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Effects of Moat Wall Impact on the Seismic Response of Base Isolated Nuclear Power Plants

Min Kyu Kim[a*], Gilberto Mosqueda[b], Jung Han Kim[a], Alireza Sarebanha[b]
[a]*Integrated Safety Assessment Division, Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Youseong, Daejeon, 305-353*
[b]*Department of Structural Engineering, University of California, San Diego, USA*
[*]*Corresponding author:minkyu@kaeri.re.kr*

1. Introduction

Base isolation can be an effective strategy to protect critical facilities such as Nuclear Power Plants (NPPs) from the damaging effects of horizontal earthquake ground shaking. To be effective in reducing accelerations and deformations of the structure above, the seismic isolation bearings can be subjected to large displacements. In the case of an extreme earthquake, bearing displacements need to be limited by a hard stop in order to prevent failure of the bearings. Impact to the hard stop, which is often the moat wall at the basement level, is also of significant concern due to the potential for increased transfer of forces and amplification in response of the structural system, piping and other contents. However, the consequences of impact or factors important to mitigate its effects are not very well understood. The objectives of this study are to examine the effects of impact on the response of seismically isolated NPPs and identify characteristics of the isolation hardware and hard stop that minimize these effects. Considering variable distances to the hard stop and properties of the moat wall, the amplification in response is reported for acceleration and floor spectral accelerations at different points along the height of a NPP containment structure.

2. Development of Numerical Model for Impact Analysis of NPP Structure

Per ASCE-4, a hard stop or displacement restraint is required at 90th percentile BDBE (Beyond Design Basis Earthquake) displacement along each axis. A moat wall around the basement of the NPP is expected to serve this purpose. In this preliminary study aimed at studying the effects of seismic pounding in NPPs, different Clearance to Hard Stop (CHS) distances were assumed. Modeling the moat wall as the hard stop required the concrete wall and soil backfill to be included in the structural model. Figure 1 shows a schematic of the isolation level of the NPP and the surrounding moat wall. For this study, a moat wall model is included based on provided properties of the wall assumed to be 20 m high, 1.524 m thick, and 48.76 m wide. It became apparent in this study that there is very little information in the public literature on modeling the behavior of the moat wall with soil backfill under impact forces as required here. To address this need and better estimate the properties of the model, FEA analysis were performed using LS-Dyna.

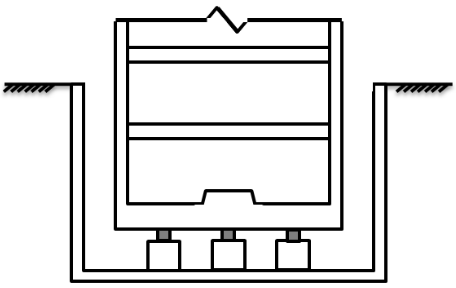


Figure 1. Schematic view of NPP with Moat wall and Backfill Soil

Soil Model

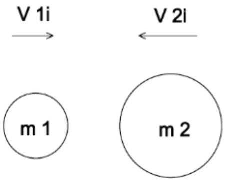
Based on provided soil properties, the backfill soil is assumed to be Coarse Gravel (BYU 2005).

Table 1. Soil Properties

Mass Density	140 lb./ft.3
Poisson's ratio	0.33
Angle of friction , F	40°
Modulus of elasticity	1,590 kips/ft2

Impact Model

The Hertz model was originally proposed for static contact of two bodies, in which stresses and deformations near the contact point are described as a function of the geometric and elastic properties of the bodies.



$$K_h = \frac{4}{3\pi}\left(\frac{1}{\lambda_1+\lambda_2}\right)\sqrt{\frac{R_1R_2}{R_1+R_2}}$$

$$F_c = K_h\delta^{3/2} + \xi\delta^{3/2}\dot{\delta}$$

Figure 2. Two elastic bodies colliding

The contact force is related to the relative indentation of two bodies with a nonlinear spring. This stiffness depends on material properties and shape of impacting bodies.

