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SEISMIC RESPONSE ANALYSIS OF A FREESTANDING MODEL OF SPENT FUEL STORAGE CASK

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ABSTRACT

The seismic response analyses of a freestanding spent fuel storage cask are performed for an artificial time history acceleration generated on the basis of the US NRC RG1.60 response acceleration spectrum. This paper focuses on the structural stability regarding seismic loads to check the overturning possibility of a storage cask and the slip displacement on the concrete installation bed. A simple structural analysis model for the storage cask is developed to perform the parametric effect analyses regarding the seismic responses. Two parameters considered in the analyses are the magnitude of the seismic load and the interface friction between the cask's bottom surface and the upper surface of the concrete installation bed. The analyses results show that the seismic responses of the storage cask are influenced by a combination of the two parameters and the storage cask also has a large marginal integrity for the maximum overturning angle and the slip distance for the design and beyond design seismic loads.

Keywords: Spent fuel storage cask, seismic response analysis, lumped-mass model.

1. INTRODUCTION

The spent fuels from a nuclear reactor are usually stored in storage casks or a facility in site or outside a reactor plant when the internal capacity of the spent fuel storage building is full. In Korea, a conceptual study for storing the spent fuels in a concrete storage cask was started recently [1]. There are several concepts for the storage cask and many researches including a seismic response analysis are performed [2,3]. The proposed concept in Korea is that the spent fuel assemblies of a PWR type are stored in a dry type concrete storage vessel system, which is consisted of a canister and a storage cask body containing the canister. The canister accommodates 24 spent fuel assemblies of a PWR type. The storage cask is a steel cylindrical shell structure and contains the canister as shown in Fig.1[1]. The storage cask consists of the inner and outer shells, and a thick concrete shield between the inner and outer shells. This system is a free standing structure on a concrete installation bed. It should resist a seismic load and not be overturned, and be within a limited slip distance. The seismic load type is the artificial time history (ATH) acceleration data generated by using the seismic acceleration spectrum of the NRC Reg. Guide 1.60. The time history data are generated for the horizontal and vertical directions. The design SSE level is 0.3g for a horizontal direction and 0.2g for a vertical direction.

In this paper, the parametric effect analyses of the acceleration magnitudes and the friction coefficients between the concrete bed and the cask bottom are performed by the ABAQUS computer program[5]. The acceleration magnitudes range from 0.3g to 1.0g for the seismic response analyses. The friction coefficients range from 0.2 to 1.0. The seismic response evaluations for the storage cask are undertaken based on the analysis results such as the maximum rocking angle, the maximum acceleration response, and the maximum sliding distance on a bed.

2. DESCRIPTION OF THE CONCRETE STORAGE CASK

The schematic design drawing of a concrete storage cask is represented in Fig 1[1]. The cask's overall height is 5.88m, the total weight of the storage cask is 154 tons including the canister and fuels of 33.4 ton. The diameters of the outer and inner shells of the cask body are 3.52m and 1.92m, respectively. The thicknesses of the inner and outer shells are determined as 50mm and 20mm, respectively. The two shells are the load-carrying structures, which are made of SA350. The canister accommodates a fuel basket for holding 24 PWR spent fuel assemblies and is installed inside the storage cask. This is made of SA240 type 304. The canister can be separated from the cask body through the overpack lid. The cylindrical concrete shield of the cask body is supported by the enclosed annulus of the inner and outer shells, the shield is not treated by a load-carrying structure. The cask body has an air duct cooling system for removing the decay heat of the spent fuels. The concrete installation bed is assumed to be designed to have the required width and depth dimensions.

