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Division V

MODELING OF MOAT WALL COMPLIANCE DURING IMPACT IN SEISMICALLY ISOLATED NUCLEAR POWER PLANTS

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ABSTRACT

Seismic isolation is an effective strategy to protect critical facilities including Nuclear Power Plants(NPPs) during seismic events. Seismic isolation can improve the seismic performance of NPPs by reducing transmitted acceleration and forces to the structure above the isolation layer at the expense of large displacements in the isolation system hardware. To accommodate these displacements, a horizontal clearance or moat can be installed around the structure with the minimum required gap specified in design guidelines. Under extreme seismic loading condition, however, there exist a potential for impact of the isolated structure to the moat wall. The surrounding moat wall can be intended to function as a stop to limit the isolation system displacements and prevent bearing failure. Despite the low probability of impact, the potential consequences of impact on the response of the isolated structure and the behavior of the moat wall need to be better understood. This study examines an Archetype Nuclear Test (ANT) three-dimensional model based on the APR 1400 power plant model under different seismic excitations and proposes a moat wall model to capture impact forces at large displacements. The system parameters that influence the effects of impact are examined along with the amplification of the superstructure response such as floor spectral accelerations along the height of the power plant. The effectiveness of the moat wall to function as a stop and limit the displacement of isolation system is also examined. Based on the results of a numerical study, a simplified method is proposed to estimate penetration into the moat wall considering the impact velocity and basic properties of the moat wall and backfill soil.

INTRODUCTION

Seismic isolation has been proven as an effective strategy to protect critical facilities including NPPs from the damaging effects of horizontal earthquake ground shaking (Buckle and Mayes, 1990). Seismic isolation is typically achieved by installing a flexible layer of seismic isolation bearings and other hardware at the base of the structure. The increased flexibility and resulting elongation of the natural vibration period of the structure leads to significant reductions in forces transmitted to the structure above the isolation level at the expense of large displacements in the isolation system hardware. To accommodate these displacements, the isolated structure requires a large horizontal clearance at the basement level that is often limited by a moat wall. Design of seismically isolated NPPs requires a stop to limit isolator displacement to a verified displacement capacity (ASCE, 2017) and the moat wall can potentially serve this purpose.

ASCE 4 specifies the minimum required clearance to stop (CS) as the 90th percentile horizontal displacement for Beyond Design Basis Earthquake (BDBE). This value is considered to be the maximum displacement of the isolation system. However, in the potential case of impact to the moat wall, larger displacements can be observed in the isolation system as a result of penetration into the moat wall. The amount of penetration, and the effects of impact on the isolation system and superstructure are largely unknown due to limited studies on this topic.

Impact of an isolated structure to a moat wall can results in a significant amplification in the seismic response of the structures (Masroor and Mosqueda, 2012; Komodromos et al., 2007). In NPPs, the potential impact to a stop is of significant concern due to the increased transfer of forces and amplification in response of the structural system, piping and other contents. ASCE (2017) requires explicit analysis of the isolated structure system for impact loading if the provided clearance is less than the required CS. Minimal guidance is provided for procedures to model or factors important to mitigate the effects of impact. In this paper, a moat wall model is proposed to examine the seismic response of base isolated NPPs considering pounding to moat walls and its effects on the superstructure response. Results for impact response parameters including penetration depth, impact velocities and forces are reported and analyzed in an effort to determine a simplified methodology to estimate these parameters.

NUCLEAR POWER PLANT MODELS

NPPs are considered critical infrastructures designed to stringent safety criteria for daily operation as well as for the consideration of different hazards including seismic loading. For the seismic analysis of NPPs, simplified stick model to detailed finite elements models have been developed to examine the response of these structure under different loading conditions. For these studies examining the effect of impact, the Archetype Nuclear Test (ANT) model based on the APR 1400 NPP was used for the superstructure (Shao et al., 2016). The superstructure is considered as stick model while the base mat and isolation system are modeled in more detail to capture the response of the seismic isolation system and base mat impact to a moat wall. A moat wall model is proposed as a macro element that considers impact behavior, the dynamic response of the retaining wall, and backfill soil. This section describes details of the ANT models used to conduct simulations with moat wall impact under uni- and bi-directional horizontal excitations.