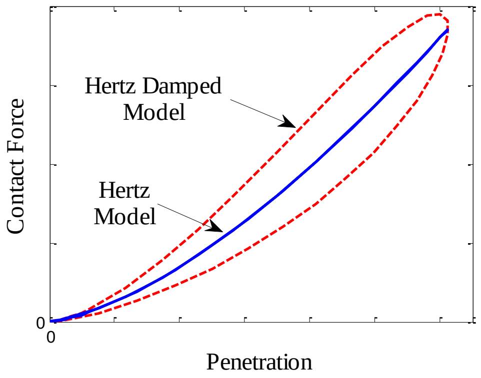


Figure 3. Contact Force-Penetration relation for Hertz and Hertz Damped Model

This hertz damped model was modeled in OpenSees using the available Impact Material. The required parameters for this material model are as follows.

- Gap: corresponds to 350, 400 and 450 % shear strain in the isolators
- Equivalent spring stiffness: (For massive plane surface) $K_h = \frac{4}{3\pi}\left(\frac{1}{\lambda_1+\lambda_2}\right)\sqrt{R_1}$,where R_1 radius of the equivalent sphere volume of the block
- Coefficient of restitution $(e = 0.8)$
- Ratio of yield displacement over maximum displacement $(a = 0.1)$

Implementation of Impact, Moat wall and Backfill Soil

Figure 4 show the implementation of the Impact, Moat wall and Backfill soil models on the sides of the NPP 2D model. The response will be compared later at two nodes identified on the figure.

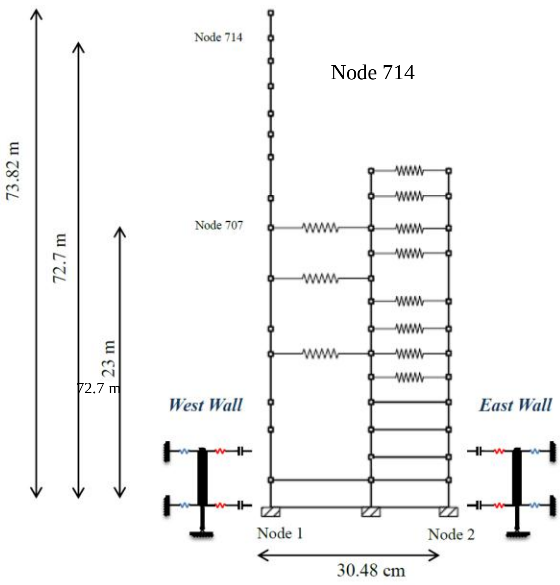


Figure 4. NPP with Moat wall Model

3. Parametric Study Cases

In order to study the effect of different properties for the impact in the NPP, different cases have been considered for Intensity level, Clearance to Hard Stop (CHS), Ground Motions, Material Properties, and different Stiffness Ratios for the isolators. Moat wall variability will be considered in the next section.

Intensity Level (IL):

Ground motions have been scaled to fit the RG1.60 response spectrum for 0.5 g for DBE motion without distortion. In order to study the Beyond Design Basis Earthquake (BDBE), ground motion were scaled by a factor of 2 (which is more conservative than the recommended values of 150 % per ASCE-4). Moreover, to be able to further study the effect of impact, another case has been added which corresponds to spectral acceleration of 1.25 g since impact is likely to occur for most ground motions at this intensity.

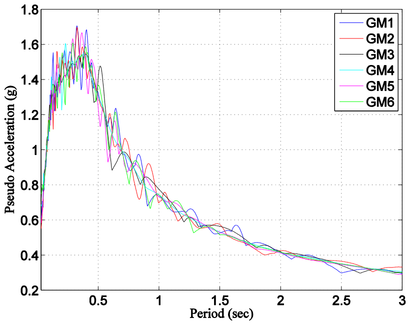


Figure 5. Spectra acceleration (5% damping) for different GMs

Clearance to Hard Stop (CHS):

Three different cases have been considered for the CHS. These values correspond to 350, 400, and 450 % shear strain in the rubber assuming the height of the rubber is 0.21 m.