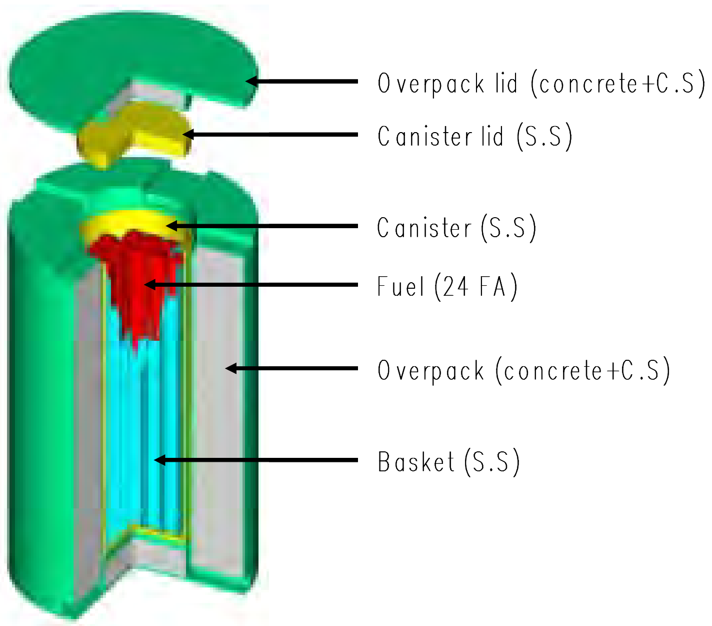


Figure 1 Conceptual drawing of spent fuel storage cask

3. SEISMIC RESPONSE ANALYSIS

3.1 Seismic Analysis Modeling for Cask

For the time history response analyses for a seismic load, a simple structural model for the storage cask is developed. In the simple model, the shield concretes are assumed to have a uniform mass distribution along the cask's longitudinal direction. The canister and fuels are considered in the model as lumped masses to reduce the computing time. The model consists of a stick beam and several lumped masses.

The JOINTC nonlinear spring element of the ABAQUS computer program is used for modeling the contact normal force between the lower bottom of the cask and the concrete installation bed. The element transmits a compressive force, only in the vertical direction. The finite element analysis model for the storage cask has 5 nodes, 4 beam elements, and 5 lumped mass elements. The user subroutine UMAT is used to simulate the slipping friction condition in the horizontal direction [4,5]. The friction force is obtained by the friction coefficient and the varying normal force at each time. Fig.2 is the simple displacement-force diagram for the JOINTC nonlinear spring and ABAQUS user subroutine input.

The compressive contact stiffness(S_1) of the installation bed can be obtained by the relationship of the normal force and the deflection. In this paper, 7,840 x 10^6N/m is used for the eight contact points supporting the storage cask in the vertical direction [5]. The Coulomb's friction coefficients are used to simulate the horizontal slipping motions. The effects for the overturning and slipping response according to the friction values are checked by the variations of the parameters. The lumped mass and beam model for the seismic response analysis is shown in Fig. 3. The eight spring elements are used to model the contact condition. To simulate the bottom circular shape of the storage cask, 16 rigid beam elements are used. The radial rigid beam ends are connected to the neighboring beam ends.

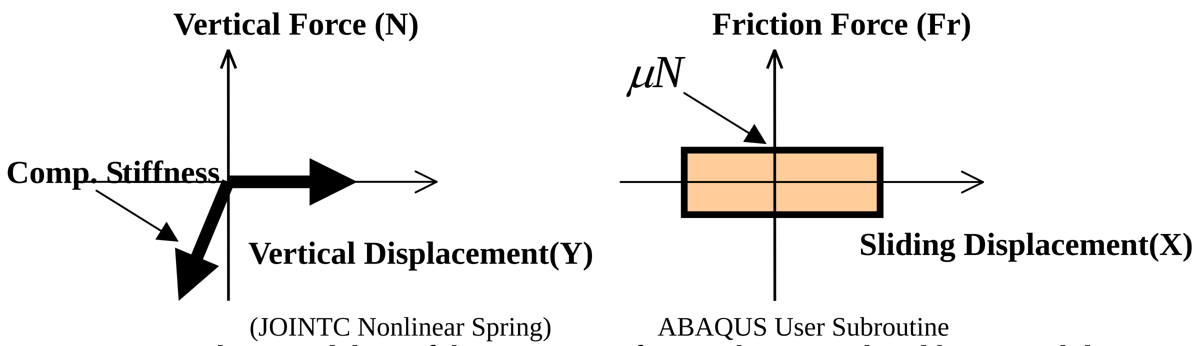
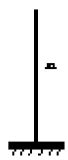