NPP Model Description

Structural models for the APR1400 nuclear power plant including the seismic isolation system were developed by KEPCO E&C. KEPCO developed a simplified Archetype Nuclear Test (ANT) stick model that consists of a Reactor Containment Building (RCB) and Auxiliary Buildings (AUX) supported on a basemat foundation with 486 bearings (Figure 1). The ANT model was converted from SAP2000 to OpenSees to use its large element library for modeling complex and nonlinear behavior of the structure including impact (Shao et al., 2016). The basemat was modeled using solid elements to capture potential redistribution of forces under the various bearing configurations and was also beneficial for impact studies conducted here. Table 1 lists the bearing properties for each individual bearing in the ANT model. Table 2 shows the modal frequencies (first 7 modes) of the isolated NPP model for the 486-bearing model. The ANT model was also analyzed in a fixed-base condition to compare with the seismically isolated case with and without impact.

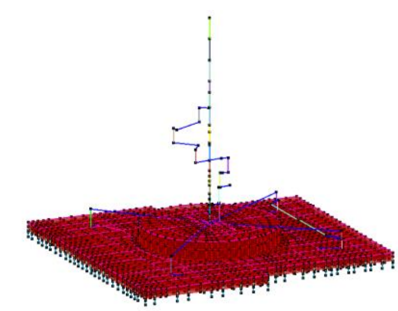

Figure 1. ANT model in OpenSees

Table 1: Bilinear bearing model parameters for individual isolators in ANT model

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

Table 2: Modal frequencies of isolated NPP model

Mode	Frequency (Hz)	Direction
1	0.477	Isolation – Horizontal X Translation
2	0.477	Isolation – Horizontal Y Translation
3	0.711	Isolation – Torsion
4	3.539	RCB - Horizontal Translation
5	3.546	RCB - Horizontal Translation
6	7.023	ACB - Horizontal Translation
7	7.521	ACB - Horizontal Translation

Moat Wall Model with Impact

A macro model for the moat is proposed to simulate the impact force in seismically isolated NPP. The macro model is based on the observed mode of deformation in FEM simulations using LS-Dyna (Figure 2). The macro model consists of a Hertz damped spring model for the impact interface, elastic beams and nonlinear rotational springs modeling the moat wall structural behavior, and springs to capture the contributions of the backfill soil. The components of the macro model consist of existing elements in OpenSees. The structural wall is composed of *elasticBeamColumn* elements along the height of the moat with non-linear rotational springs included as *zerolength* elements at the base, top and bottom contact points of the mat foundation. These rotational springs are placed where non-linear behavior or plastic hinges may form in the moat wall as indicated by the deformation and largest strains observed in the FEM simulations. Backfill soil was modeled using springs at key locations with *HyperbolicGap* Material and *Impact* Material was used for the contact element springs. The effective mass of the moat wall and soil are included in model.

