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Probabilistic seismic analysis of concrete dry cask structures

Majid Ebad Sichani, Jamie E. Padgett*, Vahid Bisadi[1]

Department of Civil and Environmental Engineering, Rice University, 6100 Main Street, MS-318, Houston, TX 77005, United States

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ABSTRACT

Dry casks are vertical reinforced concrete cylinders, which are used to store spent nuclear fuel. In a seismic event, impact between adjacent casks, due to excessive horizontal displacements or large rocking angles, might cause damage to the structure, potentially leading to release of radioactive material. This paper analyzes the displacement and rocking response of dry casks subjected to seismic loads and proposes a two-layer probabilistic seismic demand modeling strategy to predict cask response. To enable this probabilistic modeling, virtual experimental data for seismic cask response is derived using a validated 3D finite element model. Latin Hypercube Sampling is used to generate 160 cask-pad-soil configurations across typical ranges of structural, geometric, and material properties, and nonlinear time history analyses are performed with a suite of ground motion records selected representative of regions where storage facilities are located or with moderate to high seismicity. Five-fold cross-validated response surface models are used to predict the probabilistic horizontal and vertical accelerations of the cask center of gravity. Then in the second step of the metamodeling strategy, probabilistic models of cask horizontal displacement and rocking are developed through stepwise regression in which the cask accelerations are tested as predictors in addition to structural, geometric and material parameters. The two-layer approach proposed herein offers an advance over traditional probabilistic seismic demand modeling methods, improves the performance of the developed metamodels and can be employed to study the seismic response of other rigid-body-type structures. The resulting probabilistic models are used in seismic fragility analyses, and parametric studies are conducted to explore the influence of different parameters on the fragility. Finally, the annual probability of failure, defined as the probability of seismic displacement or rocking response exceeding a prescribed limit, is evaluated for different locations in the United States.

1. Introduction

In order to keep nuclear power plants operational, the spent fuel removed from reactors has to be stored in a safe and efficient manner. Long-term storage of the spent fuel at a site which meets all safety requirements would be ideal; however, it is difficult to choose such a site due to safety concerns [1]. In the absence of a long-term storage option, spent fuel pools are used for the short-term storage of the nuclear waste. The spent fuel remains in the spent fuel pools for at least five years before it is transferred to independent spent fuel storage installations (ISFSIs) and stored in dry storage structures. Different dry storage designs such as horizontal rectangular modules and vertical cylindrical casks have been used in ISFSI facilities. The focus of this study is on vertical concrete casks that are cylindrical tanks made of reinforced concrete, which are supported by a concrete pad. Typically, the spent fuel is placed inside a steel canister and transferred from the pool to the casks' location and stored inside the casks. These casks are freestanding structures that are prone to horizontal displacement, caused by sliding or wobbling, or rocking due to natural or man-made hazards. In case of large horizontal displacements or rocking motions, collision between adjacent casks is possible. The canister and the cask design should be such that they can prevent any radiation from the nuclear waste if such incidents happen. However, considering the consequences of any release of radioactive material, the likely response and risk of damage to these structures should be assessed. The risk assessment results offer insight into potential weaknesses of this storage system and support mitigation actions if necessary.

The horizontal displacement and rocking response of dry casks can be better understood by first reviewing the response of rigid bodies to dynamic loads. In this regard, there are many studies focusing on the rocking response of rigid block–admittedly there are several key distinctions between these systems and the unique behavior of dry casks under earthquake loading. Many researchers [2–9] analyzed the rocking response of 2D blocks subjected to various conditions such as

* Corresponding author.
E-mail addresses: me15@rice.edu (M. Ebad Sichani), jamie.padgett@rice.edu (J.E. Padgett), vahid.bisadi@rms.com (V. Bisadi).
[1] Present address: Risk Management Solutions Inc., 7575 Gateway Boulevard, Newark, CA 94560, United States.

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free rocking, rectangular acceleration, sinusoidal acceleration, and seismic loads. Considering pure sliding motions of rigid bodies, Lopez Garcia and Soong [10] investigated the seismic sliding response of unrestrained block-type structures by solving the equation of motion numerically. In an experimental study, Konstantinidis and Makris [11] investigated the sliding response of laboratory equipment to seismic loads. There are also studies [12–14] that consider different motions, such as rest, sliding, rocking, lift-off, and combinations of them, for 2D blocks and analyze the block's response subjected to dynamic loads. Although the above mentioned studies provide the readers with some insight on the dynamic response of rigid blocks, their application is limited to plane motions, which cannot capture the effect of the second horizontal component of earthquake in the case of ground motion excitations. Studies on 3D blocks, such as [15], cannot be applied to the dry casks because of the different geometric properties of casks and blocks. The equations of motion developed in [16,17] for cylinders and conical frustums might be applied to the cases with no slipping or lift-off motions. In addition, in order to analyze the response of dry casks, subjected to dynamic loads, the equations developed in these references need to be solved numerically, which requires additional effort and is usually not favorable to those in practice. In a risk assessment study on ISFSI facilities, simple models of critical responses such as maximum horizontal displacement or rocking angle are preferred, which can capture the effect of parameter variations, the nonlinear contact between the cask and the pad, and also important features of the applied loads.