Figure 2 Analysis modeling of the contact surface in the vertical and horizontal directions

3.2 Dynamic characteristics of the storage cask

The several mode shapes of this model are calculated by the ABAQUS and are represented in Fig.4. The first natural frequency is the rotational mode of 10.7Hz by the compressibility of a half side of the cask's bottom. The vertical motion is 31.9Hz by the uniform compressibility of the concrete installation bed and the cask's bottom. These are related to the cask's rigid body motion. So the seismic load transmitted to the storage cask through the installation bed can be amplified to some extend by the two modes of 10.7 Hz and 31.1Hz. The seismic responses in a time history analysis are mainly influenced by the stiff compression stiffness and zero tension stiffness between the storage cask and the concrete bed. The zero tension is resulted from a freestanding condition of the storage cask on the bed. The first bending mode of the storage cask body itself is 61.1Hz, which is much higher when compared to the 29 Hz of the simple beam theory as roughly calculated by the following equation when the bottom end is assumed to be a fixed condition.

$$f_n = \frac{(0.597\pi)^2}{2\pi}\sqrt{\frac{EI_{cyl}}{l^4 m}}$$, m = mass per unit length,



In the equation, the bending stiffness of the two annuls shells are simply summed to get the total moment inertia of the two cylindrical shells connected by welds at the top and bottom parts.

3.3 Parametric effect analyses for the seismic responses

The nonlinear time history analyses method are performed for the parameter effect evaluation of the rotation and sliding responses. The input load is an artificial seismic load as shown in Fig. 5, which is generated by the design acceleration spectrum in US NRC Reg. Guide 1.60. Time increment for the time history analysis is 0.004 seconds for 25 seconds. In all the analyses, a gravity force of 1.0g is applied for the whole model in the vertical direction.

The seismic response analyses are performed for the several possible combinations of the seismic acceleration input magnitudes and the friction coefficients. The seismic load magnitudes used are 0.3g, 0.4g, 0.6g, 0.8g, 1.0g in the horizontal direction and 2/3 times in the vertical direction. The friction coefficients are applied as 0.2, 0.4, 0.6, 0.8 and 1.0. The parametric effects to the seismic responses are analyzed from the analysis results. The summary results are represented in Fig.6 to Fig.8.

The maximum slipping occurs at the low friction and large seismic load level as shown in Fig. 6. As for the rotational uplifting motion, the maximum rotation angle is increased as the friction coefficient increases as shown in Fig.7. The maximum acceleration response is increased when the seismic input magnitude and the friction coefficient are increased as shown in Fig.8. The combination results suggest that the acceleration responses can be decreased for a certain friction coefficient such as 0.6 even though the seismic input magnitude is increased.

3.4 Response Analyses for beyond design seismic loads

To get the extreme seismic response value, the precise analyses for one seismic load level(1.0g) and two friction coefficients (0.2 and 1.0) are performed using a more detailed model. The maximum accelerations for the beyond design seismic input of 1.0g and the friction coefficient of 1.0 are 23.5g in the vertical direction and 6.8g in the horizontal direction at top of the storage cask as shown in Fig. 9. The acceleration response spectra are widely distributed in the high frequency range as shown in Fig.10. The high frequency is caused by the impact effects of the cask's bottom face. The maximum uplift of the cask's bottom face is calculated as 26.2cm. The value is less than the overturning limitation value of 184cm. The corresponding maximum rocking angle is 3.82^o, which is much less than the overturning angle of 31.1^o. The dominant frequency of the cask's rocking motion is near 0.7 Hz as shown in Fig. 11. As for the friction coefficient of 0.2, the maximum sliding distance is calculated as 53.3cm as shown in Fig.12 for a seismic input acceleration of 1g. In this case, the maximum acceleration is 1.8g in the vertical direction at the top of the storage cask as shown in Fig. 13. The most of the seismic energy has been absorbed in the slipping motions for low friction condition.

