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SEISMIC ISOLATION OF AN EMERGENCY DIESEL GENERATOR SYSTEM FOR NUCLEAR POWER PLANTS

Ricardo Bustamante[1], Gilberto Mosqueda[2]

[1] Ph.D. Student, University of California, San Diego
[2] Professor, University of California, San Diego (gmosqueda@ucsd.edu)

ABSTRACT

The post-earthquake functionality of an Emergency Diesel Generator (EDG) is critical for the safe shut down of Nuclear Power Plants (NPPs). The EDG performance requirements are embedded in the proposed seismic evaluation and qualification procedures of regulatory agencies, with both structural and functional failure modes considered. This paper evaluates the applicability of a 3D seismic protection system to enhance the seismic performance of an EDG under a relatively large seismic hazard. The proposed system consists of two isolation layers to decouple the seismic demand. The upper layer consists of linear springs and dampers to handle the vertical seismic demand, while the bottom layer consists of lead-rubber bearings to mitigate the horizontal seismic demand. The performance target is to reduce the EDG acceleration while limiting the isolation system lateral displacement based on the Engineering Demand Parameters (EDP) of the critical components. The isolation system design is challenged by the trade-off between reducing the acceleration response of the EDG and the displacement capacity across the isolation plan that can affect the performance of umbilical lines. The seismic performance of the seismically isolated EDG is examined under NCR R.160 seismic hazard imposing large accelerations and displacements at low periods and demonstrates that seismic isolation can be effectively reduce acceleration while limiting displacements.

INTRODUCTION

In the event of Loss of Offsite Power (LOOP), the functionality of Emergency Diesel Generators (EDG) is critical for the plant operation and, if necessary, safe shut down (Kančev et al., 2013). This function makes the EDG one of the most critical equipment within nuclear power plants required to maintain operations following an earthquake or other hazards and prevent potential core damage. These seismic performance requirements for EDGs considering independence, redundancy, and testability are embedded in the proposed seismic evaluation and qualification procedures (U.S. Nuclear Regulatory Commission, 2007, 2020). To maintain operation, both structural and functional failure modes have been considered for the EDG, with functional failure modes largely based on limited experimental data from testing on shaking tables (Jeong et al., 2019). A structural failure mode consists of stress damage to the equipment frame, the anchorage system, the pipelines, and ducts connected to the EDG. More generally, the EDG seismic performance and associated damage states have been related to Engineering Demand Parameters (EDP). Typically, the EDP used to assess the probability of damage has been the acceleration experienced by the EDG unit and accounts for functionality.

Past studies indicate the expected failure mode of an EDG during seismic shaking is anchor failure at the attachments; seismic isolation has been proposed as a solution to substantially reduce forces transferred to the anchor bolts and the foundation and increase the seismic capacity (Y.-S. Choun et al., 2007). In addition, a seismically isolated EDG can experience a significant reduction of the horizontal acceleration response, thus increasing the safety margin for critical EDP. Nevertheless, introducing seismic isolation imposes additional challenges. The first is the vertical acceleration component, which can be amplified given the typical range of the natural vertical frequency of bearings, as evidenced in buildings (Ryan et al., 2013). The second challenge is related to the lateral displacement of the isolation system that should have sufficient clearance to move freely, and any umbilical crossing the isolation system must have sufficient deformation capacity. This introduces the need to consider an additional EDP based on lateral deformation of the isolation system. For example, the fuel pipeline is a critical umbilical line required for an EDG unit to remain functional. The third concern is related to the lateral deformation capacity of the bearings, typically expressed in terms of the shear strain, and can be characterized by a lateral displacement EDP.

A three-dimensional (3-D) seismic isolation system is designed for an EDG unit consisting of Lead Rubber Bearings (LRB), coils springs, and viscous dampers, merging the benefits of these devices to meet operational and seismic requirements. The 3-D isolation system is configured in two isolation levels considering the target design objective of decoupling the seismic demand in the horizontal and vertical directions. LRB are considered for isolation in the horizontal direction since they are widely accepted and applied in practice. Coil springs and dampers are considered for the vertical component, considering both the seismic and vibration operational demand though only seismic demands are examined here. The seismic isolation systems properties are determined, and bearing are designed to ensure feasibility. The proposed system is studied by performing a deterministic analysis using Engineering Demand Parameters to define and quantify its seismic performance.

