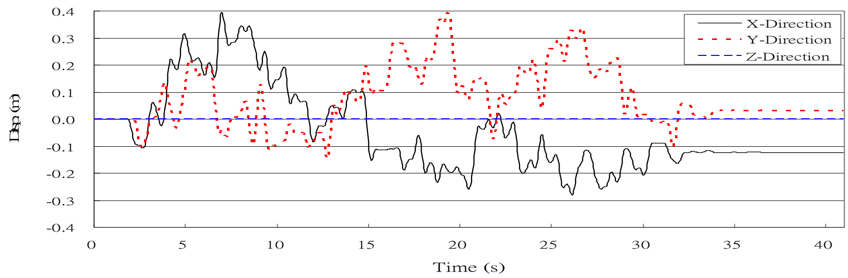
The main concern of this study is to investigate the seismic behavior of cask and the influence of friction coefficient during the specified earthquake excitations. Therefore, the primary cask responses in seismic analysis to be monitored consist of the displacement at the center of the cask pedestal and the rocking angle of the cask axis from the vertical axis, which are representative of the motion type of the cask (sliding or rocking) and help to judge the contact status between the cask and the pad.

ANALYSIS RESULTS OF THE FREE-STANDING CASK

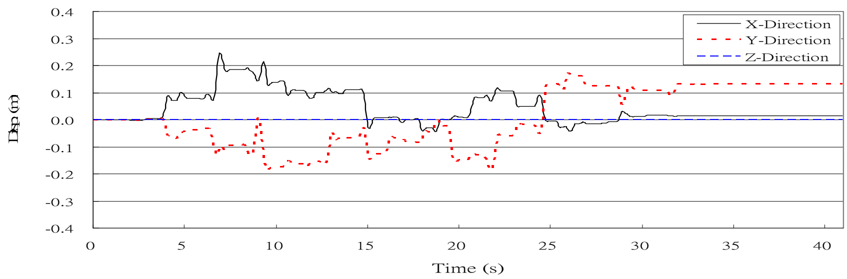
The displacement time histories of the cask pedestal relative to the top of pad in X, Y and Z directions for μ is equal to 0.2, 0.4, 0.6 and 0.8 are shown in Fig. 5. The excitation of the earthquake induces the horizontal and vertical displacements of the cask and causes a residual horizontal displacement after the earthquake. For the case of μ=0.2 is shown in Fig. 5(a), the maximum displacements in X and Y directions are both 0.40 m; while the residual displacements in X and Y directions are -0.12 m and 0.03 m, respectively. The same phenomenon can also be found when μ=0.4 in Fig. 5(b). The maximum displacement in X and Y direction are 0.25 m and 0.17 m, which were less than μ=0.2. However, there is almost no vertical displacement. This means that only the sliding motion of the cask occurred, and no uplift or rocking responses was induced in this case.

Fig. 5(c). shows the relative displacement results when μ=0.6. The maximum displacement are -0.08 m and -0.11 m in X and Y direction, which were the least displacement in X and Y direction when μ ranges from 0.2 to 0.6. However, the behavior of cask during the earthquake was changed from pure sliding motion to sliding-rocking motion. The maximum displacement in Z direction is 0.02 m. The max rocking angle of cask are -0.61° and -0.18° in X and Y direction.

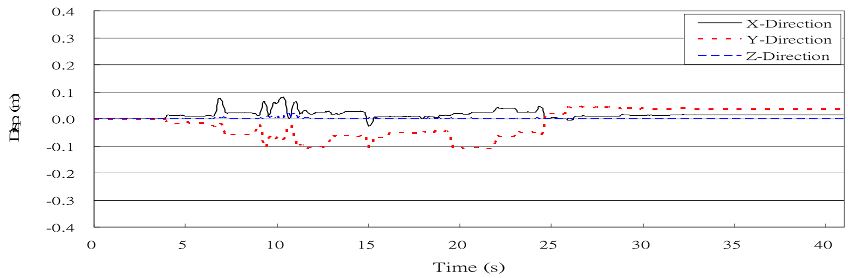
The displacement of the cask pedestal for μ=0.8 is shown in Fig. 5(d). The tendency of the displacement of cask is obviously different from the cases of μ = 0.2 to 0.6. The maximum displacements in X, Y and Z direction are -0.41 m, 0.27 m and 0.28 m, and the residuals are -0.21 m and 0.03 m in X and Y direction. In addition, Fig. 6 shows the rocking angle time history in X and Y direction of the cask. The maximum rocking angles toward X and Y directions are 7.16° and -4.90°, respectively. Therefore, significant rocking motion was induced rather than sliding motion in this case. However, considerable horizontal displacement of the cask pedestal is still observed and could be larger than the cases of μ = 0.2~0.6.