The maximum acceleration of 23.5g is less than the maximum value of 45g which occurred in the drop analysis [1]. The structural integrity is assured because the drop integrity was guaranteed.

4. CONCLUSIONS

The seismic responses of the spent fuel storage cask are performed for various sliding friction coefficients and seismic acceleration levels. The sliding distance is increased as the seismic input level is larger and the fiction coefficient is smaller. The acceleration and rocking responses are increased as the seismic level is increased, but the responses can be reduced at a certain friction coefficient because a sliding occurs at first even though the seismic level is high.

The maximum acceleration is 23.8g in the horizontal direction at the friction coefficient of 1.0 and acceleration level of 1.0g. The peak value is less than the acceleration (45g) caused by a drop condition. The maximum sliding distance is 53.3cm, which is not big which compared with the installation space. The maximum rocking angle is 3.82^o, which is much less than the overturning angle of 31.1^o.

Seismic response analysis using a full 3D-solid model with a surface contact is performing to check the preliminary seismic response analyses using the simple model.

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Acknowledgement

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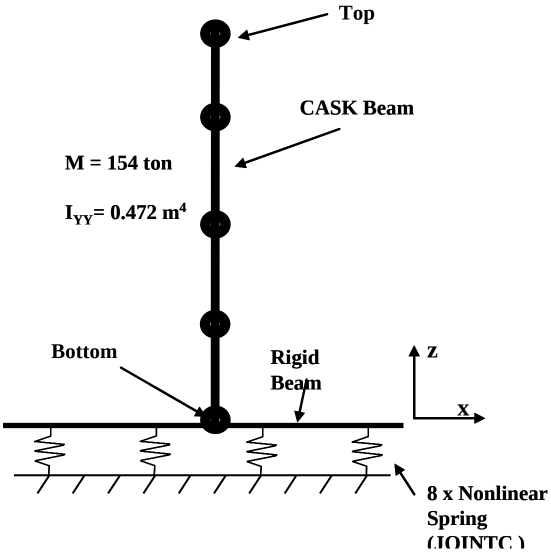


