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The shaking table experiments on sliding and overturning of CAP1400 spent fuel storage rack with the effect of FSI

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ABSTRACT

Under seismic condition, for CAP1400 (a new nuclear reactor type designed by China) spent fuel storage rack; water can flow through the channels between the rack storage cells. Unfortunately, the fluid structure interaction (FSI) effect for such perforate structure has not been studied in depth. In engineering approach of spent fuel rack's structural analysis, the perforations are ignored, leading to an over-conservative added mass. To study the friction coefficient and FSI effect for CAP1400 rack, a series of shaking table experiments had been carried out using a reduced-scale spent fuel rack model in a water tank (spent fuel pool model). To derive the friction coefficient between rack and tank wall, sweep frequency tests were carried out in shallow-water-level condition and deep-water-level condition. Large uncertainty was found in the measurements of friction coefficient; consequently, the data were organized by statistical methods. Moreover, the relationship between gap size and fluid pressure were studied. Finally, the response to seismic loading was studied in different gap size conditions. The research can provide the basic input parameter for the dynamic analysis for spent fuel storage rack; moreover, the experimental seismic response can be the benchmark for dynamic analysis of CAP1400 spent fuel rack.

1. Introduction

For the dynamic analysis of spent fuel storage rack, most simulations are based on transient finite element analysis (Moreira and Antunes, 2000; Ashar and DeGrassi, 1989). Generally, the friction, added mass and impact stiffness are the input parameters. However, for the nonlinear system like spent fuel storage rack, the uncertainty in input parameters may lead to very different results (Merino et al., 2016). Consequently, it is very important to study the uncertainty of the input parameters.

According to a report from Westinghouse (Westinghouse, 2009), the friction coefficient of lubricated stainless steel ranges from 0.2 to 0.8. Many researches adopted this value in their simulations. The friction coefficient were obtained by friction test, however, in the real situation, the rack leg may be overturning and sliding on the pool floor, the situation may be different from the standard friction test. Consequently, some researchers tested the friction in shaking table experiment. Fujita and Nakamura (1988) have carried out a shaking table experiment of a reduced-scaled spent fuel storage rack in order to evaluate the feasibility of two applications of seismic isolation system of PWR spent fuel storage rack from the view point of the seismic response. They measured the friction coefficient by applying a forced displacement of a triangular wave form to the model rack. Finally, the friction was determined to be almost constant of 0.13 to the sliding velocity in the tested velocity range. The simulation using this friction coefficient corresponded to experimental results with reasonable accuracy. In order to decrease the uncertainty in the friction coefficient, it have to be tested in real case.

The high-density spent fuel storage rack successfully improves the capacity, however, the nonlinear phenomenon like FSI bring some difficulties to the seismic response evaluation. The spent fuel storage rack can be divided into two categories, namely, honeycomb construction type and end tube connection construction type (Ashar and DeGrassi, 1989). In honeycomb construction type, the adjacent storage cells share the same wall; in end-tube-connection construction, each cell has its own wall. CAP1400 spent fuel storage rack adopts end-tube-connection construction. However, there are limited public literatures concerning the FSI parameter for spent fuel storage rack with end-tube-connection construction type. For some rack design of end-tube-connection construction type, the rack is wearing outer plate that separates the water in and outside of the rack. There are some literature concerning the fluid structure interaction of spent fuel rack

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(Stabel and Ren, 2001; Stabel, 1999). However, for some rack without outer plate, such as CAP1400, there is no recommended FSI value. Consequently, the FSI parameters for such structure is determined conservatively by the same method as that with the outer plate. The fluid force acts on the rack with outer plates is larger than that without outer plate because the rack with outer plates has a larger area receiving fluid force than the rack without outer plates. Moreover, it has been proved experimentally and theoretically that fluid force of a vibrating perforated plate is smaller than that of solid plate (Ann and Faltinsen, 2013). However, the FSI parameter of end-tube-connection construction spent fuel rack is greatly affected by the geometry of the rack, this parameter has to be tested.

As for the seismic experiment of spent fuel rack, Japanese researchers has contributed a lot. Iwasaki et al. (2012a) investigated a full-scale spent fuel storage rack with a shaking table of 15 m × 20 m. They find sliding and rocking motions of the rack with full fuel loading induced by the seismic waves including a long period range component were both larger compared to those in a short period range and a medium period range. In their further study (Iwasaki et al., 2012b), the effect of spent fuel storage rack's outer plates was investigated. Their experiment result showed the sliding distance and the rocking displacement of the rack with outer plates were smaller than the rack without outer plates due to fluid force. The detail rack design and the rack's distribution in spent fuel rack are different from CAP1400 rack. Consequently, their experimental results may not be extrapolated directly to CAP1400 spent fuel storage rack. According to the response sliding time history curve, the simulation and the experimental results are not strictly coincide.