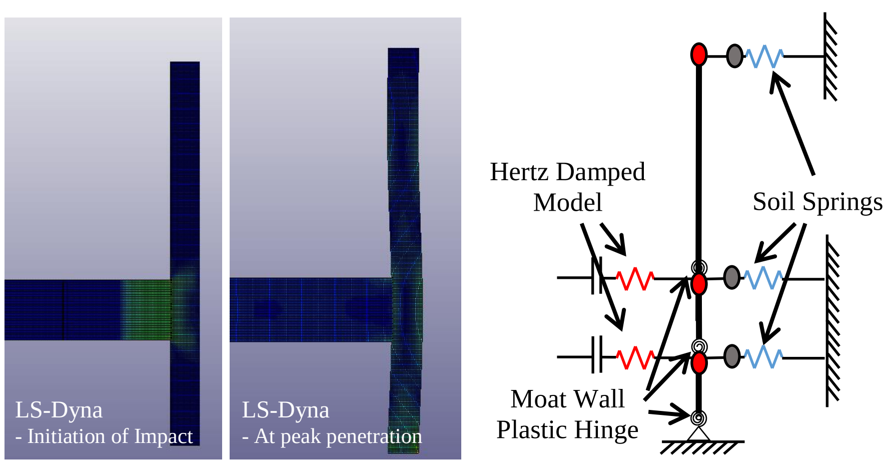

Figure 2. Slab and moat wall deformed shape modeled in LS-Dyna (left and middle), and proposed macro model to capture impact in OpenSees (right)

To capture the effects of impact to the moat wall for the ANT model, 1,240 nodes and 1,364 elements were added to the ANT structural model. These additional nodes surrounded the base mat to include the moat wall impact elements. Every node on the perimeter of mat foundation was connected through a *gap* element to the impact macro model which consists impact, moat wall elements and backfill soil springs.

NUMERICAL SIMULATIONS

A total of 36 different cases were considered to simulate the seismic response of the ANT model considering moat wall impact and examine the superstructure response. These studies considered different Ground Motions (GM), Intensity Levels (IL), and Clearance to Stop (CS). Three pairs of earthquake ground motions (Chi-Chi, Imperial Valley and Loma Prieta Earthquakes) were considered for use in these simulations and applied as 1-D and 2-D horizontal excitations. The ground motion records were obtained from the NGA database (Ancheta et al, 2013) and scaled to fit the RG1.60 response spectrum (USNRC, 2014) for 0.5 g peak ground acceleration for DBE motion without distortion. To examine the BDBE conditions, ground motions were scaled by a factor of 2, which exceeds the design recommendation of 1.5 scale factor in ASCE (2017). Moreover, an additional case was examined with the ground motions scaled to a peak ground acceleration of 1.25g, resulting in impact for most ground motions. Per ASCE (2017), functionality of the isolation system should be verified up to displacements corresponding to CS. Experimental tests on full scale bearings considered in these models have shown that these bearings can reach up to 450% shear strain prior to failure (Schellenberg et al., 2015,2016). Based on the deformation capacity of the bearings, three different cases were considered for the CS. These values correspond to 350, 400, and 450 % shear strain in the rubber with the height of the rubber equal to 0.21 m. Typically, lead rubber bearings are designed and experimentally tested for shear strains well below this level.

Results

To gain a better insight into the response of NPP with impact, detailed results 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 are presented in detail for the 2-D Loma Prieta record at 1.0g excitation and CS= 0.735 m. Results presented here are representative of the general behavior observed for all the simulations conducted.

Figure 3 shows the plan view and orientation of the basemat for the structural model. The location of the impact macro elements on west side of the NPP for which detailed results are presented later is identified by the star in the figure.

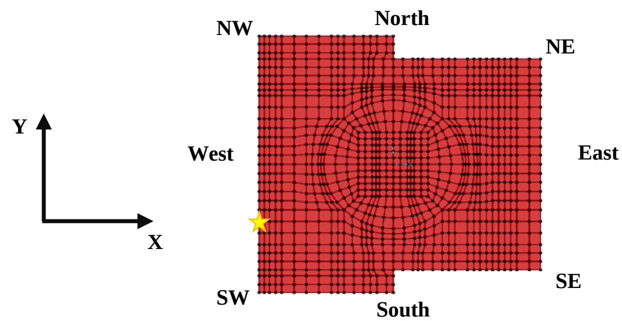

Figure 3. ANT Model plane view

The hysteresis, bearing orbits and shear interaction for a center bearing and the four corner bearings during the earthquake simulation is shown in Figure 4. Impact occurs once the bearing displacement exceeds the provided CS marked in the figure by the solid straight lines. As shown, there are two instances of impact of the NPP to the moat wall, the first at west side and the second at the north side. Also, it can be seen that the displacement demands at the corner bearings can be larger than the center bearings due to torsion. The NW and NE corner bearings are close to a 2nd impact in X-direction due to torsional effects while the other corner bearings and the center bearing have sufficient clearance to the east moat wall. The torsional effects appear to increase after the first impact. The shear force-displacement behavior for different bearings are also presented in Figure 4a and 4b with a maximum shear forces are 4,075 and 4,635 kN in X and Y directions respectively. 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_{init} 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 bearings.