Fig. 3 Seismic Response Analysis Model of the Spent Fuel Storage Cask

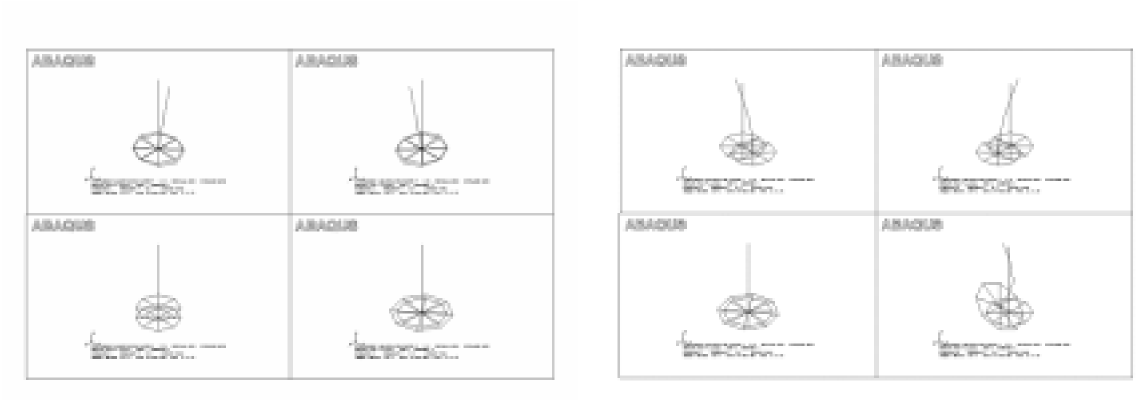


Fig. 4 Mode Shape of the Analysis Model of the Spent Fuel Storage Cask

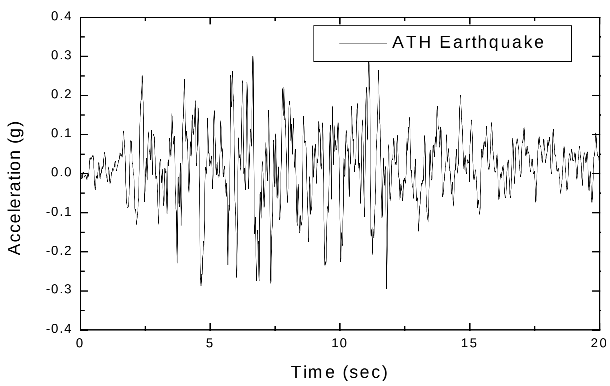


Fig. 5 Artificial Time History for the Seismic Response Analysis in the Horizontal Direction

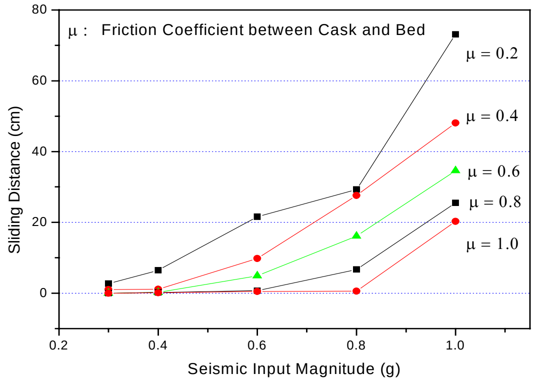


Fig. 6 Sliding Response at the bottom of the Storage Cask

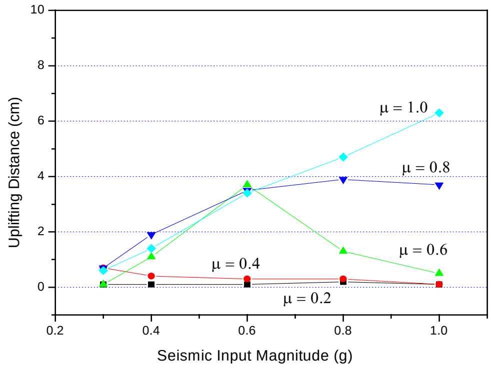


Fig. 7 Uplifting Distance of the Storage Cask

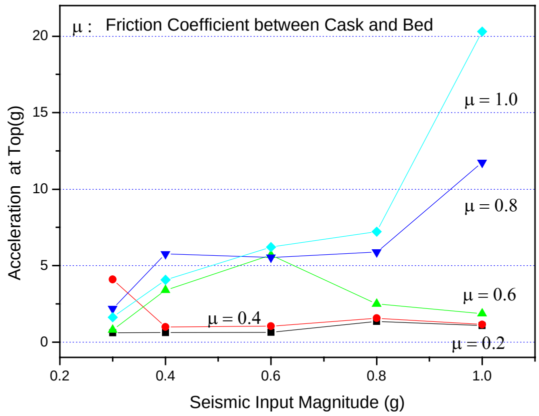
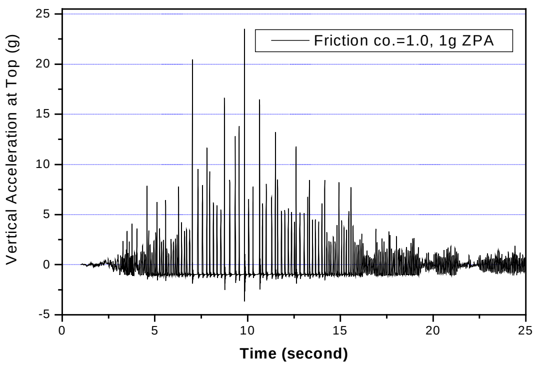