Table 2. Different case considered for Clearance to Hard Stop (CHS)

Shear Strain	350%	400%	450%
CHS (ft.)	2.411	2.756	3.100
CHS (m)	0.735	0.84	0.945

Ground Motions (GM):

Records for three different extreme events have been considered to use for this study, Chi-Chi, Imperial Valley and Loma Prieta Earthquakes. These recorded were obtained from NGA database and were not distorted to match the spectra. The two horizontal components of these records were used in the simulations.

Table 3. Different Ground Motion (GM) used in simulation

1	Chi-Chi	NGA_no_1508_TCU072-E	dt=0.005 # steps	11999
2		NGA_no_1508_TCU072-N		12068
3	Imperial	NGA_no_180_H-E05140		6800
4		NGA_no_180_H-E05230		7399
5	Loma	NGA_no_779_LGP000		4714
6		NGA_no_779_LGP090		4499

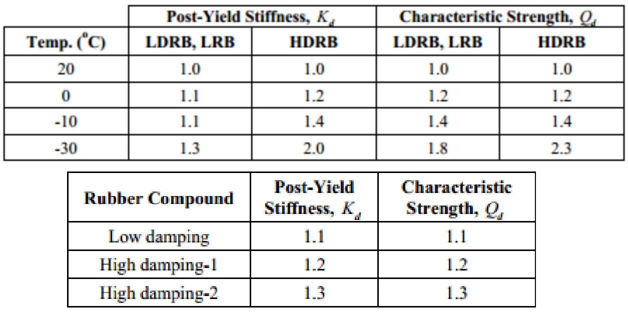
Material Properties:

In order to account for variation in properties of the isolators, three different cases are considered: Lower Bound (LB), Nominal Values (NV), and Upper Bound (UB). Provided properties of the isolator were considered to be the NV. LB and UB properties were calculated using property modification factors. These property modification factors are based on AASHTO (1999) and MCEER (2007).

Table 4. Calculated bounded properties using property modification factors

	Nominal Values	Bound values		Total Modification
K_1 (kip/ft.)	128144	128144	Lower Bound	1
		155054	Upper Bound	1.21
f_y (kip)	10555	7389	Lower Bound	0.7
		13933	Upper Bound	1.32

Table 5. System Property Modification Factor for effects of Temperature (left) and Aging (right) for Elastomeric Bearing - MCEER (2007)



	Post-Yield Stiffness, K_d		**Characteristic Strength, Q_d**	
Temp. (^{o}C)	**LDRB, LRB**	**HDRB**	**LDRB, LRB**	**HDRB**
20	1.0	1.0	1.0	1.0
0	1.1	1.2	1.2	1.2
-10	1.1	1.4	1.4	1.4
-30	1.3	2.0	1.8	2.3

Rubber Compound	**Post-Yield Stiffness, K_d**	**Characteristic Strength, Q_d**
Low damping	1.1	1.1
High damping-1	1.2	1.2
High damping-2	1.3	1.3

Stiffness Ratios:

Two different cases have been considered for post elastic stiffness over the initial stiffness ratio.

K2/K1=0.1: to represent lead rubber isolators
K2/k1=0.01: to represent friction type isolators

4. Numerical Analysis results

For each Intensity Level (0.5, 1.0, and 1.25 g), and different isolator material properties (Lower Bound, Nominal Values, and Upper Bound), 36 different cases were considered and simulated using proposed models in OpenSees. Table below shows the information for each case.