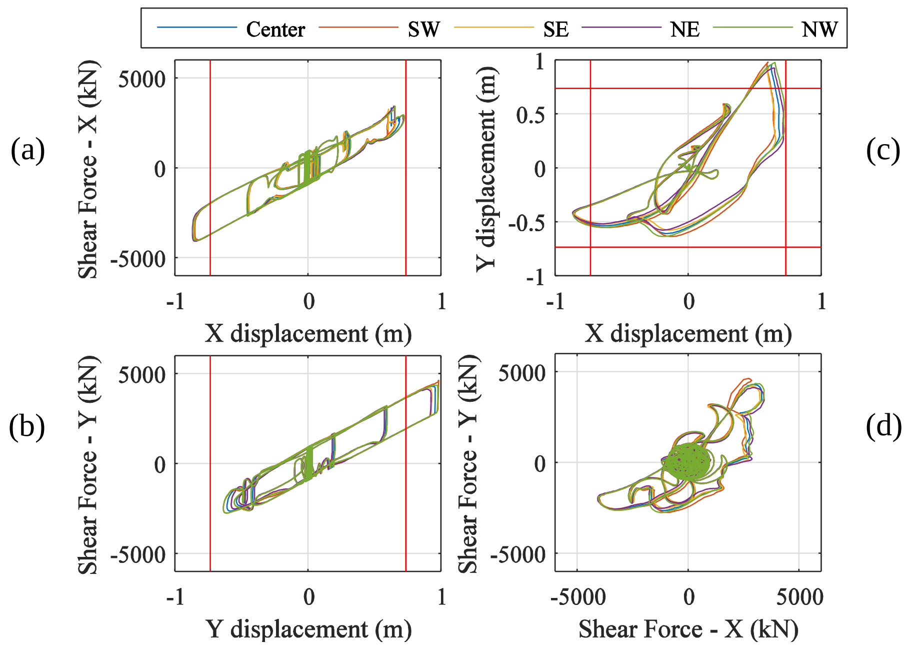

Figure 4. Response to 2-D Loma Prieta at 1.0g: (a and b) bearing hysteresis, (c) bearings orbits, and (d) shear interactions

The response for a set of elements that compose the macro model for a section of the west wall are shown in Figure 5. When the NPP displacement exceeds the provided CS (Figure 5a), the impact springs are engaged, resulting in large impact forces. Deformations shown for impact elements include both the gap distance and the indentation into the moat wall (Figure 5b). Deformations due to indentation into the moat wall are 0.82 and 2.18 cm for middle and bottom impact springs respectively. It should be noted that the bottom impact spring had higher forces even though they both have same impact properties. At impact, as the forces are transferred to the moat wall, the moat wall deforms with larger displacements at the location of upper springs. Since the moat wall is fixed at the base, the top impact springs will separate before the bottom springs based on the deformation mode and lead to larger impact forces in the lower impact spring.

Structural properties of the moat wall are assumed based on a 1.524 m (5 ft.) thick reinforced concrete wall. Results are presented for both the shear forces resistance of the moat wall and the nonlinear rotational springs along the height of the moat wall. Results for shear forces in two different segments of the moat wall are presented in Figure 5c. Shear force for the bottom segment represents the moat wall base shear force that is being transferred through the moat wall to the ground. Figure 5d shows the response of the corresponding rotational hinges on the moat wall segment. Based on these results, the moat wall reaches its ultimate capacity with significant yielding and residual displacements after impact.

