Effect of Moat Wall Impact on Seismic Analysis of Seismically Isolated NPPs

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1. Introduction

Seismic isolation elongates the natural period of a structure by adding flexible bearings at the foundation level, which significantly reduce accelerations and forces transmitted to the superstructure above it. The design tradeoff for this benefit is large displacements at the isolation level, which may be greater than the provided clearance to stop (CS) in the case of extreme ground motion. When isolators exceed the allowed CS, the superstructure can impact against the surrounding moat wall, inducing large forces at the isolation level over a short duration. Highly nonlinear energy exchanges that occur in such an event necessitate the development of robust models of moat wall impact and isolator hardware[1,2]. The objectives of this study are to review the state-of-practice in the design and modeling of moat wall, and develop advanced modeling capabilities for seismically isolated NPPs under design and beyond design earthquake loading conditions. The modeling efforts are founded on recent large scale experimental test data for pounding complemented with detailed finite element analysis modeling. The effects of the moat wall characteristic will be examined through floor response spectra that provide an indication of loading on sensitive equipment, piping and other content.

2. Methods and Results

2.1 Modeling of NPP, Moat Wall and Backfill Soil

For impact studies presented in this paper, a detailed model the base mat supported with 486-bearing lead plug rubber bearing (LPRB) was used. This 3D model can capture the torsional response of the NPP, which can be important for impact studies since the corner displacements can increase and initiate impact with a corner contact. Table 2-1 lists the bearing properties for each individual LPRB bearings in the NPP model and assumes they are all similar. This model was also analyzed in a fixed-base condition to compare with the seismically isolated case with and without impact.

The impact macro element for the moat wall was added to the ANT model by introducing 1,240 and 1,364 nodes and elements respectively. These additional nodes surrounded the base mat (Fig. 1.) and every node on the perimeter of the mat foundation was connected through a gap element to the impact macro model which consists impact, moat wall elements and backfill soil springs (Fig. 2.).

Table I. Bilinear bearing model parameters for individual isolators in NPP model.

Bearing Properties	
K_{ini} (kN/m)	2524.65
F_y (kN)	936.35
Post-elastic/elastic stiffness ratio	0.0072
Height of rubber (m)	0.21

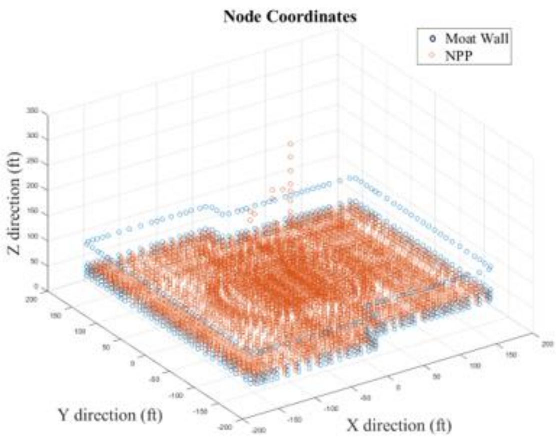

Fig. 1. NPP and moat wall node coordinates.

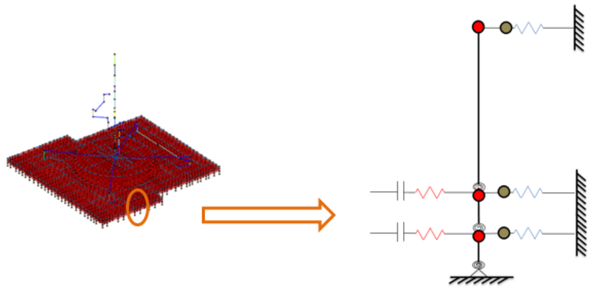

Fig. 오류! 지정한 스타일은 사용되지 않습니다.. Implementation of the impact macro element.

In order to model the contact interface, Hertz Stiffness for the impact macro elements was first calculated following recommendations described in Goldsmith [3]. This method was originally proposed for static contact of two bodies. Here, it was extended to model the impact between the NPP mat foundation and the moat wall considered as a massive plane and an equivalent sphere. To further evaluate the hertz impact stiffness for this specific application, detailed finite element simulations were performed in LS-Dyna. The finite element model was used here to gain insight on the mode of deformation of the wall and also estimate the impact force-deformation. Fitted values for hertz stiffnesses are listed in Table II for different assumed scale factors in contact stiffness.

Table II. Fitted Hertz stiffness for different scale factors in contact springs.

SFS and SFM	Fitted K_h (N/m$^{3/2}$)	Calculated K_h using Eq. 4-2 (N/m$^{3/2}$)
1	8.5e+9	2.2e+10
0.5	9.1e+9	
0.1	1.0e+10	
0.05	1.1e+10	

2.2 Numerical Simulations

Detailed results from analysis are presented including local behavior of various elements (bearing hysteresis and orbits, impact elements, backfill soil springs, and moat wall elements) as well as floor response spectra for different elevations along the height of RCB. Sample results are shown for the 2-D Loma Prieta record at 1.0g excitation and CS= 0.672 m.