SEISMIC ISOLATION OF EDG

Several authors have studied the application of base isolation to equipment and nonstructural components, including applications in the nuclear industry (Y.-S. Choun et al., 2007; Ebisawa et al., 2000; Furukawa et al., 2013; JAERI, 2000; Najafijozani et al., 2020). Different systems have been applied for vertical seismic demands, ranging from springs to dampers and a combination of both. The type of approach depends on how the horizontal isolation is considered. Najafijozani et al. (Najafijozani et al., 2020) studied adaptative vertical isolation of light-weight acceleration-sensitive equipment for a base-isolated NPP. Using a combination of springs and dampers, they achieve a reduction of the acceleration to meet the seismic capacity of the equipment. They focused solely on the vertical movement of the equipment, assuming the base isolation system of the NPP reduces the horizontal acceleration and suppresses any rocking. Since the Emergency Diesel Generator unit is typically located outside the NPP buildings, any seismic isolation system should isolate the unit horizontally and vertically.

Choun et al. (Y. Choun et al., 2006) experimentally studied the performance of the coil spring–damper unit under two different types of ground motions. Their study found amplification of the vertical acceleration of a given ground motion set and a reduction for another set, highlighting that the effectiveness of isolation is dependent on the natural vertical frequency of the coil spring-damper unit and the frequency content of the ground motion. A similar trend was found for the displacement response. Choun et al. (Y.-S. Choun et al., 2007) developed a base-isolated EDG numerical model and performed a numerical fragility analysis. The EDG was modelled as a single degree of freedom with the total weight lumped at mid-height of the equipment with a natural frequency is 34Hz. A fixed-base EDG model was developed for comparison purposes. They concluded that increasing the damping on the isolation system provides a lower failure probability. It was reported that the isolator would fail first before the EDG, while the EDG would fail at a lower PGA without isolation. The study showed that higher damping values would also decrease the lateral displacement of the system, reducing demands for the umbilical lines that cross the isolation interface. Ebisawa et al. (Ebisawa et al., 2000) studied the behavior of a horizontal isolation system and a horizontal and vertical isolation system. The latter consists of ball bearing units, coil springs, viscous dampers in the horizontal component, and air springs in the vertical direction. The vertical acceleration was reduced to

40% of the testbed acceleration. The study concluded that this isolation system effectively improves the seismic resistance and decreases the functional failure probability.

SEISMIC HAZARD AND LIMIT STATES

The effectiveness of seismic isolation is examined here for a relatively high seismic zone. The seismic input ground motions for the analysis consist of twenty dispersion-appropriate three-component ground motions that were used in a previous study for seismically isolated NPP (Schellenberg et al., 2015) following NRC RG1.60. Figure 1 shows the Pseudo Spectral Acceleration (PSA) and the ground motions, with a PGA=0.50g.