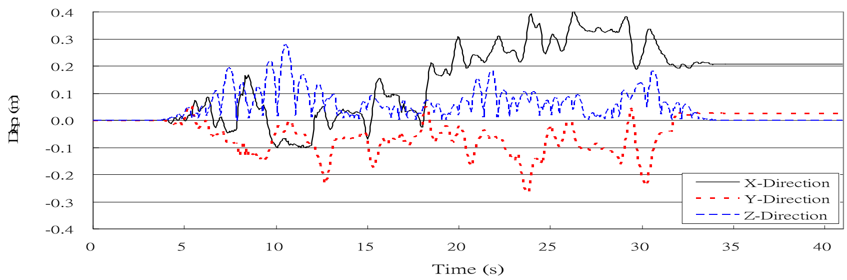
(a) μ=0.2



(b) μ=0.4



(c) μ=0.6



(d) μ=0.8

Fig. 5. Relative displacement time histories of cask pedestal

The relationship between the maximum horizontal displacement and maximum rocking angle of the cask with respect to the friction coefficient (μ). The displacement reduces sharply as μ ranges from 0.2 to 0.6, and the rocking angle increased rapidly as μ ranges from 0.6 to 0.8. From the results presented above, when $\mu \leqq 0.6$, the primary seismic response motion of cake was sliding motion and the sliding distance in horizontal decreased when μ increased. However, the displacement in the Z direction occurred and the cask began rocking since μ was greater than 0.6. When μ is 0.8, the trend of horizontal displacement of cask became more difficult to predict because it is controlled by the rocking motion.

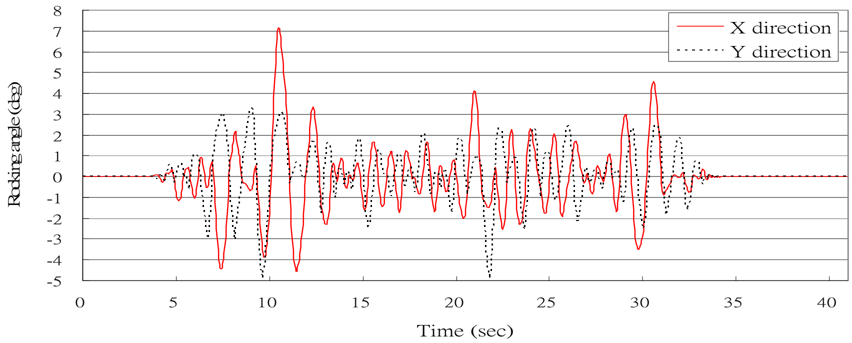
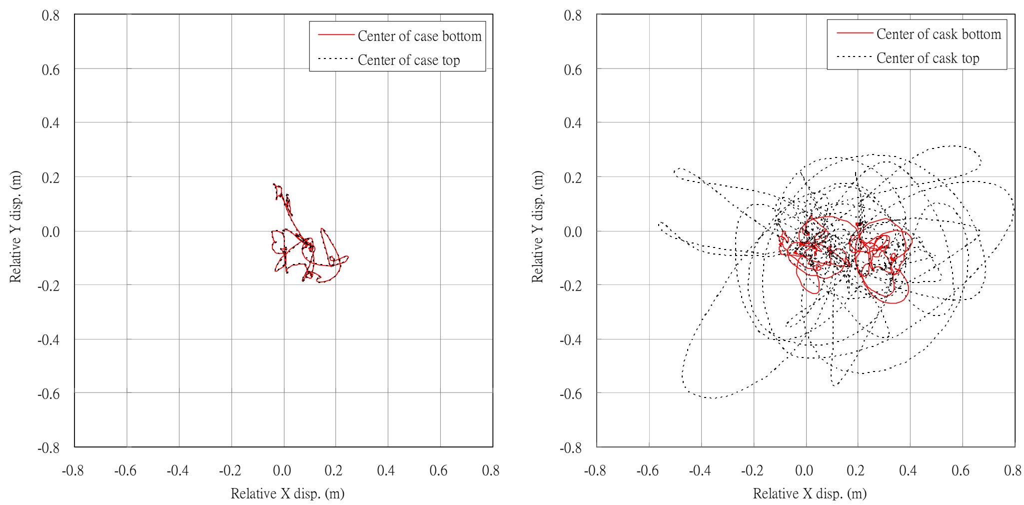