The response of the soil elements behind the moat wall is shown in Figure 5e. The *HyperbolicGap* material used to model the soil behavior in OpenSees is a compression only material assumed to be well-graded silty sand with parameters obtained from Wilson (2009). It can be seen that the top soil spring experiences some excitation before and after impact due to vibration of the node at the top of moat wall. Following the main impact, there are some residual displacements in all the soil springs.

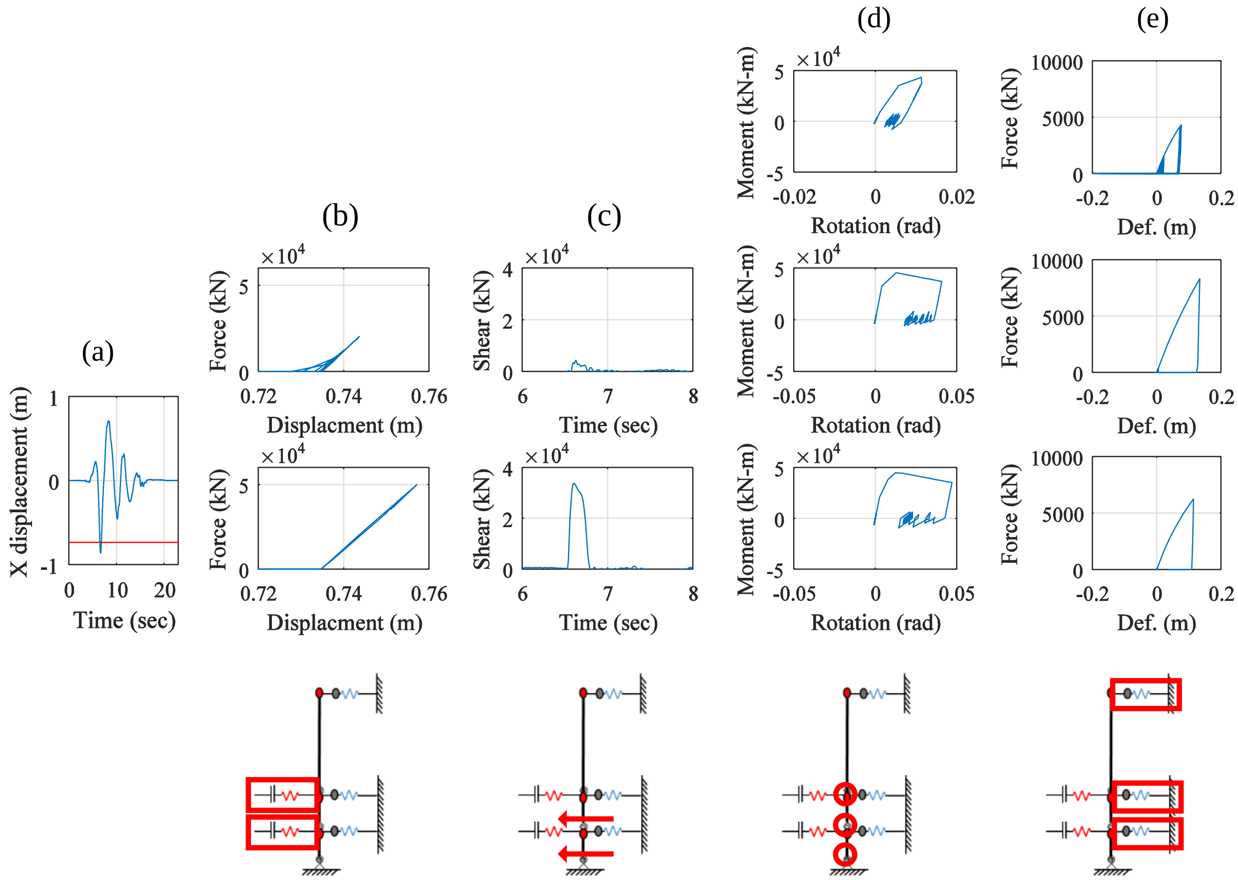

Figure 5. Response to 2-D Loma Prieta at 1.0g : (a) base displacement, (b) impact force deformation, (c) moat wall shear force time history, (d) moment rotation of rotational spring, (e) backfill soil force deformation

