Materials Research Proceedings 31 (2023) 38-45 https://doi.org/10.21741/9781644902592-5

High dimensional model representation for the probabilistic assessment of seismic pounding

R. Sinha[1,a*], B.N. Rao[1,b]

[1] Structural Engineering Division, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India – 600036

[a] rohit.sinha2096@gmail.com, [b] bnrao@iitm.ac.in

Keywords: Fragility Curves, HDMR, MCS, Structural Pounding, Response Surface Method, Meta-Model

Abstract: The study presented herein aims to analyse the seismic performance of a two-dimensional eight-storey non-ductile reinforced concrete frame against structural pounding with an adjacent three-storey stiff frame having different storey heights. The examined case of pounding refers to the extremely critical floor-to-column structural pounding for three different initial separation gaps between the said structures. Seismic vulnerability analysis is usually performed by way of developing fragility curves for a set of damage and intensity measures using a suitable fragility curve generation technique. For this study, damage measures are characterized by the percentage maximum inter-storey drifts of the taller, flexible frame while the peak ground accelerations of the ground motion data are used as the corresponding intensity measures. Displacement-based fragility curves were generated for 9 sampling points using the High Dimensional Model Representation (HDMR) technique and the results were compared with actual probabilistic data obtained using Monte-Carlo Simulations (MCS). The results of this study imply that the proposed use of HDMR provides excellent fragility curves for the estimation of pounding risks with a significant reduction in the number of simulations required, thereby reducing the computational cost by huge margins. Results also indicate that fragility curves for target separation distances can also be obtained using HDMR without performing additional simulations. This can further be used for the mitigation of pounding risks and for the reliability-based design of buildings for target separation distances and damage measures.

Introduction

Structural pounding between adjacent buildings with insufficient separation distance is an undesirable event and has often been a cause of severe structural damages [1]. This issue particularly prevails in metropolitan cities where land resources available for construction practices are limited [2].

Seismic Pounding has been proven to be detrimental to structural systems rather than benefit them. This is especially true for buildings present on corners of a series configuration [1]. Its main effects include an increase in the acceleration and drift demand at different storey levels [3, 4]. The past three decades have seen extensive research being conducted to develop ways of mitigating pounding risks and over the years, numerous ways of minimizing these effects have been suggested [5-7]. However, modern seismic codes have opted to adopt the simplest approach of minimizing the risks associated with pounding by prescribing a minimum separation gap between adjacent buildings. This approach even though efficient, lacks elegance since the prescribed clearance may not always be available. Such a procedure is also characterized by uncertain levels of safety and does not allow explicit control over the pounding risk [8].

This highlights the need for advanced probabilistic methods to accurately estimate damage levels. Conventionally, seismic vulnerability is represented by either Damage Probability Matrices (DPMs) [9] or fragility curves. DPMs describe discrete relationships between damage and intensity measures whereas, fragility curves are continuous representations of the cumulative probability distributions of performance limits and prove to be useful tools for the estimation of the probability of structural damage.

The simplest and most straightforward method to obtain failure probabilities is the Monte-Carlo Simulation (MCS) technique. It is the most accurate methodology but is known to be computationally burdensome due to the substantial number of simulations it requires for probability estimation. Other efficient approaches to generate fragility curves within modern performance-based frameworks [10] such as the Probabilistic Seismic Demand Model (PSDM) [8] have also been developed and widely used [11-13]. A problem with the PSDM framework, however, is the homoscedasticity assumption associated with it. Such an assumption may lead to major disparities where the variance of error terms is not constant.

Hence, there appears to be a need to develop modern methods that maintain a higher level of coherence with the actual data. A simple meta-model based approach to do so is the use of response surface methodology (RSM) [14] which is particularly an efficient technique for representing multivariate responses. RSMs possess the distinct advantage of representing complex and implicit phenomena as simple polynomial expansions that are easier to work with. This study attempts to introduce the concept of response surface based fragility curve generation for the pounding risk of adjacent structures using High Dimensional Model Representation (HDMR). As a response surface meta-model, HDMR represents a large set of data in the form of simple closed-form multivariate polynomial equations. HDMR has been adopted in previous studies to develop seismic fragility curves [15, 16] with a prominent level of accuracy and minimal computational cost.

The present study adopts the nonlinear time history analyses (NLTHA) technique to simulate pounding effects on an eight-storey Reinforced Concrete Ordinary Moment Resisting Frame (RC-OMRF) against a shorter and stiffer three-storey RC frame. A series of 831 nonlinear dynamic analyses have been performed on this configuration using a suite of 20 real accelerograms for three initial separation distances, d_g = 0.0 cm, 5.5 cm, and 11.0 cm. The peak ground accelerations (PGAs) of the accelerograms have been scaled in the range between 0.005g and 0.7g. Displacement-based fragility curves have been generated using HDMR for the percentage maximum inter-storey drifts (IDR_{max}) at the level of Immediate Occupancy (IO) for PGA as the intensity measure (IM). These fragility curves have been compared with those obtained using MCS. Additionally, fragility curves have also been approximated for randomly chosen initial gaps of d_g = 2.6 cm and 6.1 cm to verify the validity of HDMR-based fragility curves in the estimation of failure probabilities for target separation distances.

The primary aim of this study is to introduce HDMR as a suitable, accurate and computationally efficient methodology to generate fragility curves for the mitigation of risks associated with the seismic pounding.

Overview of HDMR

HDMR is a response surface methodology describing a family of multivariate representations to capture the input-output relationships of complex high-dimensional systems with many input variables. This is an efficient technique that systematically reveals the hierarchical correlations amongst input random variables. The general foundations of HDMR were laid by Rabitz [17] and it has since been actively applied in various disciplines [18-20]. The meta-models obtained by using HDMR are not only simpler than the original complex and nonlinear systems but are also accurate and computationally efficient in the uncertainty analysis of the computationally burdensome models.

HDMR is a general set of quantitative model assessment and analysis tools for capturing the high dimensional relationships between sets of input-output variables [21]. Since the effects of input random variables may or may not be independent, for an N-dimensional vector of input variables $X = \{x_1,\ x_2,\ x_3, \dots\dots, x_N\}$, HDMR inherently expresses the output $f(x)$ as a hierarchical correlated expansion to account for the cooperative effects of all inputs. Generally, an HDMR expansion up to the second order (Eq. 1) is sufficient to describe output responses.

$$f(x) = f_0 + \sum_{i=1}^{N} f_i(x_i) + \sum_{i=1}^{N} \sum_{j=1}^{N} f_{ij}(x_i, x_j) \quad (1)$$

here, the constant term f_0 represents the mean response to $f(x)$, and $f_i(x_i)$ and $f_{ij}(x_i, x_j)$ represent the first and second-order terms of the HDMR expansion, respectively. The first-order term considers only the individual contribution of each input variable, while the cooperative effects of a pair of input variables are accounted for by the second-order term.

HDMR can be broadly classified into (1) ANOVA-HDMR; (2) Cut-HDMR [16]. Among these, the Cut-HDMR methodology has been adopted for this study. In Cut-HDMR, the convergence limit is invariant to the choice of reference point and thus, it returns exact results along the lines, planes, volumes etc. through and around the reference point $c = \{c_1,\ c_2,\ c_3, \dots\dots, c_N\}$ defined in the variable space. The expansion terms are determined using the following equations:

$$f_0 = f(c) \quad (2)$$

$$f_i(x_i) = f(x_i, c^i) - f_0 \quad (3)$$

$$f_{ij}(x_i, x_j) = f(x_i, x_j, c^i) - f_i(x_i) - f_j(x_j) - f_0 \quad (4)$$

In every higher-order term, the previous lower-order terms are subtracted. This is done to remove their dependence and provide a unique contribution from the new expansion function. Since the increment of the order of HDMR expansion makes it more computationally expensive than the previous, this study has been limited to the use of second-order HDMR expansion only.

Estimating HDMR-based fragility curves

The first task in estimating seismic fragility curves is to define the input and response variables. This is followed by choosing appropriate limit states corresponding to the chosen damage measure. For this study, the damage measure, or Engineering Demand Parameter (EDP) of IDR_{max} has been chosen as the output response while d_g, and the IM - PGA have been chosen as the input random variables. Aleatory uncertainties from earthquakes are implicitly accounted for by using a sufficiently large suite of real accelerograms.

Various combinations of input variables representing different scenarios of earthquake-structure interaction are generated. These serve as the sampling points for HDMR expansion. The mean and standard deviation for the ground motion records (20 records for this study) are calculated and meta-models are formulated by applying the HDMR technique. The polynomials so obtained can then be used for identifying reliability indices using FORM/SORM which will yield the failure probabilities.

Application: Pounding Risk of Adjacent Buildings

Structural Layout of the Building Frame: Fig. 1 (a) shows the details of the eight-storey RC-OMRF used for this study. Each storey is 3 m high and spans three 6 m wide bays. The supports are assumed to be fixed. The studied frame has been designed using the commercially available finite element software package CSI SAP2000 with two-dimensional beam and column elements. In addition to the self-weight of structural members, a live load of 18 kN/m has also been considered in the design of the frame. Nonlinear hinges have been provided at the possible locations of yielding. Nonlinear constitutive relations for concrete and steel have been defined, with concrete following the modified model of Mander *et al.* [22], and steel following the constitutive relation given in IS 456:2000 [23].

Damage and Intensity Measures: Fig. 1 (b) shows the examined case of the non-eccentric pounding of the flexible eight-storey RC-OMRF against a short and stiff three-storey RC frame with different storey heights. Uncertainties in system response are taken into account by using Fault Normal (FN) and Fault Parallel (FP) components of a suite of ten pairs of three-component ground motions extracted from the PEER NGA-West2 Database [24] for the target elastic response spectrum given in the Indian Standard Code IS 1893-1:2002 [25]. NLTHA using this suite of ground motion data provides the storey displacement records which have been used to evaluate the IDR_{max} for PGA values ranging between 0.005g and 0.7g. Thus, values of IDR_{max} and PGA serve as the EDP-IM pairs for the current study.

Performance Limit States: To indicate the level of structural distress, it is imperative to define performance limit states. Due to the non-ductile nature of the flexible frame studied, limit states for maximum storey drifts (θ_{LS}) defined by Ghobarah [26] have been found to be the most consistent. These limit states have been summarized in Table 1.

Table 1: *Limit States for various performance levels of IDR_{max}*

Limit State	ND	LD	IO	LS	CP
Damage Description	No Damage	Light Damage	Immediate Occupancy	Life Safety	Collapse Prevention
$\boldsymbol{\theta_{LS}}$(%)	0.1	0.2	0.5	0.8	1.0

This paper focuses on the fragility curves obtained for a threshold level of 0.5% storey drift corresponding to the performance level of IO only.

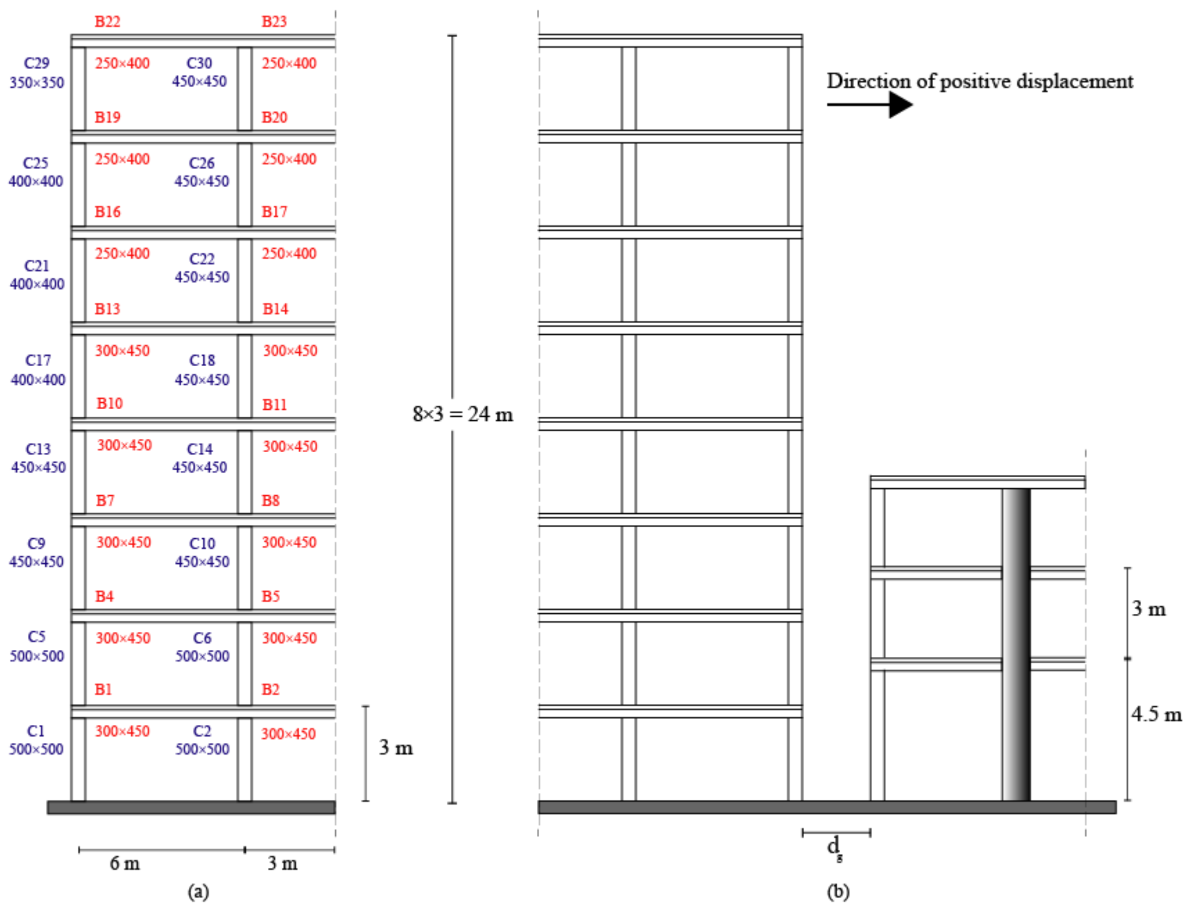

Figure 1: *(a) Skeletal Framework of the designed eight-storey RC-OMRF (b) Floor-to-Column Pounding Case under consideration*

Results

This section illustrates the seismic risk evaluation for the inter-storey pounding case demonstrated by Fig. 1(b). Risk estimates have been found for three initial separation gaps of (1) d_g = 0.0 cm (signifying direct contact of buildings built in tight spaces); (2) d_g = 5.5 cm (mean value of the minimum and maximum separation gaps considered); and (3) d_g = 11.0 cm (minimum recommended separation gap as per IS 1893-1: 2002). HDMR is employed to evaluate failure probabilities for IDR_{max} values exceeding the limit state of IO. These failure probabilities are used to develop failure fragility curves against the actual fragility curves obtained by applying MCS to the acquired dataset.

Fig. 2 shows the comparison of fragility curves obtained using HDMR with those obtained by using MCS. It is to be noted that the fragility curve obtained by using MCS gives the exact representation of failure probabilities, but is used only as a reference and not for fragility curve generation in general due to the high computational cost associated with it.

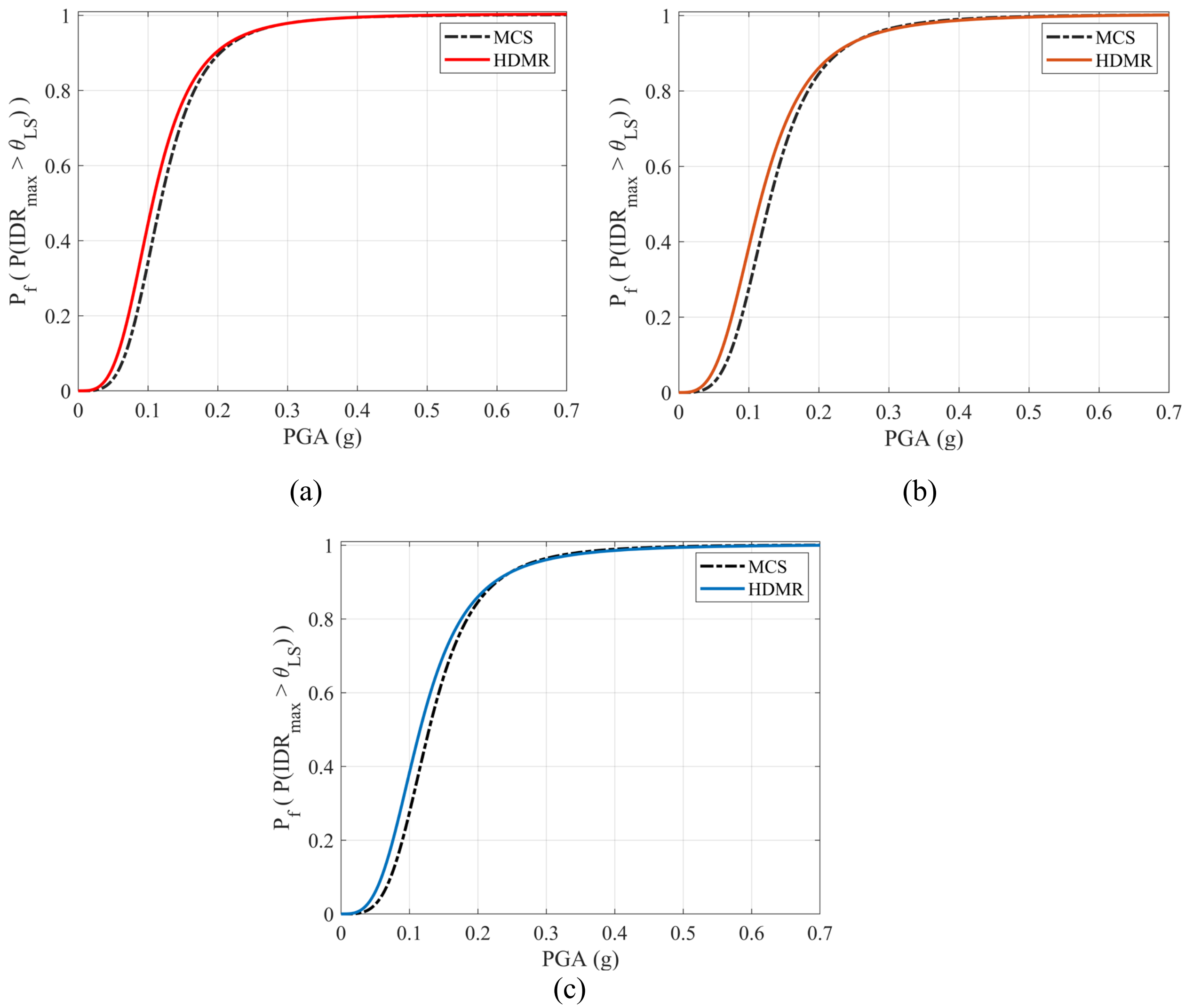

Figure 2: *Fragility Curves for IDR_{max} using HDMR vs MCS at separation distances (a) d_g = 0.0 cm, (b) d_g = 5.5 cm and (c) d_g = 11.0 cm*

From Fig. 2, it is clear that HDMR shows a remarkably close relationship with the actual probability data. For small values of PGA, the HDMR-based fragility curves not only lie close to the actual MCS-based failure probabilities displaying only slight overestimates but also continue with the same slope as their MCS counterpart until convergence. As an illustration of the estimation accuracy of HDMR, an error of only 5.46% was observed in the estimated failure probabilities at a PGA level of 0.1685g for d_g = 11 cm. For higher PGAs, HDMR-based fragility curves usually end up merging with the MCS data demonstrating a supreme level of accuracy. It thus proves to be an efficient tool to develop pounding-based seismic fragility curves.

Fig. 3 shows the comparison of HDMR-based fragility curves with their MCS counterparts for randomly chosen d_gs. This test in particular focuses on the fact that the recommended separation gap between adjacent buildings may not always be available, and that the field personnel will have to operate with whatever amount of space is available on site. Target separation gaps randomly chosen to be d_g = 2.6 cm and 6.1 cm were used to perform 554 simulations in addition to the 831 nonlinear dynamic analyses already performed. Structural responses obtained from the extra NLTHAs were used to develop actual fragility curves using MCS as shown in Fig. 3. However, instead of the data so obtained, the HDMR meta-model already formulated (from the previous 831 NLTHAs for separation gaps d_g = 0.0 cm, 5.5 cm, and 11.0 cm) was used to derive failure probabilities for the randomly selected target separation distances.

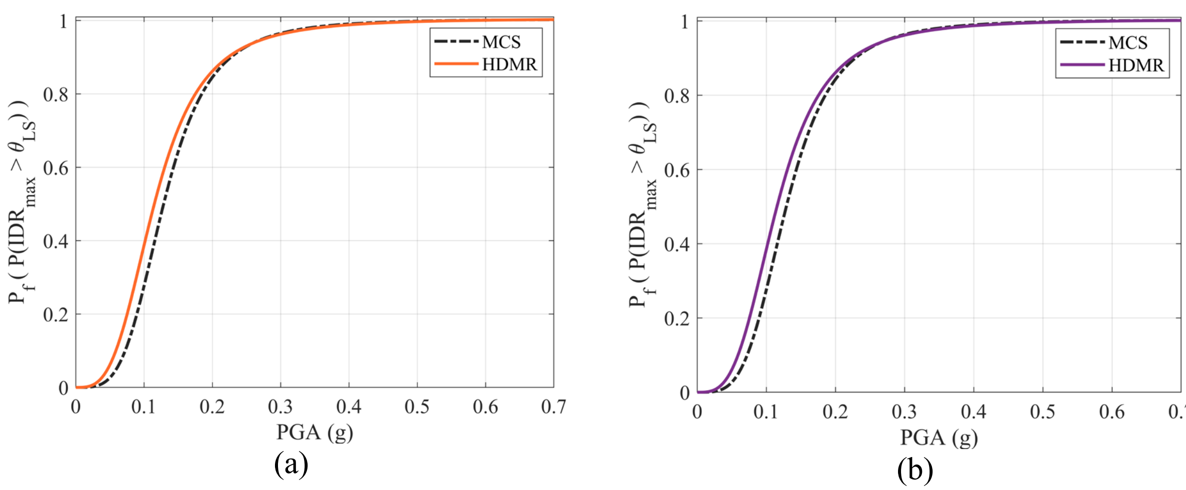

Figure 3: *Fragility Curves obtained for randomly chosen separation gaps (a) d_g = 2.6 cm, (b) d_g = 6.1 cm using HDMR (without performing simulations) vs MCS (after performing simulations)*

As expected, results for the randomly chosen d_gs showed similar trends as those for the separation distances for which NLTHAs were initially performed. For lower PGAs, HDMR-based fragility curves were again close to the actual failure probabilities and showed the same slope for most of the regime, beyond which, HDMR and MCS-based fragility curves began to converge. The use of HDMR thus saved 60% of computational effort. With a similar level of accuracy, the widely used PSDM model would have required either additional simulations or regression analysis to identify failure probabilities for target separation distances. With HDMR, it also becomes easier to include numerous variable characteristics affecting seismic responses in the same equation. This can be used to mitigate seismic risks related to pounding by estimating accurately the probabilities of failure for target separation distances in the pre-construction phases which can be utilized in reliability-based structural design for target failure probabilities.

Summary and Conclusions

This paper presents HDMR as an accurate and computationally efficient technique to assess the seismic vulnerability of adjacent structures subject to seismic pounding. This was the first time that this response surface methodology was used for the development of fragility curves for seismic pounding risks. The case study was based on a structural system consisting of an eight-storey RC-OMRF subject to floor-to-column structural pounding against a shorter and stiff three-storey RC frame. Displacement-based fragility curves (HDMR-based fragility curves were made against MCS-based fragility curves) for IDR_{max} were developed for the IM ranging between PGA values of 0.005g and 0.7g.

It was observed that fragility curves developed by using HDMR show a consistent level of efficiency and accuracy when compared with the actual probabilistic data obtained from MCS estimation. It was also observed that at low PGAs, the HDMR-based fragility curves showed errors as small as 5.46% and maintained nearly similar slopes as their MCS-based equivalents. Results established also implied that at higher levels of PGA, HDMR-based fragility curves tend to converge well with their MCS-based counterpart. Similar levels of accuracy and efficiency were obtained for randomly chosen separation distances within the range of the study. It was inferred that the use of HDMR eliminates the need to perform additional NLTHAs for target separation distances or to use regression techniques on the existing fragility curves to estimate failure probabilities for a target d_g. A 60% reduction in the computational effort was obtained for two randomly chosen target separation distances. It is proposed that due to such a level of accuracy, efficiency, and computational economy, HDMR can be used to obtain excellent fragility curves for the estimation of pounding risks. It is proposed that this method could be used for the determination of critical separation distances between adjacent building structures, as well as for performing the reliability-based design of buildings for actual on-site available separation spaces thereby mitigating pounding risks even in the pre-construction phases. The present study used only the separation distance between the adjacent structures and the peak ground acceleration of seismic excitations as the input random variables. Future studies could include a greater number of random parameters including real characteristics of the structural systems to extract a much higher accuracy out of the studied methodology. Future studies could also ponder upon the usage of HDMR for curvature-based fragility curve generation for local structural responses to establish an overall supremacy or limitation of the studied method.

References

[1] Anagnostopoulos, S. A. 1988. “Pounding of buildings in series during earthquakes.” Earthq. Eng. Struct. Dyn., 16 (3): 443–456. https://doi.org/10.1002/eqe.4290160311.

[2] Maison, B. F., and K. Kasai. 1990. “Analysis for a Type of Structural Pounding.” J. Struct. Eng., 116 (4): 957–977. https://doi.org/10.1061/(asce)0733-9445(1990)116:4(957).

[3] Polycarpou, P. C., and P. Komodromos. 2010. “Earthquake-induced poundings of a seismically isolated building with adjacent structures.” Eng. Struct., 32 (7): 1937–1951. Elsevier Ltd. https://doi.org/10.1016/j.engstruct.2010.03.011.

[4] Skrekas, P., A. Sextos, and A. Giaralis. 2014. “Influence of bi-directional seismic pounding on the inelastic demand distribution of three adjacent multi-storey R/C buildings.” Earthq. Struct., 6 (1): 71–87. https://doi.org/10.12989/eas.2014.6.1.071.

[5] Wolf, J. P., and P. E. Skrikerud. 1980. “Mutual pounding of adjacent structures during earthquakes.” Nucl. Eng. Des., 57 (2): 253–275. https://doi.org/10.1016/0029-5493(80)90106-5.

[6] Hideo Takabatake and Masaaki Yasui and Yoshihisa Nakagawa and Akiko, K. 2007. “Relaxation method for pounding action between adjacent buildings at expansion joint.” Pacific Conf. Earthq. Eng., (056): 1–6. https://doi.org/10.1002/eqe.2402.

[7] Tubaldi, E. 2011. “Dynamic behavior of adjacent buildings connected by linear viscous/viscoelastic dampers.” Struct. Control Heal. Monit., (May 2011). https://doi.org/10.1002/stc.1734.

[8] Tubaldi, E. and Freddi, F. and Barbato, M. 2007. “Probabilistic seismic demand model for pounding risk assessment.” Pacific Conf. Earthq. Eng., (056): 1–6. https://doi.org/10.1002/eqe.2725.

[9] Whitman, R. V, J. M. Biggs, J. E. Brennan, C. A. Cornell, R. L. de Neufville, and E. H.

Vanmarcke. 1975. “Seismic Design Decision Analysis.” J. Struct. Div., 101 (5): 1067–1084. https://doi.org/10.1061/JSDEAG.0004049.

[10] Porter, K. A. 2003. “An Overview of PEER’s Performance-Based Earthquake Engineering Methodology.” 9th Int. Conf. Appl. Stat. Probab. Civ. Eng., 273 (1995): 973–980.

[11] Gardoni, P., K. M. Mosalam, and A. Der Kiureghian. 2003. “Probabilistic seismic demand models and fragility estimates for RC bridges.” J. Earthq. Eng., 7: 79–106. https://doi.org/10.1080/13632460309350474.

[12] Ramamoorthy, S. K., P. Gardoni, and J. M. Bracci. 2006. “Probabilistic Demand Models and Fragility Curves for Reinforced Concrete Frames.” J. Struct. Eng., 132 (10): 1563–1572. https://doi.org/10.1061/(asce)0733-9445(2006)132:10(1563).

[13] Flenga, M. G., and M. J. Favvata. 2021. “Probabilistic seismic assessment of the pounding risk based on the local demands of a multistory RC frame structure.” Eng. Struct., 245 (July). https://doi.org/10.1016/j.engstruct.2021.112789.

[14] Box, G. E. P., and K. B. Wilson. 1951. “On the Experimental Attainment of Optimum Conditions.” J. R. Stat. Soc. Ser. B, 13 (1): 1–38. https://doi.org/10.1111/j.2517-6161.1951.tb00067.x.

[15] Bhasker, R., and A. Menon. 2022. “A seismic fragility model accounting for torsional irregularity in low-rise non-ductile RC moment-resisting frames.” Earthq. Eng. Struct. Dyn., 51 (4): 912–934. https://doi.org/10.1002/eqe.3597.

[16] Chowdhury, R., B. N. Rao, and A. M. Prasad. 2009. “High-dimensional model representation for structural reliability analysis.” (April 2008): 301–337. https://doi.org/10.1002/cnm.1118.

[17] Rabitz, H., and Ö. F. Aliş. 1999. “General foundations of high-dimensional model representations.” J. Math. Chem., 25 (2–3): 197–233. https://doi.org/10.1023/a:1019188517934.

[18] Rabitz, H., Ö. F. Aliş, J. Shorter, and K. Shim. 1999. “Efficient input-output model representations.” Comput. Phys. Commun., 117 (1): 11–20. https://doi.org/10.1016/S0010-4655(98)00152-0.

[19] Li, G., C. Rosenthal, and H. Rabitz. 2001a. “High dimensional model representations.” J. Phys. Chem. A, 105 (33): 1–26. https://doi.org/10.1021/jp010450t.

[20] Li, G., S. W. Wang, C. Rosenthal, and H. Rabitz. 2001b. “High dimensional model representations generated from low dimensional data samples. I. mp-Cut-HDMR.” J. Math. Chem., 30 (1): 1–30. https://doi.org/10.1023/A:1013172329778.

[21] V. U. Unnikrishnan, A. M. Prasad, and B. N. Rao. 2007. “Development of fragility curves using high-dimensional model representation.” Pacific Conf. Earthq. Eng., (056): 1–6. https://doi.org/10.1002/eqe.2214.

[22] Mander, J. B., M. J. N. Priestley, and R. Park. 1988. “Theoretical Strss-Strain Model for Confined Concrete.” J. Struct. Eng, 114 (8): 1804–1826.

[23] Bureau of Indian Standards New Delhi. 2000. “IS 456 - Plain and Reinforced Concrete - Code of Practice.” 1–114.

[24] PEER Ground Motion Database. 2011.

[25] Bureau of Indian Standards New Delhi. 2002. “IS 1893 Part 1 - Criteria for Earthquake Resistant Design of Structures - General Provisions and Buildings Part-1.” Bur. Indian Stand. New Delhi, Part 1 (1): 1–39.

[26] Ghobarah, A. 2004. “On drift limits associated with different damage levels.” Int. Work. performance-based Seism. Des. concepts Implement., (February): 321–332.