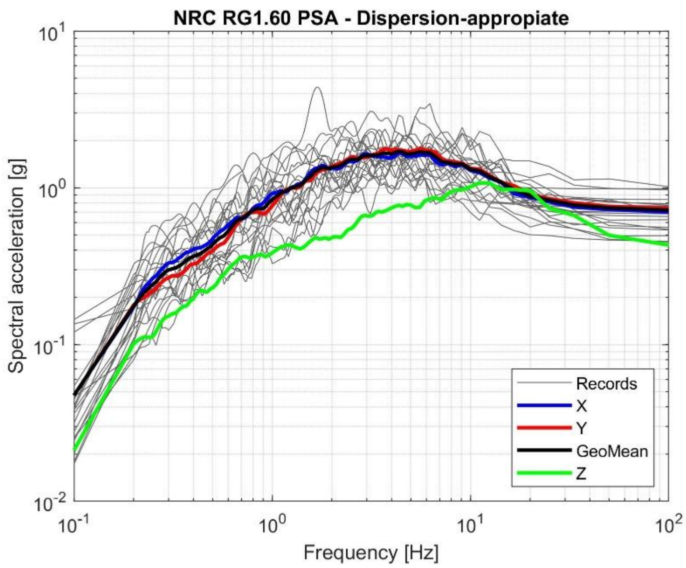

Figure 1. Pseudo Spectral Accelerations with records

The seismic performance of the equipment is evaluated based on Engineering Demand Parameters (EDP) reported in the literature. The probability of failure of an EDG unit can be characterized by the acceleration experienced by the unit. In contrast, the base isolation system and the umbilicals crossing the isolation plane are characterized by their displacement capacity. Therefore, two different types of capacities are examined, with the Limit States considered for each EDP listed in Table 1 with some of the values reported a High Confidence Low Probability of Failure (HCLPF).

Table 1: Engineering Demand Parameters for system components

EDP	Limit State	Value	Reference
Isolation Lateral Displacement	Pipeline	127mm	(Jeon et al., 2015)
	Bearing	250% shear strain	(JAERI, 2000)
EDG Acceleration	EDG	0.41g	(Liu & Aziz, 2007)

EMERGENCY DIESEL GENERATOR ANALYSIS MODEL

The study considers seismic isolation of an Emergency Diesel Generator with a weight equal to 150 Tf. Past studies (Bustamante et al., 2022) under a lower seismic hazard showed that a two-layer isolation system can improve the seismic performance of the EDG. Figure 2 shows a schematic configuration of the EDG and seismic isolation system following (Bustamante et al., 2022).

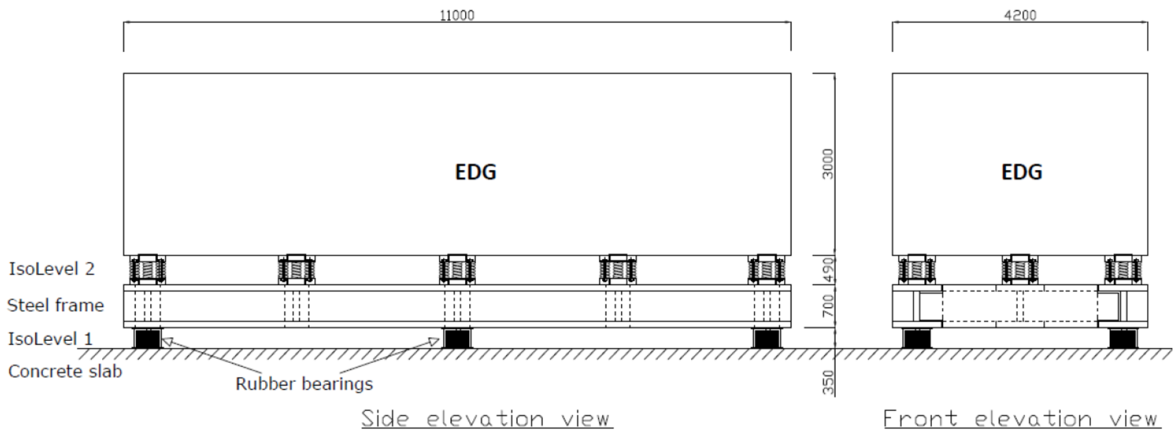

Figure 2. Configuration of the proposed seismic isolation system

The first isolation layer (IsoLevel 1) is intended to mitigate horizontal vibration transferred to the EDG from ground shaking and consists of LRB devices that can be designed to provide a range of effective stiffness and damping values to limit the lateral displacement. As previously mentioned, however, these devices are vertically stiff and can amplify the vertical shaking transmitted to the EDG. To address this concern and operational requirements, the second isolation layer (IsoLevel 2) consists of springs and damper supported on top of the LRB isolation layer. This system can mitigate the effect of vertical shaking by modifying the vertical frequency. A rigid frame is considered between the two isolation levels, assuming it provides an adequate rocking restraint system with vertical guides. The numerical model of the EDG and isolation system was developed in OpenSees (McKenna et al., 2020). The EDG is modelled as a single degree of freedom with the weight equal to 150 Tf at mid-height of the unit and a primary vibration frequency of 34 Hz [5].