The main purpose of this study is to develop an understanding of the friction, FSI and seismic response for rack with end-tube-connection construction like CAP1400 spent fuel rack. In this paper, a series of shaking table experiments on a scaled model of spent fuel storage rack were carried out. The displacement curves of the rack were recorded. Equations for friction coefficient were derived. The fluid added mass was evaluated indirectly by the sweep frequency test according to the critical sliding accelerations in deep water level case and in shallow water level case respectively. The uncertainty in measurements were evaluated. Finally, the seismic response under two different gap sizes conditions were compared.

2. Sliding and overturning with fluid structure interaction

There are three important phenomena in the seismic response of the spent fuel rack, which are friction between rack and tank bottom, fluid structure interaction and the impact between rack and the tank. However, it is difficult to figure out their contributions to the seismic response. According to many researchers' opinion, the friction can be modeled by the Coulomb's friction model, which means the friction force equals to the perpendicular force multiplying friction coefficient. This means the friction force is irrelevant to the impact force; therefore, the friction coefficient can be measured in absence of impact.

2.1. Sliding of a rack immersed in a tank

As illustrated in Fig. 1, when the tank without water moves with an acceleration of $\ddot{T}$, assume the rack is just about to slide on the tank floor. There is no relative motion between rack and the tank, therefore, the speed of rack still equals to $\ddot{T}$. The critical sliding motion of rack can be expressed by the following equation.

$$F_t = \mu \mathrm{mg} = \mathrm{m}\ddot{T} \tag{1}$$

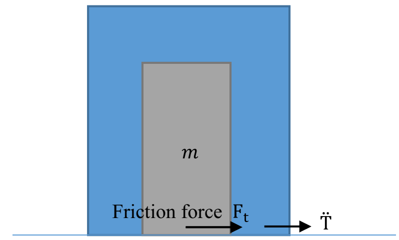

Fig. 1. Sliding analysis of a rack immersed in a tank.

where F_t is the friction force; μ is friction coefficient; m is mass of rack. Therefore, the critical sliding acceleration can be obtained as

$$\ddot{T} = \mu g \tag{2}$$

It is deduced that sliding will take place if $\ddot{T} > \mu g$. The result means that the critical sliding acceleration of the tank is only influenced by the friction coefficient. The above result is derived for a rack in air, moreover, the same analyses is valid in water, by using $m - m_d$ instead of m in Eq. (1), where m_d is the mass of the water displaced by the rack. It is worthy notice that the sliding in water will take place for the same acceleration μg already obtained for the in air configuration.

2.2. Overturning of a rack immersed in a tank

As illustrated in Fig. 2, if there is no sliding before overturning, when the tank is moving with an acceleration of $\ddot{T}$, assume that the rack in air is just about to overturn. The equation describing the torque of the rack with respect to the corner of the rack denotes,

$$-\mathrm{mg}\frac{\mathrm{L}}{2} + \mathrm{m}\ddot{\mathrm{T}}\frac{\mathrm{H}}{2} = 0 \tag{3}$$

where L and H are the length and height of the rack; N is the supporting forces which equals to mg. The above equation can be simplified as

$$\ddot{T} = \frac{\mathrm{L}}{\mathrm{H}}\mathrm{g} \tag{4}$$

It is deduced that overturning will take place if $\ddot{T} > \frac{\mathrm{L}}{\mathrm{H}}\mathrm{g}$. The result means that the critical overturning acceleration of the tank is only influenced by the rack's width and height. The above result is derived for a rack in air; moreover, the same analyses is valid in water, by using $m - m_d$ instead of m in Eq. (3), the critical acceleration of the rack in water still equals to $\frac{\mathrm{L}}{\mathrm{H}}\mathrm{g}$, the same with that in air.

2.3. Interactions between sliding and overturning

Complex interactions may take place between the sliding and the overturning. If L/H < μ (slender structure) the overturning will

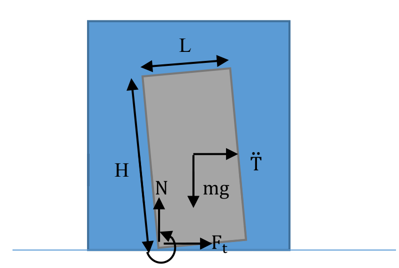

Fig. 2. Overturning analysis of a rack immersed in a tank.