The bearing hysteresis, bi-directional displacement orbits and shear interaction for a center bearing and the four corner bearings are shown in Fig. 3. Impact occurs once the bearing displacement exceeds the provided CS marked in the figure by the solid red straight lines. The shear force-displacement behavior for different bearings are also presented in Fig. 3. (a) and (b) with a maximum shear forces of 3,992 and 4,507 kN in X and Y directions respectively. As shown in the displacement orbit, there are three instances of impact of the NPP to the moat wall, the first at west side, the second at the north side and the third is a partial side impact due to torsion in the NPP. The displacement demands at the corner bearings can be larger than the center bearings due to torsion. The NE corner of the base mat had a second impact in the X-direction due to torsion, while the SE corner had sufficient clearance to the east moat wall. The torsional effects appear to increase after the first impact. The almost solid circle in the shear interaction plot indicates many cycles of excitation within the initial elastic bearing behavior. These vibrations are related to the initial stiffness of the bearing K_{ini} and excites the structure at higher frequencies. The radius of the formed circle is about 935 kN, which corresponds to the yield force of the bearing model.

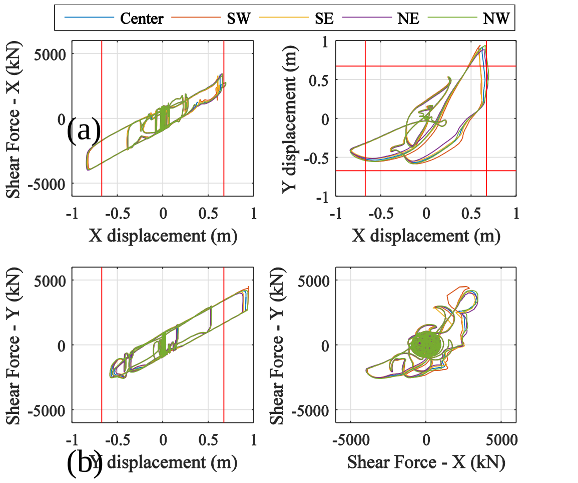

Fig. 3. Response to 2-D Loma Prieta at 1.0g: (a and b) bearing hysteresis, (c) bearings orbits, and (d) shear interactions

Floor response spectra are shown in Fig. 5. for two different elevations along the height of RCB (see Fig. 4.) and for three different models: Isolated NPPs with and without the moat wall, and the fixed-base condition. Elastic response spectra were generated by analyzing single mass linear-elastic oscillator in the X and Y direction assuming 5% damping. The reported spectral quantities are vector norms of the response quantities in the two horizontal directions.

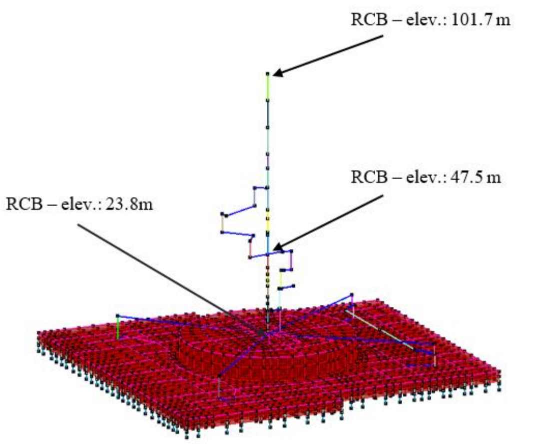

Fig. 4. Location along elevations of RCB selected to examine floor response spectra.

The response spectra for the input ground motions are also included. Peaks can be identified in the spectra at several distinct frequencies. For the RCB, the largest peak in the floor response spectra occurs at ~3.7 Hz, which corresponds to the first horizontal mode of vibration of the RCB. As Fig. 5. clearly shows, there is another distinctive frequency around 0.32 Hz, which corresponds to natural frequency of the isolated NPP. For frequencies below 0.5Hz, the spectral acceleration of the fixed-base NPP is lower than the isolated NPP with and without moat wall. This is likely due to the amplification in response of the isolation system at its 1st natural vibration frequency while the fixed-base NPP has a much higher natural frequency. Impact in isolated NPP results in higher spectral acceleration for frequencies above 0.4Hz in comparison to the response of isolated NPP without moat walls. However, the response of the content with natural frequencies above 0.5Hz in the isolated structure without or with the moat wall including impact is expected to be lower than in the fixed-base structure. A similar behavior was observed for the other ground motions.

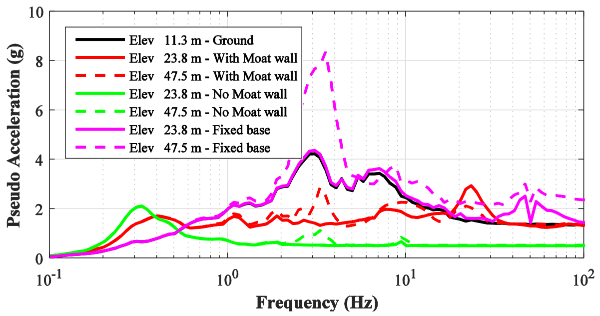

Fig. 5. Floor response acceleration for RCB at different elevations for fixed-based and isolated NPP with and without moat wall to 2-D Loma Prieta at 1.0g

3. Conclusions

A detailed analysis model was used to investigate the seismic response of isolated NPP considering impact to moat walls. The macro element proposed in this dissertation was used to capture the impact force between the NPP and the moat wall. To more accurately model the Hertz stiffness at impact, results from finite elements simulation results in LS-Dyna were used to examine the stiffness between the mat foundation and the moat wall. The estimation of impact parameters would benefit significantly from validation using experimental tests. Comparing the floor response spectra, it can be concluded that the spectral acceleration of the isolated NPP without and with a moat wall including impact are generally lower in comparison to the fixed-base NPP under the same level of excitation. As a result of impact, the acceleration may increase significantly along the height of the NPP. This increase can be up to 1.3 times of the acceleration response for the NPP without a moat wall for intensity level of 0.75 g corresponding to BDBE events.

4. Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) granted funded by the Korea government (NRF-2017M2A8A4039749).

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