Fig. 8 Acceleration Responses at the Top of the Storage Cask



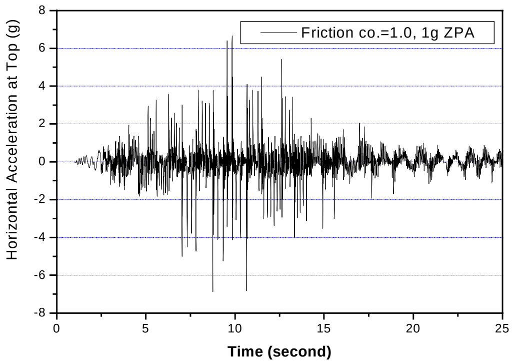
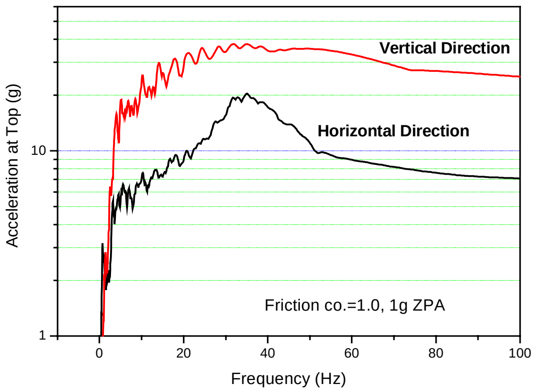


Fig. 9 Vertical and Horizontal Accelerations at the Top of the Storage Cask



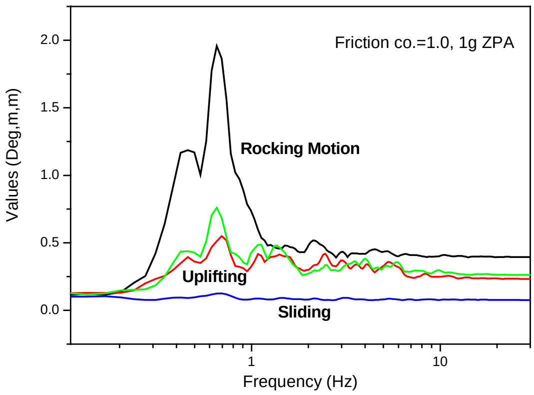
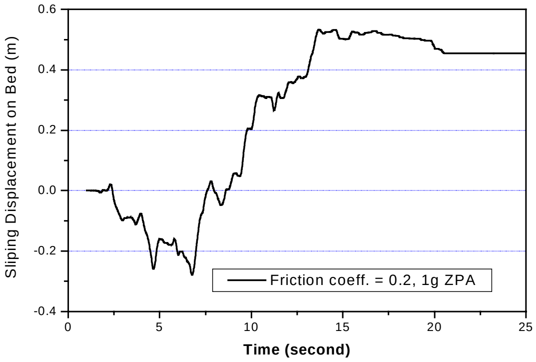


Fig. 10 Acceleration Response Spectra at Top of the Cask Fig. 11 Seismic Response Spectra for the Storage Cask



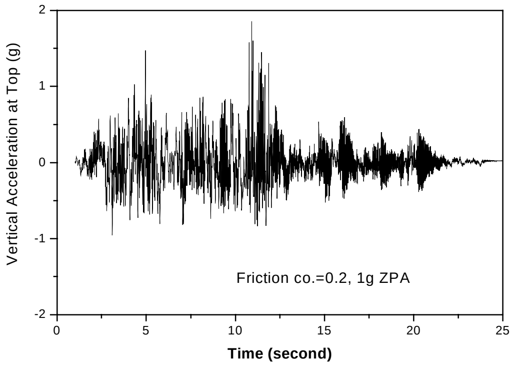


Fig. 12 Sliding Displacement of Storage Cask on a Bed

Fig. 13 Vertical Acceleration at Top of the Storage Cask