Floor response spectra are shown in Figure 6 for two different elevations along the height of RCB 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. 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 ~3.5 Hz, which corresponds to the first horizontal mode of vibration of the RCB. As Figure 6 clearly shows, there is another distinctive frequency around 0.34 Hz, which corresponds to natural frequency of the isolated NPP. For frequencies below 1Hz, 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.

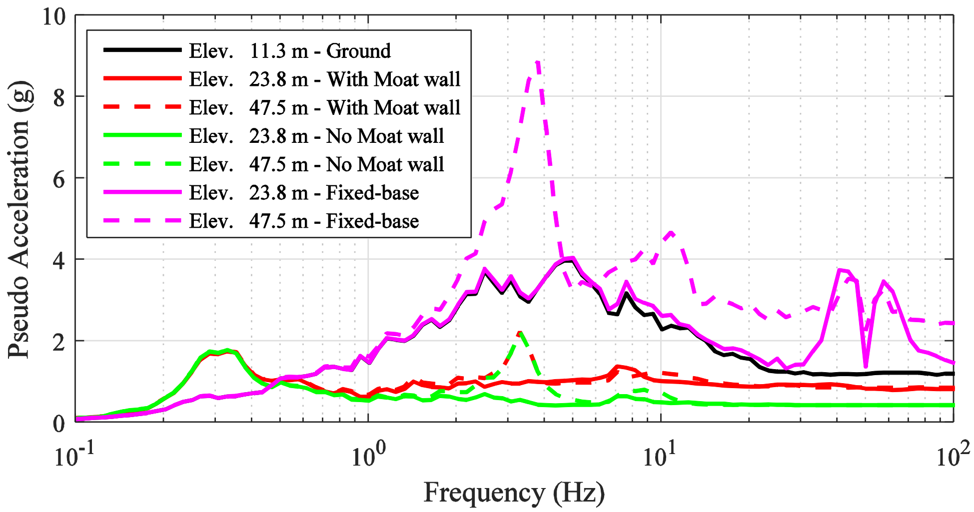

Figure 6. Floor reponse acceleration for RCB at different eleveations for fixed-based and isolated NPP with and without moat wall to 2-D Loma Prieta at 1.0g

Contribution to Moat Wall Force Resistance

The total impact forces including contributions from the concrete moat wall and backfill soil springs are presented for the north and west impact of the NPP (Figure 7). These total forces were calculated by adding the recorded forces of different components together for every impact macro element along the entire length of wall for the given side. These forces are then normalized by the total weight of the NPP (W = 4,730,292 kN). As Figure 7 shows, the shear forces in the concrete moat wall increases rapidly at impact while the compression force from backfill soil increases at a slower rate. This is due to the fact that the soil stiffness is relatively lower than the horizontal stiffness of the moat wall. Therefore, the moat wall has a higher influence on limiting the penetration compared to the backfill soil.