In order to perform a risk analysis for an ISFSI project, the dry casks should be analyzed subjected to seismic loads [18]. To this end, several studies have focused on the seismic analysis of dry cask structures. These studies range in model fidelity and parameters considered, but in general are all deterministic in nature. Moore et al. [19] and Bjorkman et al. [20] studied the seismic performance of HI-STORM 100 casks, a common configuration of dry casks, by using simple finite element models. They analyzed the effects of pad flexibility, soil properties, and cask layouts on the seismic response. Singh et al. [21] used Lagrange's method and developed equations of motion which predict the dynamic response of the dry casks. They proposed ¼ of the cask's diameter and ¼ of the cask's rocking angle at the onset of tip-over as the controlling limits for the maximum sliding and maximum rocking angle, respectively. Shaukat and Luk [22] considered the dynamic coupling of cask, pad, and soil in their finite element models and analyzed the effect of cask design, coefficient of friction, soil properties, and ground motion records on the casks' seismic behavior. Their analyses showed that earthquakes might lead to the casks sliding, but the maximum rocking angle of the casks subjected to earthquakes would be negligible [22]. Luk et al. [23] simulated the response of two different dry storage structures subjected to ground motion time histories adjusted to three spectral shapes. They considered various coefficients of friction and soil properties in their study and concluded that the cask's behavior is governed by the ground motion time history [23] but did not elaborate the impact of other parameters on the response. Shirai et al. [24] conducted experimental tests on a scale model cask using a 2D shake table and, based on the results, concluded that the energy spectrum approach proposed by Akiyama et al. [25] provides a conservative estimate for the possibility of tip-over [24]. Ko et al. [1] developed 3D finite element models of the seismic response of a dry cask facility, which was going to be installed in Taiwan, and concluded that the design earthquakes make the cask slide but not tip over. Maree et al. [26] studied the seismic response of dry casks experimentally and numerically and investigated the sensitivity of response to the friction coefficient and the alignment of the cask relative to the pad. A parametric evaluation of the seismic performance of a dry cask configuration is presented in NUREG/CR-6865 [27]. However, this study does not address the uncertainties in the problem. Furthermore, ASCE/SEI 43-05 [28] provides seismic design criteria for structures, systems, and components in nuclear facilities and suggests a deterministic predictive model for the sliding and rocking responses of rigid bodies based on the Reserve Energy Approach [29].

For a risk analysis of ISFSI projects, the probability of failure of the casks due to seismic events should be evaluated. Estimation of the probability of failure usually requires running a large number of finite element models of the problem, especially when using methods such as Monte Carlo. Since running 3D nonlinear finite element models is time-consuming and computationally expensive, there is a need for probabilistic demand models that can accurately predict the highly-nonlinear seismic response and be used to estimate the failure probability. Current methods used to evaluate seismic response of dry casks adopt a deterministic approach which does not take into account the epistemic and aleatory uncertainties such as the uncertainties in material, geometric, and structural properties and those coming from the ground motion records. NUREG-1864 [18] performs a probabilistic risk assessment on a dry cask storage system. However, it uses point estimates of parameters and conservative assumptions when enough information is not available. Therefore, the provided results are subjected to change by considering the uncertainties in the problem. Some researchers such as Purvance et al. [30], Bakhtiary and Gardoni [31], and Konstantinidis and Makris [11] have developed probabilistic models for the rocking response of rigid blocks and laboratory equipment, but these models are not applicable to dry casks because blocks/laboratory equipment and dry casks have different geometries and hence the unique design details of casks are not reflected. In addition, the models were developed for bodies with smaller dimensions than the dry casks dimensions. In this regard, according to Yim et al. [4] and Kafle et al. [8], the size of the rigid bodies is important in assessing the rocking response. Given the lack of existing probabilistic models in the literature, this paper proposes a method for probabilistic seismic demand modeling of dry casks subjected to seismic loads. Probabilistic seismic demand models (PSDMs) for the maximum horizontal displacement and maximum rocking angle are developed via a two-layer approach in which the cask maximum accelerations are predicted in the first layer and then are used in the second layer to estimate the target responses. The developed PSDMs are applicable to a wide range of geometric properties of the casks, enabling application to different cask configurations for fragility analysis and risk assessment of this critical piece of energy infrastructure. Such a risk analysis can be used to evaluate the seismic safety of current dry storage facilities and advise on taking preventive measures if needed.

In the next section of the paper, the finite element modeling approach is presented, along with the statistical experimental design and ground motion suite used for nonlinear dynamic analysis. Section three presents the proposed two-layer probabilistic seismic demand modeling approach. Fragility analyses and parametric studies are presented in section four, followed by section five that estimates the risk at different locations where ISFSIs exist in seismic zones. Section six concludes the paper including practical implications and suggestions for future research.

2. Dynamic analysis

2.1. Finite element modeling

In order to generate virtual experimental data needed to develop probabilistic demand models, nonlinear finite element models of the dry casks are created in LS-DYNA and the dynamic seismic response, under three-component ground motions, is analyzed by the software's explicit solver [32]. Fig. 1 shows one of the finite element models developed in this study. The models include the full geometry of the cask, canister, and pad. Since the motion of the cask due to seismic loads is in general a rigid body motion, the components (e.g., cask, canister and pad) are not expected to exhibit nonlinear material behavior, and hence linear elastic material models are adopted. Eight-node solid elements with one integration point are used to model cask, canister, and pad,