Fig. 6. Relative rocking angle time histories of cask pedestal when μ=0.8

For a deeper understanding of the rocking motion of the cask during an earthquake, the horizontal displacement loci of the top and the bottom of the cask in X and Y direction for μ = 0.4 and 0.8 are depicted in Fig. 7. It can be found that the locus of the cask top almost coincides with that of the cask pedestal for μ = 0.4, which means that the response of cask is controlled by sliding motion. In contrast, the loci of the top and bottom of the cask are different for μ = 0.8, indicating the rocking motion has occurred, and the difference is more significant for the later. Accordingly, the borderline value of the friction coefficient which differentiates the initial motion type of the cask may be between 0.6 and 0.8, which is smaller than that obtained from the quasi-static equilibrium analysis, 0.714.

From Fig. 7., it is also noted that the horizontal displacement is significant for the rocking-controlling cases (μ = 0.8) because the nutation motion (along the circumference of cask bottom) occurred, which followed the initiation of the rocking motion. Since the nutation motion is highly nolinear and unpredictable, the relationship between the horizontal displacement and μ is thus irregular. Thus, the seismic design of freestanding dry storage facility needs to consider: Avoiding the rocking motion of cask during an earthquake is due to the nutation motion and huge horizontal displacement will occur with the rocking motion. Permitting the sliding motion occurs to dissipate the energy of seismic by the frictional resistance between the cask and pad.



(a) μ = 0.4 (b) μ = 0.8

Fig. 7. Horizontal displacement locus of the cask

CONCLUSION

In this study, a 3D finite element model consisting of a freestanding VCC and a concrete pad was established and the seismic behavior of the cask was investigated by the explicit finite element code ANSYS/LS-DYNA. Results of the analyses in this study are follows.

1. According to the rigid-body quasi-static equilibrium analysis, the r/h_{cg} value of a vertical cylindrical cask (VCC) represents a borderline value of the coefficient of friction that differentiates the motion type of the cask at the onset of motion between sliding and rocking.
2. The friction coefficient (μ) between the cask and pad will influence the seismic behavior of VCC significantly. When μ=0.2, 0.4, and 0.6, the primary seismic response motion of cake was sliding motion and the sliding distance in horizontal decreased when μ increased, and the cask began rocking since μ was greater than 0.6
3. The factors affect the stability of freestanding dry storage facility are including a_h, a_v, μ and r/h_{cg}. The a_h and a_v are the accelerations of earthquake in the horizontal and vertical direction. The conservative analysis is necessary to improve the reliability because the seismic motion uncertainties.
4. The effect of the μ and r/h_{cg} in seismic design of freestanding dry storage facility are available to concern:
   A. Sufficient large value of r/h_{cg}: To avoid the rocking motion bring the unfavorable nutation motion and sliding motion, and to increase the stability of freestanding dry storage facility, the design of r/h_{cg} needs larger than a_c necessarily.
   B. Adequate large value of μ: In the premise of the motion of cask just sliding not rocking, the horizontal sliding displacement decreases with μ increases. The appropriate μ between the cask and pad will decrease the sliding displacement and increase the capability of energy dissipation of seismic.

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