Three-hundred and twenty-four different simulations were considered to examine the effects of the different parameters described in previous section. For Intensity level 0.5 g, no impact occurred between the NPP and provided CHS. As expected, LB bearing properties resulted in more cases with impact for 1.0 and 1.25 g intensity levels. For intensity level equals to 1.0 g, 58.3 %, 33.3%, and 5.5 % cases with impact were observed for Lower Bound, Nominal Value and Upper Bound bearing properties respectively. The ratio of impact cases are 100, 80.6, and 50 % for 1.25 g intensity level.

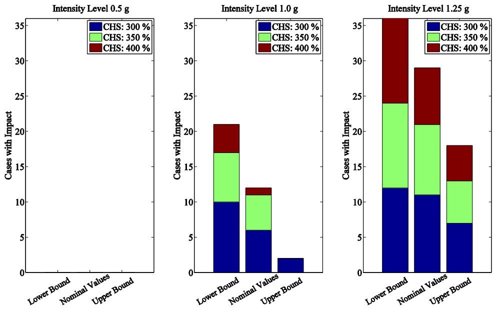


Figure 6. Impact cases for different GM Intensity Levels

For all different cases considered in this parametric analysis, displacement demands normalized by clearance to hard stop are presented in Figure 7. Also, the same simulations were run without the moat wall to evaluate the amplification in response due to the effect of moat wall impact. For cases with this ratio less than one indicates that the NPP displacement demand was less than the provided clearance and did not impact.

Seismic pounding to the moat wall will result to increase in the superstructure response, which may lead to damage of non-structural component due to increase in the acceleration. For this analysis, absolute acceleration at node 707 with elevation 23 m above the base of the Nuclear Power Plant is presented. The following figures show absolute acceleration for all cases with and without moat wall (impact model) for positive and negative directions. Although not identified here, the acceleration increase in one direction corresponds to the first impact while the second impact on the opposite side, which is typical, increases acceleration in the other direction. This increase in absolute acceleration can be up to 2.24 and 2.37 times in positive and negative directions for intensity level of 1.0 g corresponding to BDBE events.