The LRBs sizing is defined based on a target isolation system displacement and base shear transferred to the EDG. Using the procedure in FEMA P-751 (FEMA, 2009), assuming 5% damping, the criterion used in a previous study (Bustamante et al., 2022) was to choose the intersection of both curves shown in Figure 3, to reduce the acceleration while limiting the lateral displacement. If the same criterion is used for this seismic hazard, the effective period is 1.60s, as shown in Figure 3. Three options are explored for this seismic hazard and detailed in Table 2.

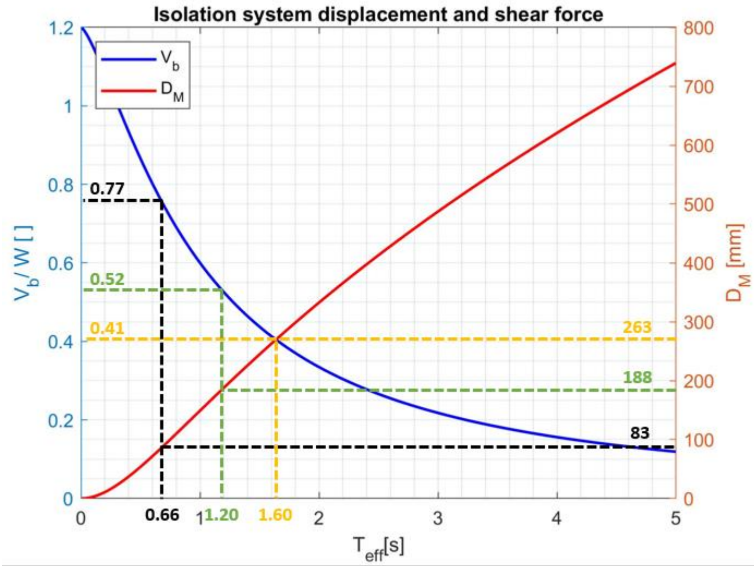

Figure 3. FEMA P-751 feasibility domain

Table 2: LRB sizing options using FEMA P-751

Option	T_{eff} [s]	V_b/W	D_M [mm]
1	1.60	0.41	263
2	0.66	0.77	83
3	1.20	0.52	188

It is assumed here that the target isolation displacement is limited by the pipeline Limit State of 127mm. While a flexible pipeline connection can be designed for larger displacements, this limit is considered here as a tested system reported in the literature related to this application. Option 1 leads to a large lateral displacement compared to the pipeline Limit State even though the LRB can provide additional damping. Option 2 significantly limits the lateral displacement, with the downside of forcing the isolation system to underperform in its capacity to reduce the EDG acceleration. The spectral acceleration is similar to the fixed base option for this case.

The design displacement of Option 3 is 188mm for 5% of critical damping. The lead rubber bearings provide an effective damping of 23.1% with an expected displacement reduction factor of about 1.5, reducing the design displacement to 125mm, below the pipeline Limit State shown in Table 1. Option 3 is considered to balance displacement and acceleration demands and is examined in more detail considering that a more rigorous iterative design process can lead to more optimal performance. The LRB are designed for Option 3 with the dimensions shown in Table 3. The LRB are modelled as bilinear assuming Shear Modulus of rubber G_R=0.4MPa and yield stress of lead of σ_{yL}=7.9MPa.

Table 3: Bearing dimensions and properties

# bearings	D_{ext} [mm]	$D_{lead\ core}$ [mm]	t_r [mm]	# layers	β_{eff}
6	470	100	8	16	23.1%

The coil springs are sized for operational vibration (vertical static deflection) and vertical frequency content of the ground motion, targeting a vertical frequency of less than 2.0 Hz and a static deflection of less than 200mm to satisfy both conditions. The coil springs' vertical frequency is 1.29 Hz with a static deflection of 150mm. Linear viscous damping is assumed and sized following a parametric study examining the reduction of the ground acceleration amplification, with a damping of 11% of critical.

Time-history analysis

A nonlinear time history analysis is performed of the EDG subjected to the 20 triplets of ground motions. The result from Record 8 are shown to examine the behavior of the system. Record 8 is representative of the mean isolation lateral displacement. Figure 4a compares shear force-lateral deformation hysteresis of the isolation system, while Figure 4b compares the orbital displacements. Figure 4a shows that the bearings exhibit limited nonlinear behavior for Record 8 with 31% shear strain in the rubber. The limited deformation was intended to reduce the lateral displacement of the system based on the capacity of umbilical lines, which causes the large shear force and acceleration transferred to the EDG unit.

The displacement response results for the 20 ground motions in shown in Figure 5. The average and 99th percentile displacement is added in Figure 5 considering ASCE 43(ASCE43-05, 2006) defines as goal for Design Basis Earthquake shaking to comply with 1% or less probability of unacceptable performance. Only one record exceeds this threshold, with also slightly above the pipeline Limit State deformation capacity considered equal to 127mm.

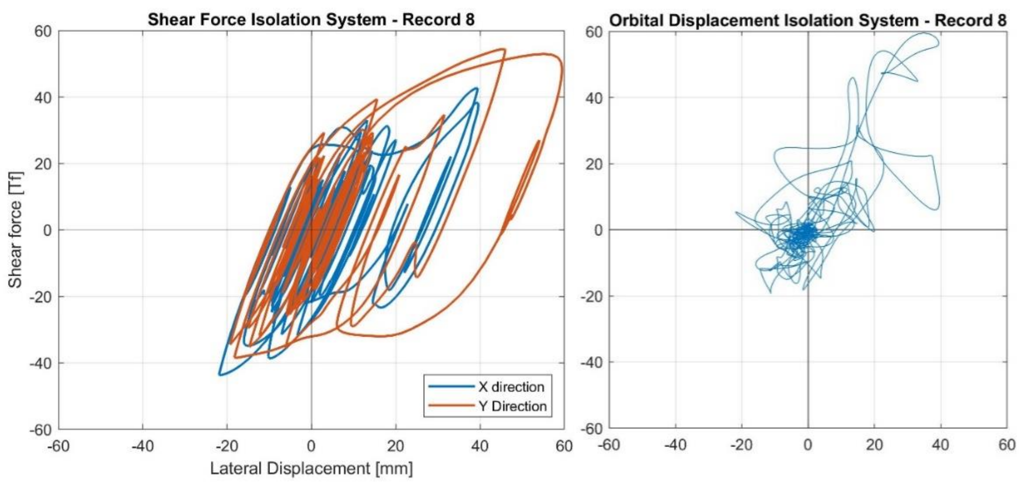

Figure 4: (a) Isolation level shear force – lateral displacement for Record 8 – X Direction (b) Plan view Orbital lateral displacement for Record 8

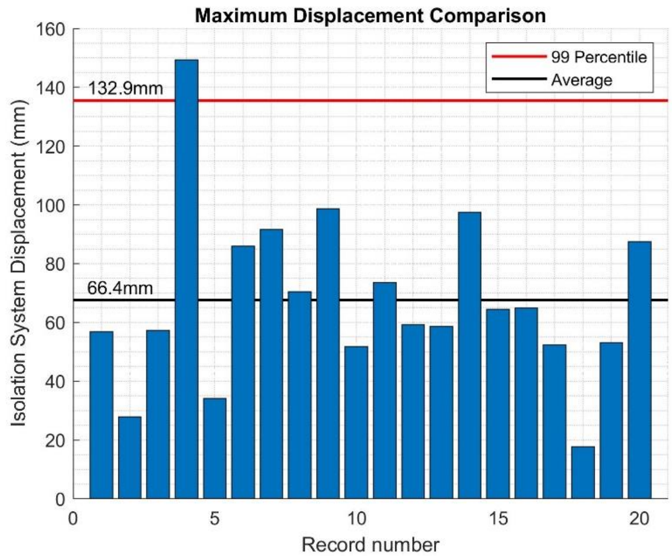

Figure 5: Maximum bi-directional horizontal displacement comparison for each record.

The acceleration time history of the EDG compared to input motion for Record 8 is shown in Figure 6. As shown in Figure 6a, the proposed seismic isolation system is able to reduce the peak acceleration by a factor of two. Figure 6b shows that the vertical acceleration experienced by the EDG is reduced slightly and not as effective as in the horizontal direction. The EDG acceleration is the most commonly reported Engineering Demand Parameter though typically specified as the PGA at the base with some amplification expected to non-seismically isolated systems. To contrast the performance of the isolation system, the bi-directional horizontal acceleration of the EDG unit is reported in Figure 7 for all the ground motions considered. The seismic hazard has a PGA equal to 0.50g, while the average EDG unit acceleration is 0.33g, showing that the isolation system effectively reduces the acceleration. Note that he 99 percentile acceleration shown no amplification in response.

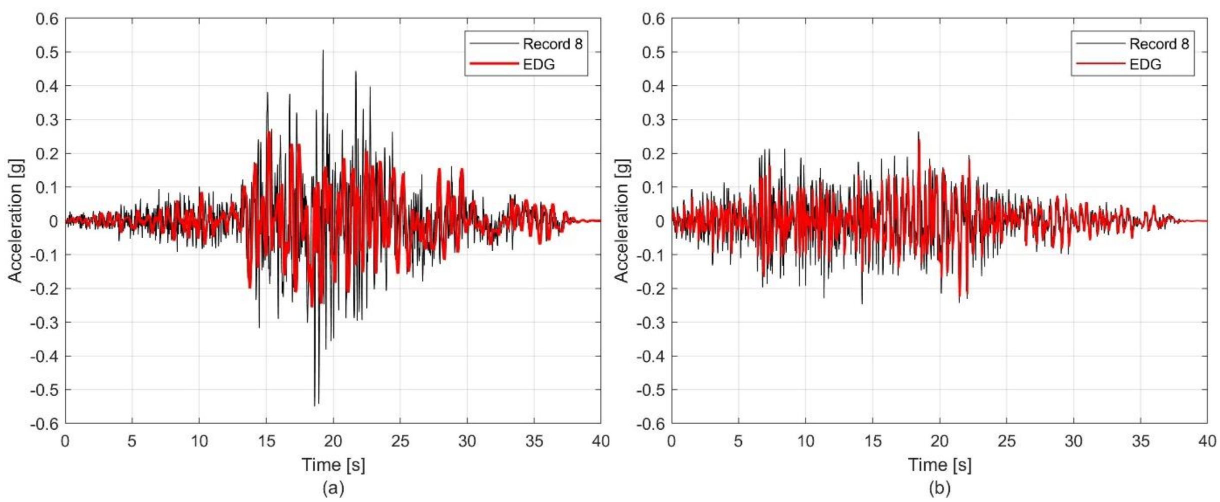

Figure 6: EDG acceleration time history response Record 8 (a) Horizontal direction 'X' (b) Vertical direction 'Z'

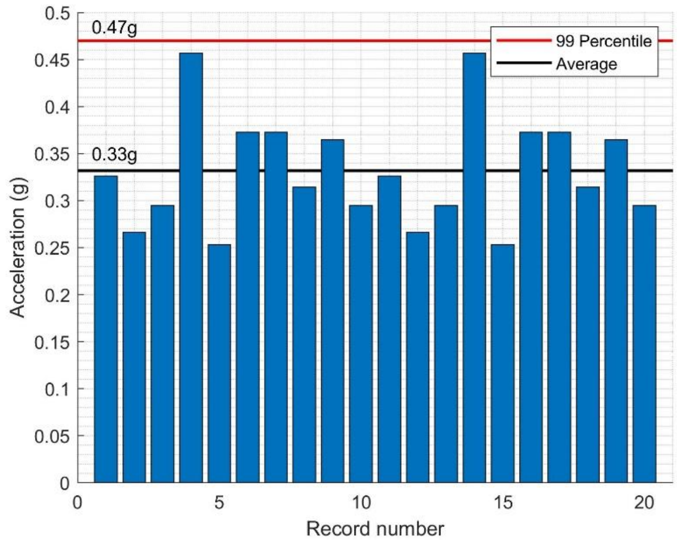

Figure 7: Maximum bi-directional horizontal EDG acceleration comparison for each record.

Figure 8 plots in grayscale the Pseudo Spectral Acceleration (PSA) corresponding to 5% of critical damping for all records at the EDG level for the horizontal and vertical directions. This is representative of the forces experience by electrical and mechanical components attached to the EDG. The ground motion PGA is shown for comparison to the average PSA at the EDG. The horizontal PSA in Figure 8a shows an amplification of the ground motion at 2 Hz, consistent with the effective period attained by Record 8. Figure 8b shows the vertical PSA for the EDG unit, which does not exhibit an overall acceleration amplification for any of the motions and a significant reduction in the average PSA.

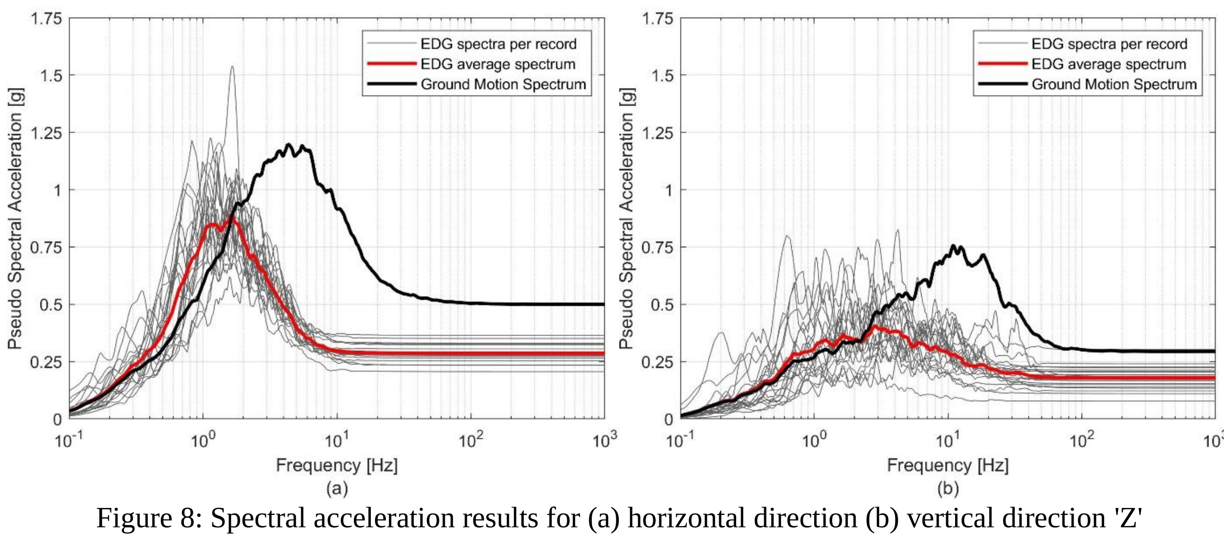

Figure 8: Spectral acceleration results for (a) horizontal direction (b) vertical direction 'Z'

CONCLUSION

The Emergency Diesel Generator at a Nuclear Power Plant site is essential to maintaining a safe shutdown after an earthquake. Potential failure modes of an EDG consist of failure of the equipment frame itself, damage to umbilical lines connected to the equipment, and damage to the support and anchorage system. Typical EDG seismic isolation systems are based on a vibration control solution developed for operational mode vibration isolation, consisting of coil springs, lateral restrainers, and/or dampers. This study demonstrates the feasibility of a three-dimensional isolation system that could meet the seismic performance requirements for a high seismic zone with a PGA=0.50g. The system has independent horizontal and vertical isolation systems that enhance the seismic performance of an EDG unit compared to the fix-based unit, reducing the acceleration while controlling the lateral displacement.

The system is designed to accommodate the limited deformation capacity of the fuel pipelines crossing the isolation interface based on the capacity reported in the literature. The proposed seismic isolation system can be improved by considering more flexible umbilicals to increase the displacement capacity of the system and further reduce the reduction of acceleration and forces transmitted to the EDG unit. To further examine this approach, experimental testing of fuel pipelines and other umbilical are needed to verify their capacity and increase the displacement capacity. Experimental data of an isolated EDG unit could provide better estimates for the acceleration that the EDG unit can withstand, as well for the uncertainty parameters, to better relate to reported values in the literature in terms of PGA.

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