Seismic Sliding Response Characteristics at Inclined Surface

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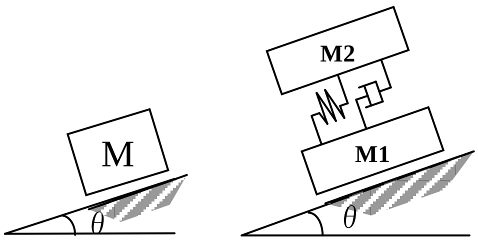
1. Introduction

The general arrangement method of free standing structures like spent fuel racks in the storage pool is locating them with a gap between adjacent modules to avoid impact in earthquake.[1] The gap in the case is determined from maximum rack sliding displacement estimated from seismic analysis plus margin. In the case, the pool bottom as a sliding surface is assumed to be a level. The rack modules, however, may be installed at an inclined support plane when the pool bottom embedment is not well constructed beyond requirements, though the modules are finally adjusted to locate in vertical position using shims near supports. Actually, a slight slope of about 0.2 degree between the rack module support surfaces can be possible theoretically even when the pool bottom embedment design and construction are well within the limit of requirement.

In the paper, the conservatism in the spent fuel storage structure gap design is checked through seismic sliding analyses for the assumed slope condition of the support surface which may affect the initial design assumption of no impact between adjacent modules.

2. Analysis Model and Simulation

To check the general seismic sliding displacement characteristics of the free standing structures at inclined surface, analysis models including a rigid block and a lumped mass spring-damper system on the level or inclined surfaces are set up as shown in Fig.1. The sliding responses of the model in slope conditions are analyzed to be compared with that in level condition.[2]



a) Block at Slope b) System at Slope

Fig. 1 Sliding Analysis Models

2.1 Equation of Motion

The equations of motion for the simple models shown in Fig.1 are made in case of seismic sliding of a block and a system on the inclined surface of angle θ and friction coefficient μ. The design parameters are assumed to be mass M_1 and M_2 for the system, and x_1, x_2, for the relative displacements of masses in the inclined direction, respectively. However, the ground motion x_g is assumed to apply in the horizontal direction to consider the inertia effect on the masses. And the damping coefficient c, spring constant k, gravity g, and the frictional force f at sliding are also assumed. Then the equations of motion of the dynamic system, for reference, can be expressed as follows,

$$M_1\ddot{x}_1 - c\dot{x}_2 - kx_2 + f = M_1(g\sin\theta - \ddot{x}_g\cos\theta) \quad (1a)$$
$$M_2\ddot{x}_2 + c\dot{x}_2 + kx_2 = M_2(g\sin\theta - \ddot{x}_1 - \ddot{x}_g\cos\theta) \quad (1b)$$
$$f = -\mu(M_1 + M_2)(g\cos\theta + \ddot{x}_g\sin\theta) \quad (1c)$$

Equation (1a) is for the sliding mass M_1, (1b) for the mass M_2, and (1c) expresses the frictional force in case of seismic sliding at slope surface. The frictional force f does not apply until the inertia force by seismic base excitation reaches the amount of the right side term of the equation (1c).[3]

2.2 Simulation by Numerical Analysis

Numerical analyses are performed for the mathematical models described in Fig.1 and equation 1 including a level surface condition using the design seismic inputs of YGN 3&4, for reference. For the sliding block shown in Fig.1a, the seismic displacements versus time are calculated to be compared between the condition of support surface at level and at slope. For the sliding system model, the peak responses are obtained from each analysis by varying the natural frequency of model from 0.1 Hz to 20 Hz which can represent the dynamic characteristics of major equipment in nuclear power plant. Similar sensitivity analyses are done to study the maximum displacement response characteristics with respect to the slope angle from the level of actual installation to a degree of 2. Typical parameters used in the analysis are 0.04 for the damping ratio of the system and 0.1 for the friction coefficient commonly for the block and sliding system which is relatively more severe than the actual design assumption for checking the response trend. The raw input data of earthquake is sampled from the used ones for the equipment design of Younggwang Nuclear Unit 3&4. The sixth order Runge-Kutta scheme and double precision were chosen for numerical integration of the equations of motion in FORTRAN. A time step of 0.005 second was used for the numerical integration when sliding and non-sliding phases were involved due to the friction mechanism.[4] The response time histories during the first 24 seconds were used to calculate the peak responses of the system.