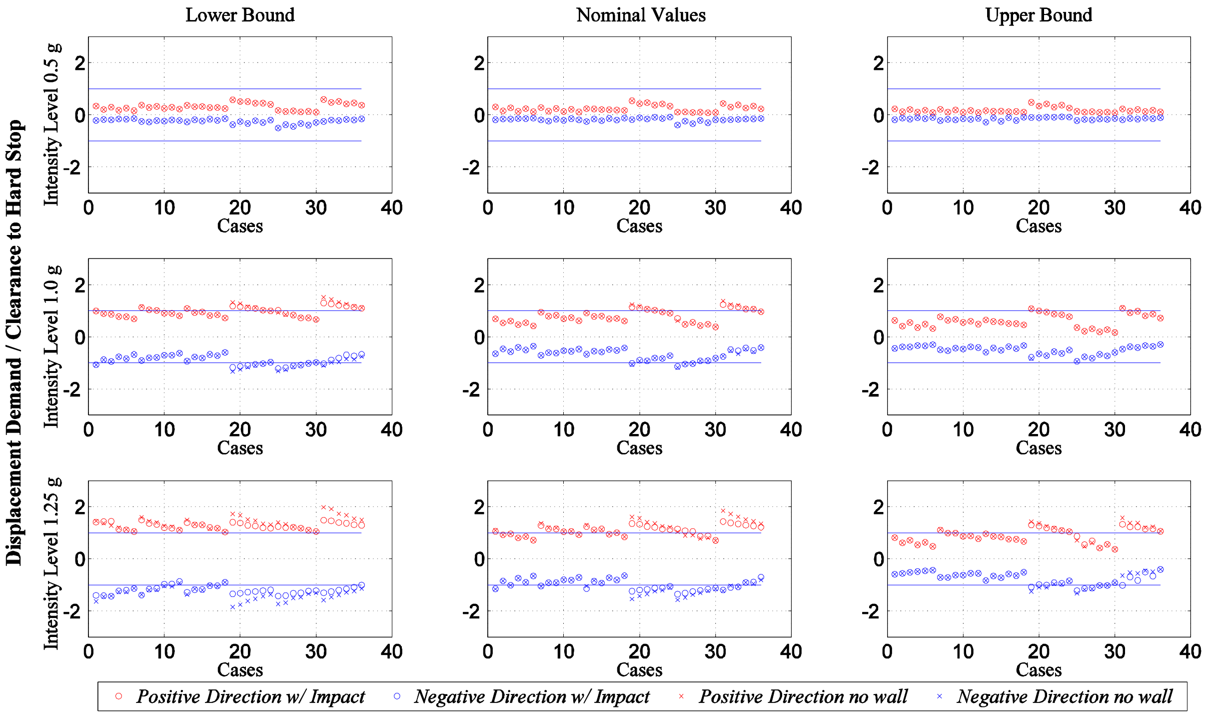


Figure 7. Displacement Demand over Clearance to Hard Stop ratio

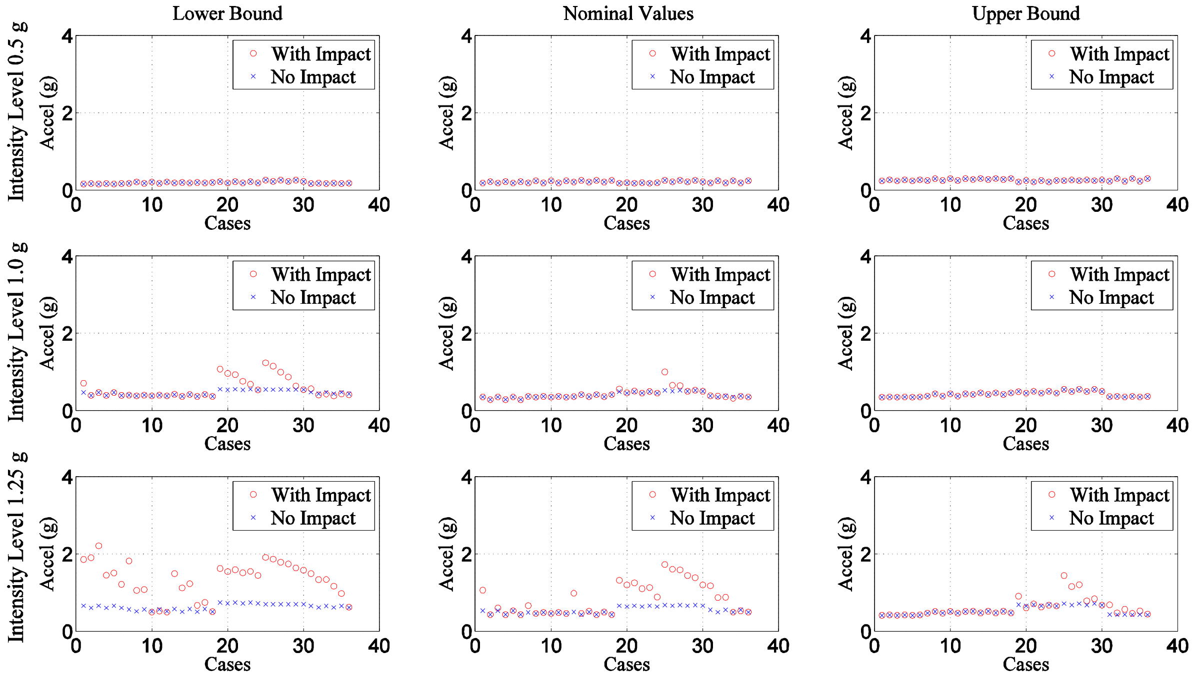


Figure 8. Positive acceleration at elevation 23m

To gain a better insight into the actual response of NPP with impact, more detailed analysis results are presented for case 25 with Nominal Values properties for Intensity Level of 1.0 g are shown in Figure 9 to 12.

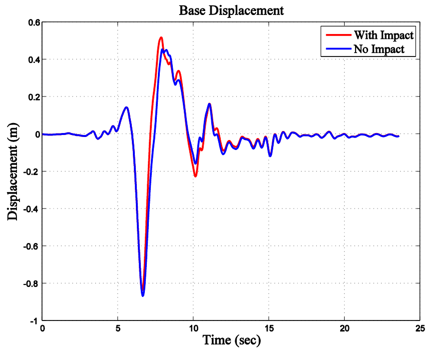


Figure 9. Base displacement time history, IL: 1.0g – NV (case 25)

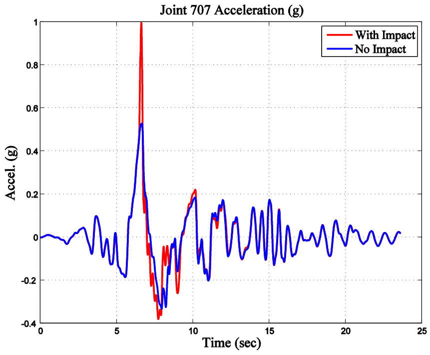


Figure 10. Acceleration at elevation 23 m, IL: 1.0g – NV (case 25)

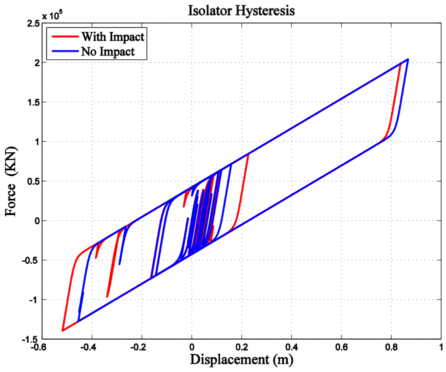


Figure 11. Isolator Hysteresis, IL: 1.0g – NV (case 25)

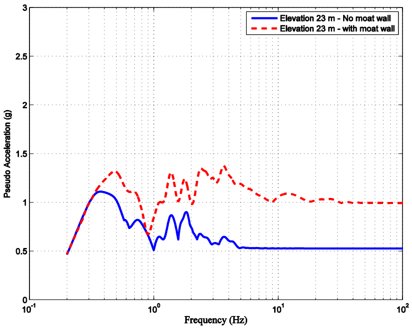


Figure 12. Floor response acceleration at ele. 23 m, IL: 1.0g – NV (case 25)

5. Conclusions

The main findings of this study are related to modeling of NPP with moat wall in OpenSees and LS-Dyna as well as observations resulting from the parametric study of the performance of the NPP under different intensity levels of seismic excitations for different properties of the moat wall and bearings.

- Variation in the isolator properties should be considered when examining seismic pounding. For BDBE even, 58.5 % cases result to the impact for lower bound properties while this value was 5.5 % for upper bound properties. Since the impact results are dependent to the assumed bearing properties, a better range of properties can be obtained from experimental testing of the bearing under large shear strains.
- Implementation of the moat wall as a hard stop for isolated NPP is able to decrease the displacement demand. However, since the NPP is relatively heavy structure designed to remain elastic during a seismic event, the moat wall and backfill soil flexibility result in a significant penetration into the wall. As a result, isolators undergo displacements exceeding design considerations based on the clearance to hard stop. Isolators should be tested beyond the hard stop to ensure functionality in the case of an extreme earthquake.
- Floor response spectral acceleration along the height on the NPP will increase significantly due to impact and this increase could be up to 2.75 times the PGA of the ground motion at the top. Bearings with higher initial stiffness generally result in higher spectral acceleration for different elevations of the NPP. It would be beneficial to examine the frequencies range of interested which affects the non-structural components in NPPs instead of the maximum spectral values to more accurately assess the change in performance.

ACKNOWLEDGEMENT

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