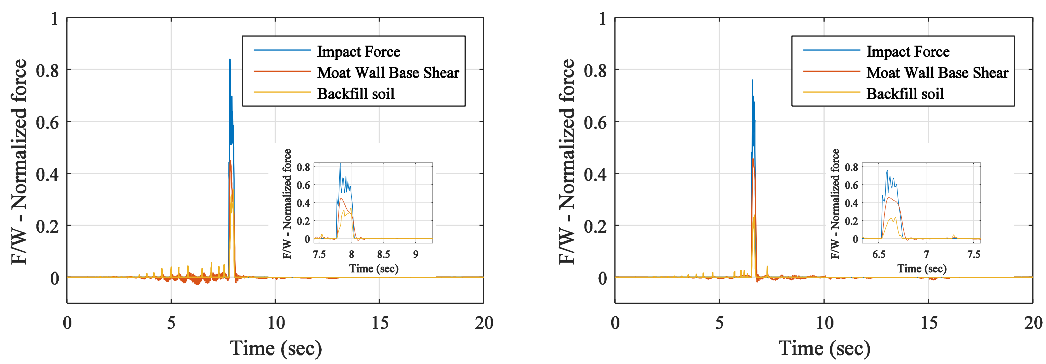

Figure 7. Response to 2-D Loma Prieta at 1.0g: total impact force, moat wall base shear, and backfill soil force time history on north (left) and west (right) side of NPP

Impact Analysis Results

Results for penetrations, impact velocities and impact forces for all considered simulations are provided in Figure 8 to examine the relationship between these impact response parameters. There are clear trends between these parameters, which can be used to develop a simplified approach to predict impact response parameters. The shear strength of the moat wall calculated using plastic design and the maximum soil contribution are noted in the figure. Two different plastic collapse mechanisms were considered to find the shear capacity of the moat wall with the lowest value corresponding to Scenario 1 (Figure 9). For backfill soil, the ultimate passive force of the soil was calculated based on total ultimate force of the soil per unit width of the wall.

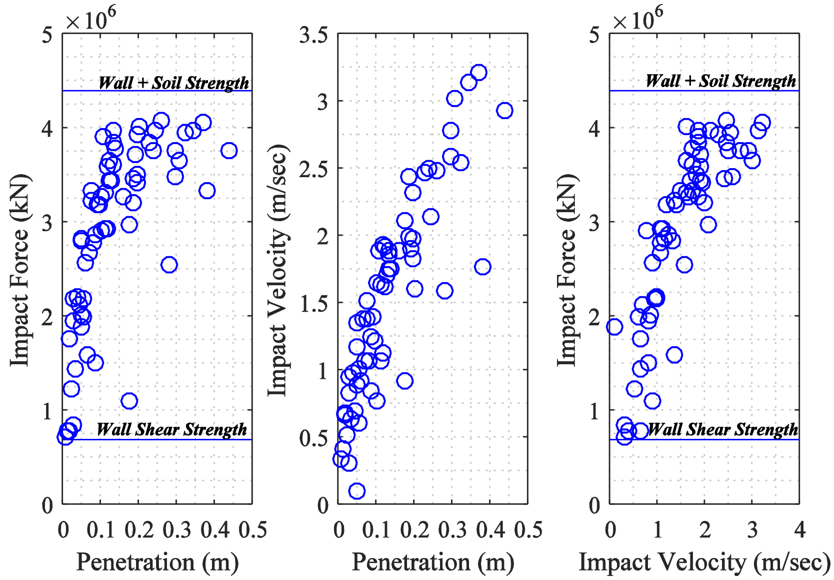

Figure 8. Relationships between different impact response parameters

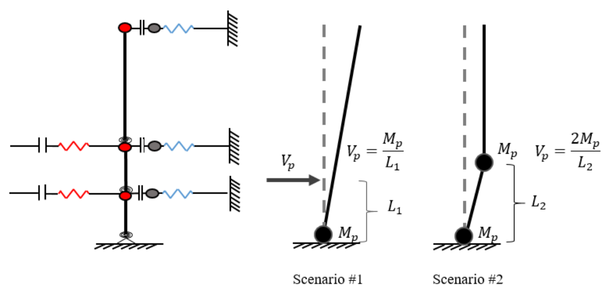

Figure 9. Shear strength of the moat wall using plastic design

Estimation of Penetration

A simplified method to estimate penetration into the moat wall based on the moat wall properties and the given impact velocity (v_{imp}) using conservation of energy is proposed. It is assumed that the kinetic energy ($E_{kinetic}$) of the NPP moving as a rigid body before impact transforms to strain and hysteretic energy (E_{strain}) that cause deformation of the moat wall and backfill soil. In this simplified approach, it is assumed that throughout the short duration of impact, there is no additional input energy from ground excitation added into the system and no energy loss during impact. The total mass of the isolated NPP including basemat and superstructure (m_{NI}) is 482,682 ton. Using conservation of energy:

$$E_{kinetic} = E_{strain} \tag{1}$$

$$E_{kinetic} = \frac{1}{2} m_{NI}. v_{imp}^2 \tag{2}$$

$$E_{strain} = \int F_{moat}. dx \tag{3}$$

Assuming an elasto-plastic model for an equivalent resisting spring, the strain energy of the moat wall system can be calculated as the area under the force-deformation curve (Figure 10). Since the resistance to the impact is primarily coming from the structural moat wall (Figure 7), the maximum force of this equivalent system was assumed to be the shear strength of the wall and the yield displacement (δ_y) was calculated from yielding rotation of the moat wall section to form a plastic hinge in scenario 1 (Figure 9).

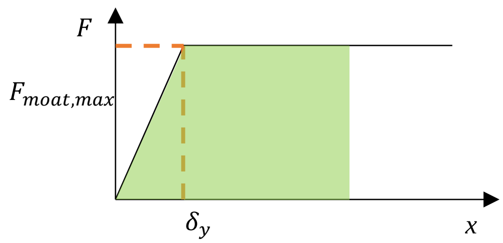

Figure 10. Shear strength of the moat wall using plastic design

Using the proposed estimation, penetrations into the moat wall for different impact velocities were calculated and compared with measured values based on numerical simulations (Figure 11). The predicted penetrations using this method provide an approximate upper bound for penetration and can be used to estimate penetration into the moat wall under different conditions.

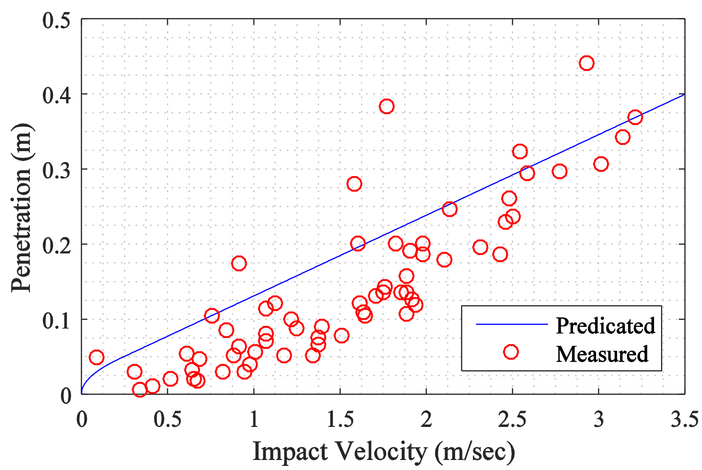

Figure 11. Measured and predicted penetrations for different impact velocities using different coefficient of restitutions

This simplified method will provide an estimate of penetration into the moat wall based on an assumed impact velocity and strength of the moat wall. This can be a useful tool for designers to check the expected displacement demand on the isolation system considering moat wall compliance. It should be noted that this simplified approach was developed using a single moat wall system and needs to be examined under a wider set of configurations.

CONCLUSIONS

A detailed analysis model was used to investigate the seismic response of isolated NPP considering impact to moat walls. A macro element was proposed to capture the impact force between the NPP and the moat wall. Based on the assumed properties for the moat wall, penetration can be significant and this additional displacement should be considered in the design of the isolation system. Results for the response of the moat wall showed that the ultimate capacity was reached and led to degradation in strength and residual displacements in the moat wall due to impact. 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.

It was shown that the influence of the moat wall to limit the displacement demand during the impact is more pronounced than the contribution of the backfill soil. Based on provided results, there were some clear trends between different impact response parameters (impact velocities, impact forces and penetrations), which was used to develop a simplified method to estimate penetration into the moat wall given impact velocity and properties of the moat wall.

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