2.3 Results and Discussions

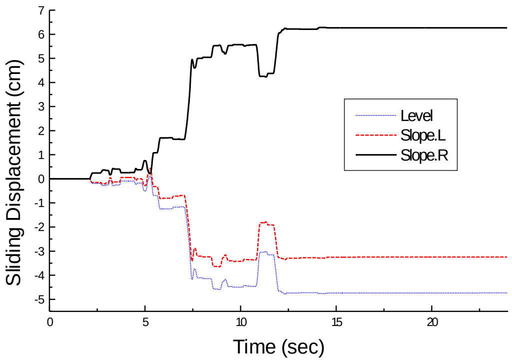


Fig. 2. Comparison of Sliding Displacement Time History of a Block between Level and Slope Conditions

From the seismic sliding analysis of a block, it is found that the displacement response in slope condition can increase more that 40% compared with that in level condition as shown in Fig.2. An interesting point from this result is the decrease of response in mirror image slope condition which is made by application of seismic input in reverse direction. This is considered to be due to the direction dependency of earthquake energy.

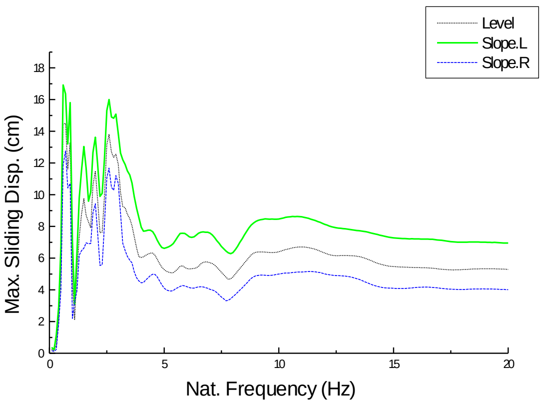


Fig. 3. Comparison of Sliding Displacement Time History of Dynamic Systems bt. Level and Slope Conditions

Similar trend is found in sliding analysis of dynamic system. In the case, maximum sliding displacements versus system natural frequency are picked up, which shows about 50% increase of sliding displacement in slope condition in on direction. However, in case of opposite directional input application, the response decreases in most range of system natural frequency in comparison to a level condition. The sensitivity of maximum sliding displacement of dynamic system by slope angle change from 0° to 2° is depicted in Fig. 4. The maximum sliding displacement grows expectedly larger as the slope angle increases in left sided slope. In right sided slope, however, goes lower near about 1° of slope angle and changes to be higher after that.

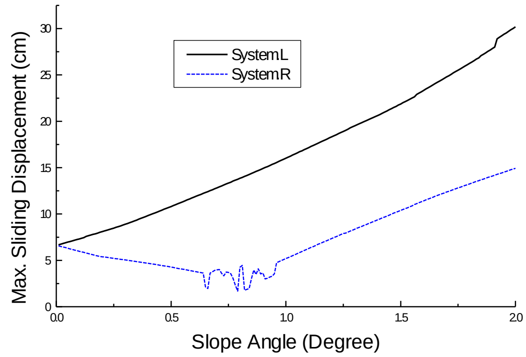


Fig. 4. Maximum Sliding Displacement of Dynamic System vs. Slope Angle

As the natural frequency of the system in the case is assumed to be 7 Hz, which is close to that of a rack module in air, the response at 0.2 degree matches well with the results in Fig.3. Fig.4 shows the slope angle of support can affect sensitively on the maximum seismic sliding which had not been considered weightily.

3. Conclusions

Simulation results show that the seismic displacement may be underestimated in case of sliding at inclined surface in comparing with the level. Therefore, care should be taken to consider such a potential slope effect when the design gap between the spent fuel rack modules is decided in the pool arrangement. And the embedment and liner plate should be more precisely fabricated to meet the relative position requirement.

4. Acknowledgement

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