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Sources of uncertainty in the seismic design of submerged free-standing racks

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Abstract

Free-standing racks are 5 m tall structures that store spent fuel removed from the nuclear power reactor on the depths of a spent fuel pool. Rack units are arranged on the floor of this 12 meters deep pool separated by only a few centimeters. Their response to an earthquake event is a troubling safety issue as they are in submerged and free-standing conditions. Such a seismic analysis deals with a highly nonlinear behavior, a transient dynamic response and a fluid-structure interaction problem. To overcome these difficulties in a cost-effective manner, the current analysis methodology implements the hydrodynamic mass concept in commercial finite element analysis software. However, some dispersion of results still exists in the application of this ad-hoc methodology. This paper reviews the seven major sources of uncertainty inherent to the current analysis methodology together with the main challenges of the seismic analysis.

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Keywords: uncertainty; seismic analysis; free-standing; racks; fluid-structure interaction; nonlinear; transient analysis; hydrodynamic mass;

1. Introduction to the rack context

Spent fuel storage racks are tailored stainless steel structures made up of an array of storage cells. They are used in the first step of the waste management process, during the wet storage of the radioactive spent fuel within the spent fuel pool. Rack units rest free-standing on the floor of a 12 meters depth pool and separated by only a few centimeters to fit within the pool dimensions (Fig. 1). Recent high density racks include neutron-absorbing materials

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to reduce the critical distance that allow putting the fuel assemblies closer and maximizing the storage capacity of each rack.

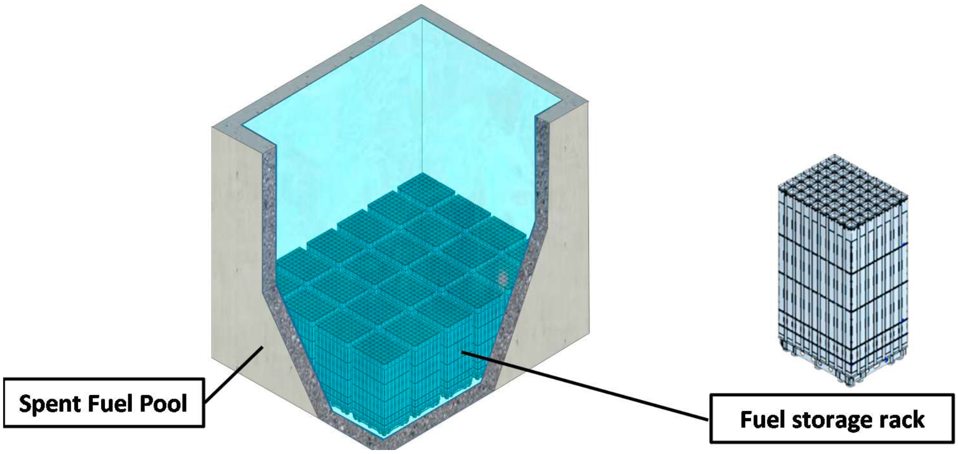

Fig. 1. Location of free-standing racks within the fuel spent fuel pool

When racks are subjected to an earthquake, they experience displacements and forces on supports that determine their final arrangement and design. Nuclear regulatory authorities classify racks as seismic category I and perform safety reviews according to the OT position paper [1], the U.S. NRC Standard Review Plan NUREG-0800 [2] and the ASME code. A complementary compilation of the few basic guidelines have been published by Ashar and DeGrassi [3] and DeGrassi [4].

The seismic analysis deals with a fluid-structure interaction problem, a very highly nonlinear behavior and a transient dynamic response. These challenges have been overcome thanks to an ad-hoc methodology, but some uncertainties remain and cause scatter in the results. Real safety margins are extremely difficult to predict, so the nuclear regulatory authorities request further studies as part of the approval and licensing process.

This paper summarizes the state of the art and improves the understanding of the underwater seismic response of storage racks, by identifying and discussing the sources of uncertainty inherent to the current analysis methodology.

2. Challenges of the seismic analysis

The seismic design of a free-standing rack faces three complex physical phenomena as described by Soler and Singh [5]:

- *Fluid-Structure Interaction* (FSI). The underwater conditions determine the dynamic response of the racks and fuel assemblies. Hydrodynamic forces arise at the wet boundary when the system of racks undergoes transient motion. These inertial fluid forces couple racks units, which otherwise were independent.
- *Highly nonlinear behavior*. The seismic load causes large displacements (e.g. sliding, rocking, twisting and turning), which involve energy dissipative effects such as friction and damping. In addition, this combination of displacements may cause impacts among racks or between the fuel assemblies and their storage cell. These singularities lead to nonlinearities to the point that Moudrik et al [6] show that the first mode frequency of the rack decreases when the excitation level increases.
- *Transient dynamic response*. The response of the rack system cannot be obtained using modal superposition due to the inherent nonlinearities. Hence, the dynamic analysis can only be performed through a time-history simulation with direct integration of the equations of motion in the three orthogonal directions. This method requires iterative step-by-step algorithms that are computationally very expensive. The entire seismic event is discretized into numerous small time steps where displacements and rotations are calculated through the basic equation of motion: