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Ground Motion Simulation Validation based on Loss Metrics

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Ground Motion Simulation Validation based on Loss Metrics

MASTER'S THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Civil Engineering

by

Poojitha Shashi

Thesis Committee:
Associate Professor Farzin Zareian, Chair
Adjunct Professor Farzad Naeim
Assistant Professor Anne Lemnitzer

2017

DEDICATION

To My Parents

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ABSTRACT OF THE THESIS

Ground Motion Simulation Validation based on Loss Metrics

By

Poojitha Shashi

Master of Science in Civil Engineering

University of California, Irvine, 2017

Associate Professor Farzin Zareian, Chair

The effect of the earthquake ground motion parameters on the probabilistic loss estimation of buildings is the major interest of this study. For the seismic performance assessment, real ground motion records from the past earthquakes are required. Estimation of repair costs in future earthquakes is the major component for seismic loss analysis. This study addresses the sensitivity of the statistical characteristics of ground motions contributing to the building loss. Among these characteristics are the ground-shaking intensity (Arias Intensity),duration,and frequency at the middle of strong-shaking phase of the ground motion. These parameters are vital in determining the seismic response of the building structure. A fine study on the sensitivity of the seismic response and corresponding loss of the building structure to ground motions model parameters is carried out using Performance-based Earthquake Engineering and Performance Assessment Computational Tool, respectively. But due to the scarcity of moderate to large earthquakes, the real records fail to match the required characteristics of motions, as there are insufficient set of data available for analysis to be carried out. Even, the of technique scaling ground motions results in overall unrealistic properties. This has led to the simulation of ground motions which will provide the additional and hopefully accurate predicted information on characteristics of the moderate to large earthquakes. Hence,a fully non-stationary stochastic model for strong earthquake ground motion model is considered which employs the statistical characteristics (waveform param-

eters) as model parameters matched with those of identified for a large sample of recorded ground motions for specified earthquake and site characteristics, to deliver simulated ground motions to examine the building loss metrics, which depends on the uncertainties in various analysis process starting from obtaining Intensity Measure (IM), Demand parameters (EDPs) to the repair cost estimates. From the predictive equations, specified earthquake and site characteristics results in the model parameters.

Further, the validity of simulated ground motion time series representing the real ground shaking during future earthquakes is a crucial step. This study employs the hybrid broadband ground motion simulation applied simulations to validate against the real records. With the help of hybrid approach, making use of wave propagation phenomena and site response characterization, effort has been taken for validation of these simulated ground motions is conducted for the sensitivity of seismic response and loss for these simulated ground motions.

Chapter 1

Introduction

1.1 Motivation

Seismic risk is one of the major concern for the engineers while designing structures. There is a need for determination of potential damage and seismic loss including the physical, economic and other casualties. Performance-based Earthquake Engineering (PBEE) deals with probabilistic methods to overcome this concern due to several uncertainties of the entity or building system prevailing during a seismic hazard. PBEE attempts to minimize the overall risk and life-cycle cost by considering the non-linear behavior and collapse of buildings during seismic events.

The seismic performance is assessed by considering the engineering demand parameters of earthquake ground motions. Identification of EDPs is important for estimating the probabilistic building loss. Due to shortage of recorded motions for many regions and design scenarios,input data are procured from database of ground motions recorded during past earthquakes, which are often modified to fit desired conditions. However, for many regions of the world and for many design scenarios of interest. This brings in inconsistency when the

ground motion parameters are scaled to large factors and cannot conform data for various combinations of source, fault type and other site characteristics. This has resulted in increase in the need for simulation methods ([26]) to bring them into engineering applications.
This research deals with determining the efficiency of the ground motion model used in validating the simulated ground motions against real records to address the issue of stability in simulation process and prove their equivalence with recorded ground motions, despite certain codes like ASCE 7-10(2010) allows the use of simulated motions for design purposes. One of the main difficulties faced in the seismic performance assessment due to the lack of real data is the determination of probable seismic loading that would be applied to the similar structures during an earthquake by the ground motions at various locations. Eventually this led to a major advancement in PBEE, the development of techniques to assemble ground motion prediction equations. Among the many designed predictions equations ([5]); ([6]), which are adequate only for linear response-spectrum, were proved not to be sufficient for the nonlinear response-history dynamic analysis as they do not provide the ground motion time-histories for specified design scenarios. To overcome this obstacle ([24]) designed ground motion prediction equations by fitting the site-based stochastic model to large data records taken from PEER NGA West Pacific Earthquake Engineering Research Center, Next Generation Attenuation of Ground Motions Project; see http://peer.berkeley.edu/smcat/) database. This approach deals with the relationship between the ground motion parameters and specified site characteristics.

Figure 1.1 illustrates the methodology adopted by PEER for PBEE. The various uncertainties in basic input Variables ([23]), involved in the process shown in the above figure explains the necessity of probability distribution in order to address the uncertainties. In order to assess the loss experienced by structures, root of uncertain variables goes down to the waveform parameters possessed by the ground motions namely the ground-shaking intensity, duration, time and frequency at middle of the strong shaking phase. In this study, the sensitivity of these parameters is determined on the response of structures to ground

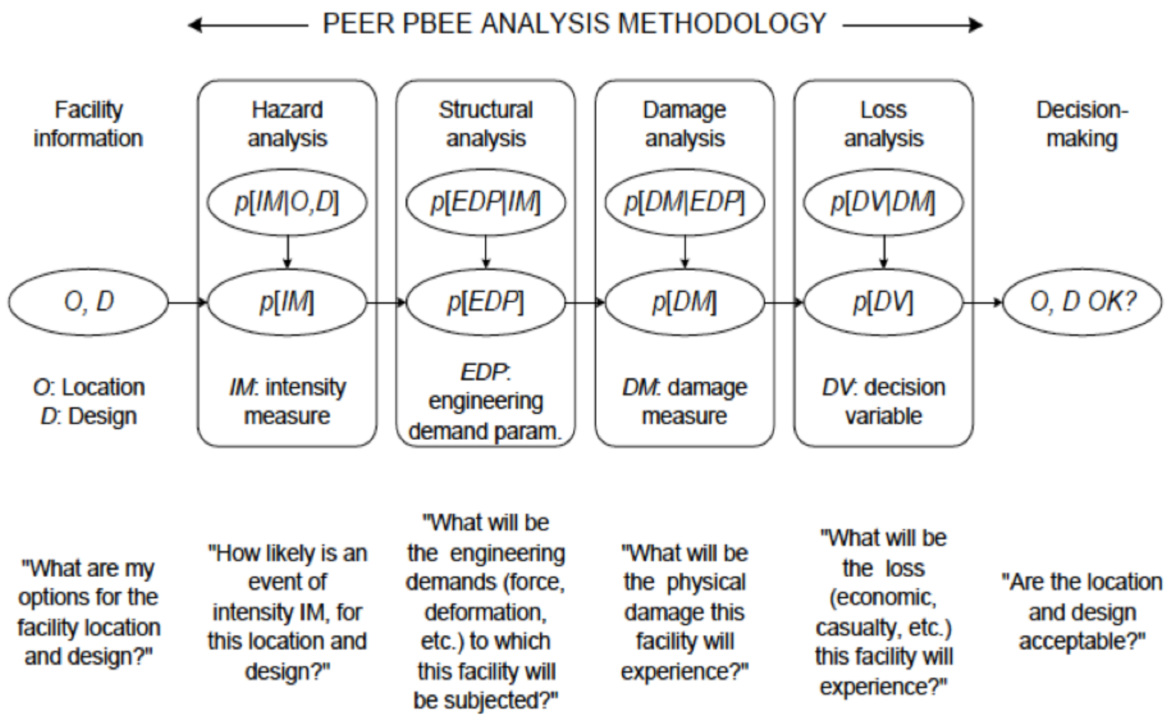

Figure 1.1: Procedure for Performance-Based Earthquake Engineering Analysis [23]

motions along with validating the sensitivity against real motions.

The effective measure of the ground motion model will be based on the loss metrics, i.e. the repair cost estimates by using (1) a stochastic model of earthquake ground motions that produces simulations by fitting the model parameters from predictive equations to the probability distribution of statistical characteristics to that of real ground motions with their respective parameters for specific earthquake and site characteristics. Since, the parameters such as Arias Intensity (AI), Duration of the motion (D), Frequency-mid ω_{mid} and Frequency slope have an impact on potential damage of the structure, the ground motions are simulated using a predictive equation ([24]) to identify the seismic loading. The approach developed here will be additional information on widening the engineering applications of simulation techniques in order to showcase a better representative of real ground motions in the future along with the previously determined methodologies

1.2 Literature Review

1.2.1 Ground Motion Models

The two different categories of ground motion models are source-based and site-based. Source-based models are those which depict the occurrence of fault ruptures at the source and propagation of the resulting seismic waves through the ground medium. Site-based models describe the ground motion for a specific site by fitting to a recorded motion with known earthquake and site characteristics. These models use vast amount of seismological principles to describe the source mechanism and wave travel path. This limits the use in regions where seismological data are scarce while increasing the need for simulated ground motions. Therefore, most of the engineers prefer site-based model over source-based models because site-based models involve the use of readily available information to the practising engineer. Among the few site-based stochastic ground motion model developed, the following models were reviewed for selection of model giving simulations matching the real ground motions.

1.Liu, SC([22]: The paper points out the importance of considering the effect the model on the vulnerable structural systems along with the matching of statistical characterizations of real-world random data with those of the model. Here, the statistical characterizations are provided by the joint probability distribution functions of the process conditioned on its duration and intensity. It employed ordinary power spectra and time-variable spectra as the base formulation for stationary and non-stationary processes. These spectra have been separated into three distinct phases treating them to be stationary showed that the input power to structures is provided by the midsection (time) of the motion. The power contained in the low-intensity fluctuations preceding and following this stationary portion is relatively small.

2.Conte, JP and Peng, BF [9]: The model proposed which is versatile and non-stationary stochastic ground motion model accounting for time-variation of both time and frequency domain reflecting the exact same of Recorded using the family of sigma-oscillatory processes. This approach is an extension of Thomsons (1982) consistent and high resolution, multiple window spectrum estimation method, aiming to estimate the evolutionary Power Spectral Density function of actual earthquake accelerogram. Based on the application examples, the model developed is able to capture very well the temporal variation of both the intensity and the frequency-content of real earthquake ground motions.

3. Rezaeian S, Der Kiureghian A (2008): A fully non-stationary stochastic model for strong earthquake ground motion is developed. The model employs filtering of a discretized white-noise process. Non stationary is achieved by time modulation of the intensity and varying filter properties. The formulation developed provides complete separation of temporal and spectral non-stationary characteristics of the ground motion. This results in the simpler, easy modeling and estimation of parameters. The model is fitted to target ground motions

by matching a set of statistical characteristics. Post-processing by a second filter results in zero residual velocity and improves the match to response spectral ordinates of long periods. (Copyright q 2008 John Wiley & Sons, Ltd).

The discussion and experimental work in determining the Loss, the uncertainties of variable that is incurred in every component from Ground motion, Building Structure and occupancy needs to be addressed. The below mentioned explains this concept:

4.[23]: The reduction in the uncertainties of the variables of earthquake performance is necessary to reduce the repair cost resulting through the seismic performance assessment. The uncertain variables considered are the building mass, ground motion intensity, Viscous damping, capacity of building assemblies to resist damage, unit and overhead costs. The methodology adopted by the PEERS Performance-based earthquake engineering is addressed in determining the most sensitive uncertain variables contributing to the damage state. The relationship between the facility information of Location to design, Intensity measures, Engineer Demand parameters, damage analysis and Loss analysis is discussed in order to make decision-making easier for the practising engineer.

1.3 Objective and Scope of the Study

The two main objectives of the research described in this study are:

1. Identify sensitivity of the loss metrics to waveform parameters. 2. Validation of the Broadband ground motion model used for simulation.

The results will be helpful in determining the most important factor to be taken care of about the ground motion waveform, which effects the structural response, in order to avoid total damage and design efficiently. The repair costs provide the estimation of loss that can occur for a design scenario, which in turn helps in minimizing the life-cycle cost and gives better way of understanding the behaviour of the structure so as to avoid damage and hence the losses. Secondly, the extent to which the Broadband based ground motion model is reliable based on the seismic response observed paves way for further development of efficient models.

Chapter 2

Stochastic Ground Motion Model

2.1 Introduction

In past years, different types of ground motion models have been developed using random processes. One such model is developed by [24]. In this model, earthquake ground motion acceleration is considered as a filtered white-noise process, i.e., a process which is obtained when white-noise process is passed through a filter. Earlier, the models were built based on the filtered white-noise process such as [2] and [27] to achieve temporal non-stationarity have time-invariant frequency content giving rise to other types of stochastic models namely [21]; [19]; [12] based on filtered Poisson processes and goal match various forms of spectral accelerations became very popular. But the drawback of these models were that, they are complicated and cumbersome to simulate for engineers, as they would not have details regarding the seismic inputs required. Hence, a fully non-stationary model was developed.
A fully non-stationary stochastic model is one which reflects the real motion by completely representing its non-stationary characteristics in both time and frequency domains. This study uses the stochastic model developed by ([26]). This model is based out of filtered

white-noise process with time-varying parameters relating the features of the motions such as evolving intensity, duration and frequency content. The model parameters are identified by fitting statistical characteristics of the model to those of real time-series. Along with this model, the predictive equations are designed (1) which allows the generation of suite of synthetic ground motions for specified site characteristics of the earthquake.

2.2 Description of the Ground Motion Model

As mentioned above, for the work carried out in this paper, stochastic model developed in ([24]) is used. This model is representation of both temporal and spectral non-stationary characteristics of the motion. The temporal non-stationarity relates to variation in intensity of the motion in time and spectral non-stationarity represents the time-varying frequency content. The simulation process generates the ground accelerations in terms of filtered white-noise process obtained by the response of linear filter with time-varying parameters to white-noise excitation. Equation 2.1 , gives the formulation for the model.

$$x(t) = q(\alpha, t)[\frac{1}{\sigma_f(t)} \int_{-\infty}^{t} h[t-\tau, \lambda(\tau)]w(\tau)d\tau] \tag{2.1}$$

The parameters $\alpha = \alpha_1, \alpha_2$ are shape modulating functions and control the intensity. It is related to the physical characteristics of an accelerogram. It combines I_a, D_{5-95}, t_{mid} variables , where I_a represents Arias Intensity, a measure of total energy,

$$I_a = \int_0^{t_n} a(t)^2 dt \tag{2.2}$$

Here, a(t) is the recorded acceleration time history, D_{5-95} represents a measure of the effective duration of the motion , which is defined as the time interval between the time of ground motion reaching 5% and 95% of the Arias Intensity. And, t_mid is the time at the middle of the strong shaking phase which is assumed to be 45% level of Arias Intensity. The parameters $\lambda(t)$ are time-varying filter frequency, $\omega_f(\tau)$, and damping ratio which control the evolutionary predominant frequency and bandwidth of the process. In this paper, to achieve the objective mentioned in section 1.3, this ground motion model has been incorporated which is defined by the statistical characteristics of the ground motion. This is an appropriate model which addresses the need for simulation technique using earthquake and site characteristics and also, provides relevant information and results required for this study.

2.3 Evaluation of Model Parameters for Specified Earthquake and Site Characteristics

A set of recorded ground motions are taken from the strong motion database which includes small subset of PEER NGA database and a subset of the data used in the development if the CB-NGA ([7]) model.([7]) to develop a fitted probability distribution for each model parameter upon statistical analysis. Subsequently, a predictive relationship is constructed for the model parameters as shown in Equation 2.3([25].

$$\Phi^{-1}[F_p(p)] = \beta_0 + \beta_1(F) + \beta_2(\frac{M}{7.0}) + \beta_3(\ln\frac{R_{rup}}{25km}) + \beta_4(\ln\frac{V_{s30}}{750m/s}) + \eta + \varepsilon, \tag{2.3}$$

if $p = I_{a,major}, I_{a,int}$

$$\Phi^{-1}[F_p(p)] = \beta_0 + \beta_1(F) + \beta_2(\frac{M}{7.0}) + \beta_3(\frac{R_{rup}}{25km}) + \beta_4(\ln\frac{V_{s30}}{750m/s}) + \eta + \varepsilon, \tag{2.4}$$

if p = D_{5-95} , t_{mid}, ω_{mid}, $\omega^{'}$, ξ_f

For the specified design scenarios, model parameters are determined using these equations and simulated ground motion accelerations are produced by using this stochastic ground motion model which is employs all the correlations and errors. In this study, chapter 4 explains the complete analysis and explains the results for the same.

Chapter 3

Broadband ground motion-simulation(Hybrid Approach)

3.1 Introduction

To address the issue of availability of only small subsets of possible earthquake records with high magnnitude and small distance, several methods have been proposed to generate simulated ground motions. These methods are utilized to achieve the goal of matching the waveform characteristics of simulated ground motions to that of real motions. One among the many, is hybrid broad approach by ([15] that is based on wave propagation phenomena, fault rupture processes and site response characteristics coupled with high computational power of the technology to generate large-scale simulated ground motions(graves). It is consists of work based out of the concepts ([18] and [20]; [3];[17]) which explains the summing of small-scale recorded ground motions summation , stochastic representation of source and wave path and combinations of various other approaches respectively.

3.2 Methodology

The hybrid approach is the combination of deterministic low-frequency (f ¡ 1 Hz) with high-frequency stochastic simulation (f ¿ 1 Hz) through a matching filter. The low frequency is representation of wave propagation effects and fault rupture; and high frequency is stochastic representation comprising of scattering effects. This methodology is based on frequency of ground motions and one of the important significance of this model is the use of site amplification factor based on V_{s30} , as V_{s30} is readily available for most of the regions. It is simple kinematic representation of slip distribution and rupture velocity on the fault surface.

- Determinitic Metholody (f $<$ 1 Hz)

  This portion of the simulation consists kinematic representation of heterogeneous rupture on a finite fault which employs factors such as Slip amplitude and rake, rupture time, Slip function.

  Rupture Initiation Time is determined using the following equation ,

$$T_i = \frac{r}{V_r} - dt(D) \tag{3.1}$$

V_r=80 % local V_s ; depth ¿ 8 km

V_r = 56% local V_s ; depth ¡ 5 km

Here, dt scales with local slip (D) to accelerate or decelerate rupture

dt(D_{avg}) = 0

where R is the rupture path length from hypocenter to a given point on the fault surface, V_r is the rupture velocity and ∂t is a timing pertubation that scales linearly with slip amplitude such that $\partial t = \partial t_0$ where slip is at its maximum and ∂t_0 where the slip is at average slip value.

Rise Time-

t = k.$D^(1/S)$ for depth > 8 km

= 2.k.$D^(1/2)$ for depth < 5 km

The scales with square root of local slip (D) with constant (k) average rise time is given by the Somerville (1999,2009).

- Stochastic Methodology (f > 1 Hz)

  The high frequency simulation methodology is a stochastic approach that sums the response for each subfault assuming a random phase, an omega-squared source spectrum and simplified Greens functions.Extension of Boore(1983;[3]) with limited kinematic representation.

  Beresnev ([1]) define a radiation-strength factor (s), which is used as a free parameter in the specification of the subfault corner frequency (f_c)

$$f_c = s.z\frac{V_r}{\pi.dl} \tag{3.2}$$

where z is a scaling factor relating fc to the rise time of the subfault source. In our approach, instead of allowing this to be a free parameter

Site Specific Amplification Factors -

Borcherdt([4]) derived empirically based amplification functions for use in converting response spectra from one site condition to a different site condition. The general form of these functions is given by

$$F_x = \frac{V_{site}}{V_{ref}}^{m_x} \tag{3.3}$$

where V_{site} is the 30 m travel-time averaged shear wave velocity (V_{s30}) at the site of interest, V_{ref} is the corresponding velocity measure at a reference site where the ground response is known, and m_x is an empirically determined factor.

In practice, these amplification functions are applied to the amplitude of the Fourier transformed simulated time histories and individual responses are combined into broadband response using a set of matched butterworth filters.

Chapter 4

Seismic Performance Assessment of Buildings

4.1 Introduction

Engineers, in recent years have raised their concern over the performance of buildings during seismic hazard and its serviceability during such events. The typical design code provisions consider only some level of safety from seismic hazards. Therefore, to achieve the desired performance of buildings or to safe guard the existing buildings, Performance-based seismic design procedures are developed by Federal Emergency Management Agency (FEMA), ASCE/SEI 41-06, [8], [10]. Performance is expressed in terms of series of discrete performance levels including Operational, Immediate, Life Safety and Collapse Prevention. These performance-based process considers both structural and non-structural components for the hazard level assessment.

For this study, the performance assessment employs, (1) location and characteristics of site, (2) building size, configuration and occupancy, (3) structural system type, configuration, strength, and stiffness; and (4) type, location, and character of finishes and non-structural systems. Basically, Performance assessment is the process used to determine the performance capability of any given building design. It is a means of quantifying the consequences associated with the response of a building to earthquake shaking in terms that are intended to be meaningful to decision-makers. The assessment involves the structural analyses to predict building response to earthquake hazards and determine the probable consequences of that damage.

Performance is expressed as the probable damage and resulting consequences associated with following measures: (1) Casualties Loss of life, or serious injury (2) Repair Cost The cost(in dollars) necessary to restore a building to its pre-earthquake condition, the total loss (3) Repair time The time, in weeks, necessary to repair a damaged building to its pre-earthquake condition (4) Unsafe placarding A post-earthquake inspection rating that deems a building, or portion of a building, damaged to the point that entry, use, or occupancy poses immediate risk to safety. The performance predicted are in form of probable impacts, considering inherent uncertainties.

4.2 Methodology

The flowchart in Figure 4.1 represents the relationship between each step taking pace in performance assessment methodology. For this study, every step is conducted by considering the applicable and relevant information.

Firstly, the data of the building assets at risk and exposed to seismic hazards are collected for establishing performance model. This includes defining of structural components and assemblies, Nonstructural components and occupancy of the building. The information includes the type of damage in terms of risk to human life, repair methods, repair costs, repair time and post-earthquake occupancy due to unsafe placarding. In this study, building model

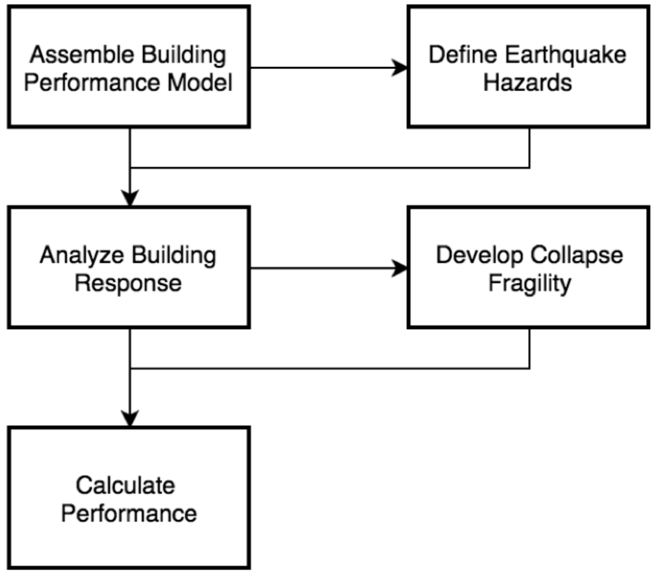

Figure 4.1: Methodology adopted by Performance Assessment Computational Tool

considered is that of 8-Story special moment-resisting frame Laboratory Building located in Sacramento, California. Next step is defining the Earthquake hazards which quantifies the intensity of effects of horizontal ground shaking. The hazards depend on types of assessment and the type of structural analysis used to quantify the seismic response of the building. In this case, the type of assessment is scenario-based as the magnitude and distance from the site-to-source is defined. Following this step, is the structural analysis which predicts the response of building to ground shaking in the form story drifts and Peak floor acceleration. Analysis produces estimated median values of structural response parameters. For the analysis of this building model, nonlinear response-history analysis is carried out as it can be used for any structure, any ground shaking intensity and generated sets of demands, Story Drifts and Peak Floor Accelerations. Non-linear analysis at multiple intensity levels ranging from the low to high intensities that cause collapse.

Lastly, collapse fragilities are established by combining the structural analysis and judgement, to assess the potential casualties. Collapse fragility represents the probability of structural collapse as function of ground motion intensity along with the modes of collapse possible in the building, where in probability of occurrence of collapse in each mode, the extent of collapse in each mode at each story and the probabilities that people occupying the areas of potential collapse will experience serious injuries is described.

4.2.1 Scenario-Based Assessment

This type of assessment evaluates the probable performance of the building assuming that it is subjected to an earthquake scenario consisting of specific magnitude occurring at specific locations relative to buildings site. Ground shaking intensity is represented by acceleration response spectra for specified magnitude-distance pairs using attenuation relationships. Since, this study involves the stochastic model and simulation is based on the specified earthquake and site characteristics, scenario-based assessment is selected. It is usually used to assess the performance of the buildings in the event of a future occurrence of earthquake. Scenario-based assessments consider uncertainty in the intensity of earthquake shaking, given that the scenario occurs and that the probable performance is conditioned on the occurrence of the specified earthquake scenario. Therefore, the selection is justified. The magnitude and site-to-source distance is defined during collection of ground motions for the analysis. Along with these,period of ground motion and ground motion prediction equation is used to scale the suites of ground motions required to obtain valid estimates of median response.

4.3 Calculation of Performance

The procedures used involves numerous and data-intensive for systems as complex as real buildings, hence Performance Assessment Calculation Tool (PACT) developed by FEMA, is used that performs all the steps mentioned above by repetitive calculations and manage data.

For the calculation of loss, this assessment process uses Monte Carlo procedure to account for various uncertainties inherent in factors affecting seismic performance including the following, but not limited to the intensity of ground shaking, vulnerability of building components and systems, the number of people within the building arena when earthquake occurs. Also, this is a highly repetitive process in which building performance is calculated for each of large number of ground motions. Each realization represents one possible performance outcome for the buildings. The assessment carried out includes generation of simulated demands, assessment of collapse, determination of damage and computation of losses in the form of casualties, repair cost and repair time, and unsafe placarding. Figure 4.2 shows the flowchart illustrating the performance calculation process for scenario-based assessments.

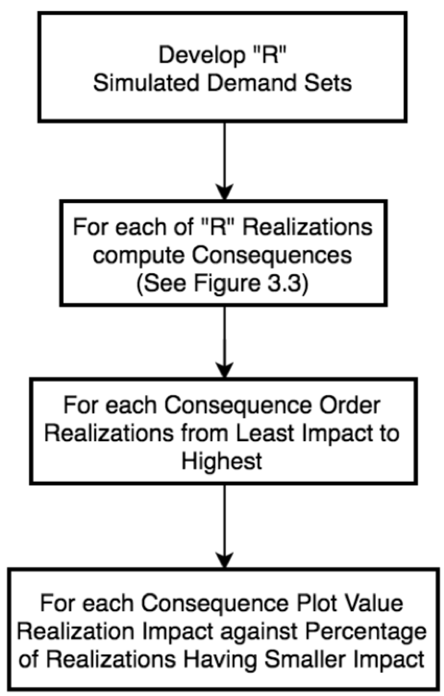

Figure 4.2: Performance Assessment Calculation Process Flowchart

The process is initiated with determining total number of realizations available and/or required for the analysis by nonlinear response history analysis, statistical distribution of initial demand sets from a series of building responses states for the specified intensity of motion

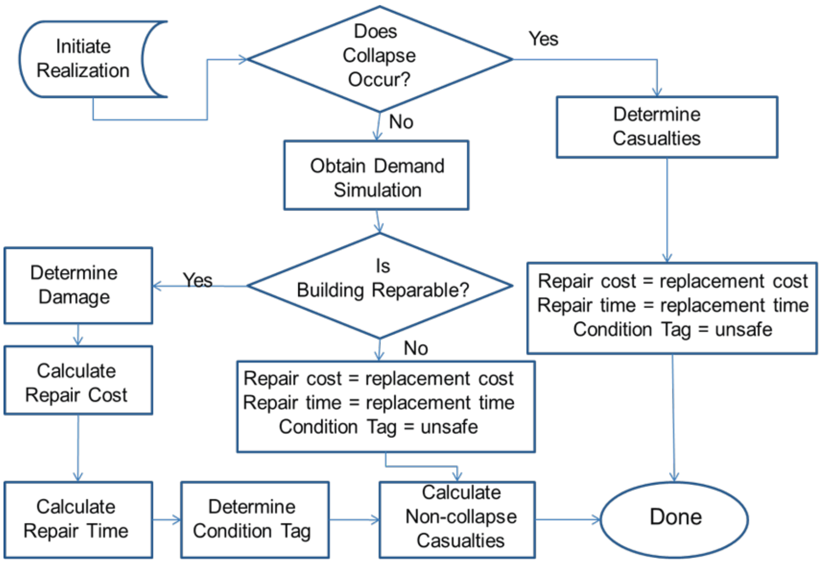

Figure 4.3: Flowchart for Assessing a Performance Outcome in each Realization [14]

is obtained. Resulting values are assembled into vectors of each demand parameter (Inter Story drift and Peak Floor Acceleration). Simulation reflects the correlation between the various response quantities predicted in analysis, uncertainties associated with the spectral content. In this study, No collapse condition is considered The demand sets obtained is used to evaluate the damage state and consequences associated with that damage is computed. The understanding of procedures and nature of losses obtained for this study can be further gained by [14].

Chapter 5

Sensitivity of Seismic Response and Loss to Ground Motion Model Parameters

5.1 Introduction

Performance-Based Earthquake Engineering attempts to minimize the risk and life-cycle cost by considering the seismic hazards and behavior of structure, as the conventional building design codes provide criteria only for minimum safety and serviceability requirements. In this study, the interest is to analyze the effect of the ground motion model parameters on seismic response of the building and its corresponding probabilistic loss. The loss analysis is conducted according to guidelines of Federal Emergency Management Agency(FEMA). According to Chapter 3, the procedure shows that performance assessment is based on the engineering demand parameters which makes loss dependent on the seismic response. The basic understanding of this concept will help in a proper structural design and analysis accounting for sufficient strength and ductility under the influence of earthquakes must be considered to assure the structural safety. In order to meet this goal, the database of ground motions from past earthquakes, which undergoes modifications to fit for the desired conditions is utilized. But, there are constraints in following this method of procurement of data for seismic analysis because of the sparsity or inadequate data available for several particular locations across the globe. Subsequently, the need for alternative comes into picture. One is to use the scaled ground motions derived by altering the frequency contents to achieve the desired characteristics. But the major concern is the validity of these approaches, the scaled motions may not accurately match with the real records. This leads to second and much better alternative of generation of synthetic ground motions. Therefore, both the real motions and simulated ground motions using stochastic ground motion model([11]) is employed in this paper.

Meanwhile, loss analysis is performed using PACT with the two engineering demand parameters, inter story drift ratio defined as the lateral displacement between two consecutive floors normalized by the inter story height and the building and Peak floor acceleration. This study of sensitivity and efficiency of ground motion simulation model in terms of potential damage to the building and waveform parameters sets a step closer in bringing the results of simulation process equivalent to that of real motions, making it easier for the simulators and engineers to understand the methodologies.

The waveform parameters considered are, Arias Intensity (I_a), Duration (D), Mid-frequency and rate of change of intensity (I_a/D). Correlation analysis from ([25]) is used for this study to determine the marginal probability distribution of three parameters conditioned on one parameter. Now, upon generation of simulated motions using the stochastic model, the loss is estimated using PACT and the results are analysed. The effect of the four parameters on structural response is analysed. This provides the verification of nature of mid-frequency and its role in the structural response.

5.2 Model Structures

In this research work, two types of buildings considered are:

- Model-1: 8-Story Research Laboratory Building situated in Sacramento, CA with Special Moment Frame system; Period of the building, T = 1.83 sec (Long Period)
- Model-2: 2-Story Research Laboratory Building situated in Sacramento, CA with Special Moment Frame System; Period of the building, T = 0.91 sec (Short Period)

Both the configurations are designed in accordance with requirements based on strength criteria and drift criteria. Response Spectrum Analysis (RSA) is the procedure employed.([28])

5.3 Assessment of Sensitivity Using Recorded Ground Motions

A set of recorded ground motions taken from the NGA database for specified design scenario: Magnitude of range 6.0-8.0, Rupture length: 20-30 m/s and V_{s30}: 20 m/s-1000 m/s and strike-slip. A total of 148 pairs of ground motions were collected. The Model-1 building response was analyzed for these ground motions accelerations by non-linear time history analysis. The resulting EDPs, inter story drift ratio and Peak Floor accelerations were then used in stochastic performance assessment framework to determine the damage measure, which describes the consequences of damage to the structure or to a component of the structural and/or non-structural system. Therefore, the loss analysis was conducted using PACT (refer chapter 3). The results obtained are shown below from Figure 5.1 through Figure 5.8. These observations illustrate that (1) The loss increases along with the increase in model parameters: Arias Intensity, Duration, (Arias Intensity/Duration). (2) Similar trend is shown with respect to EDP as well for same three model parameters as mentioned above. (3) ω_{mid} shows a different trend than the rest of the parameters. There is a decrease in the loss and EDP as the mid-frequency increases.

A conclusion can be drawn that, the variability in the loss is due to variability in the EDP. The EDPs considered for this study are inter story drift ratio and Peak Floor Acceleration. However due to small values of PFA, most of the loss was distributes by Story Drift.Hence, relationship between structural analysis and loss analysis is relatively linear. If there is an increase in the drift, consequently there is an increase seen in the corresponding loss for these ground motions, i.e. the sensitivity of seismic response is similar to that of seismic loss to the ground motion model parameters. Since, the trend observed for ω_{mid} is different when compared to the rest of the parameters. There is a need to understand in detail the of role of ω_{mid} on structural behavior and reason behind that type of trend obtained. Further detailed study about ω_{mid} is explained in following section.

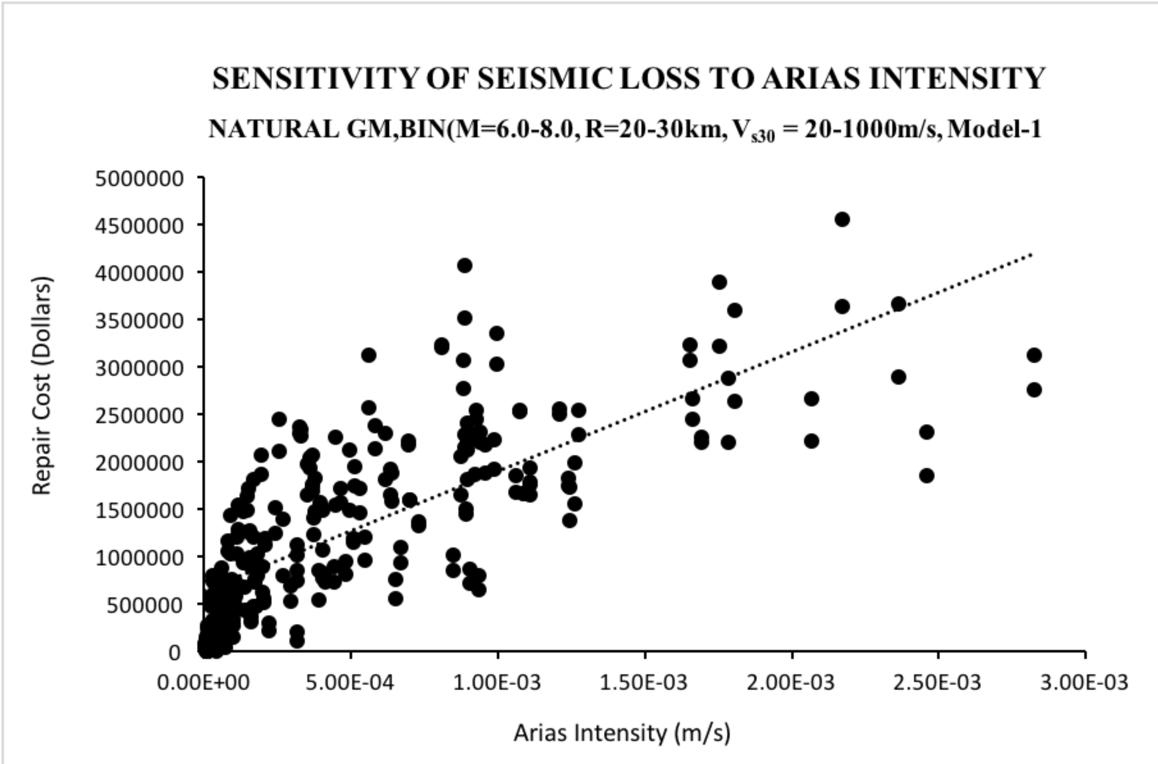

Figure 5.1: Sensitivity of Seismic Loss to Arias Intensity

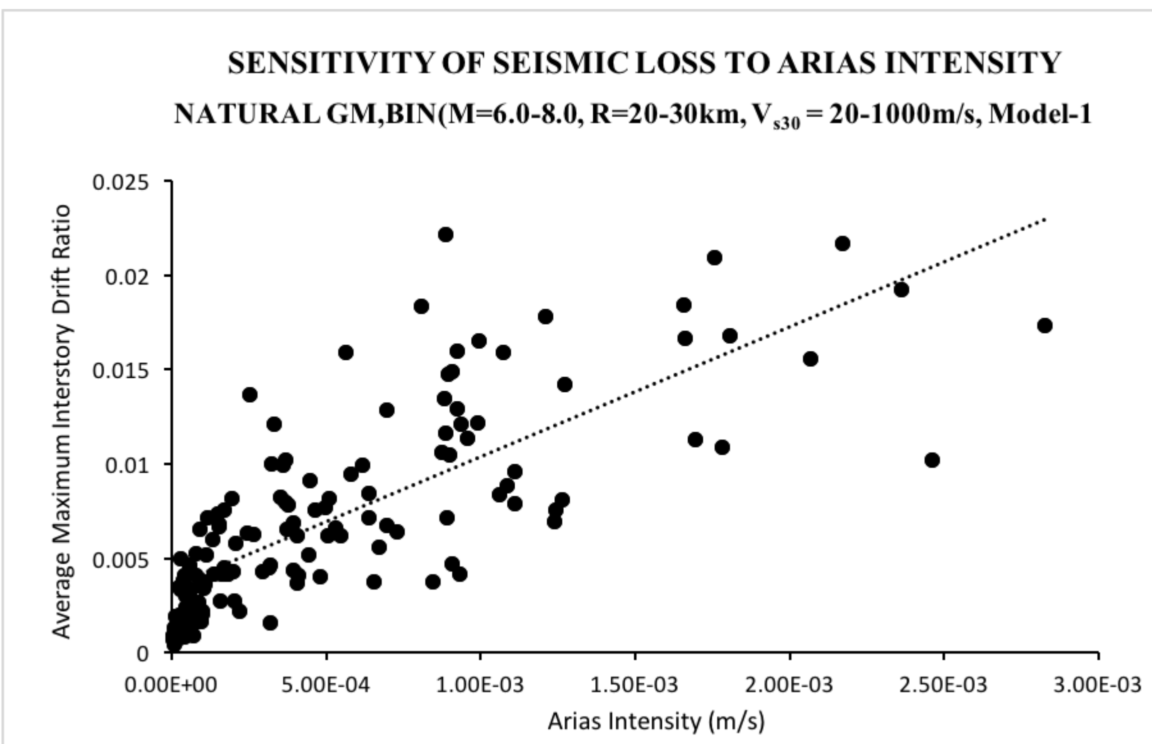

Figure 5.2: Sensitivity of EDP to Arias Intensity

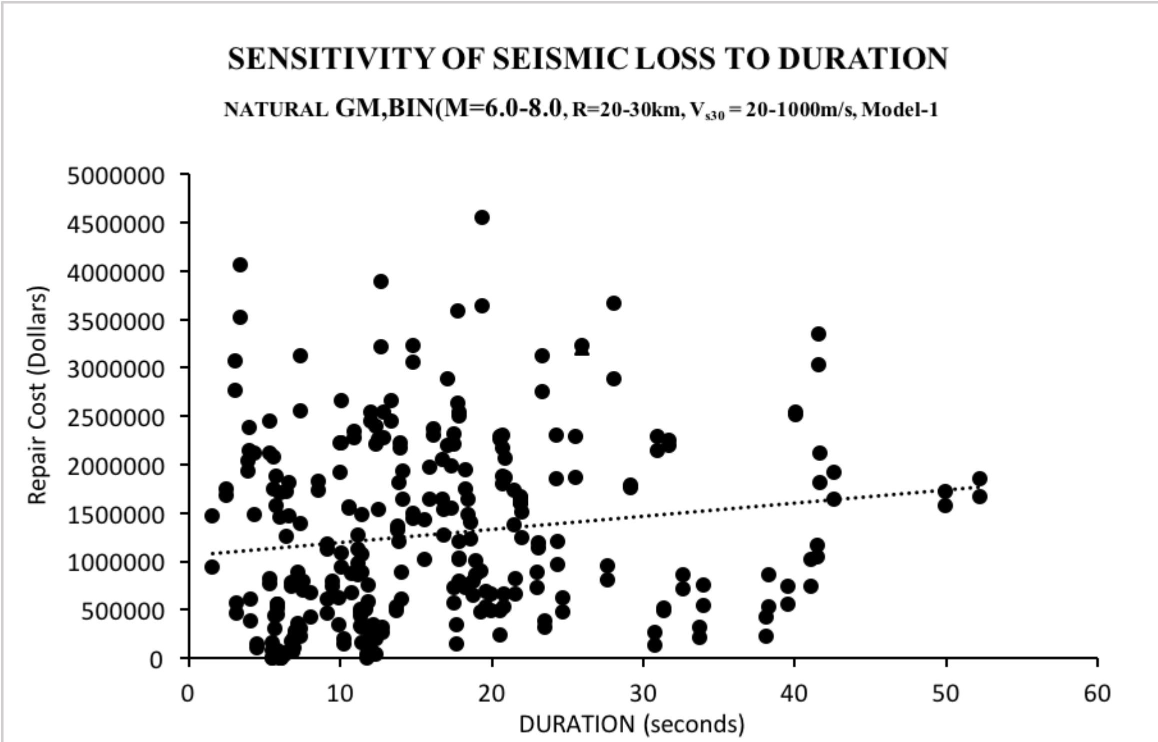

Figure 5.3: Sensitivity of Seismic Loss to Duration

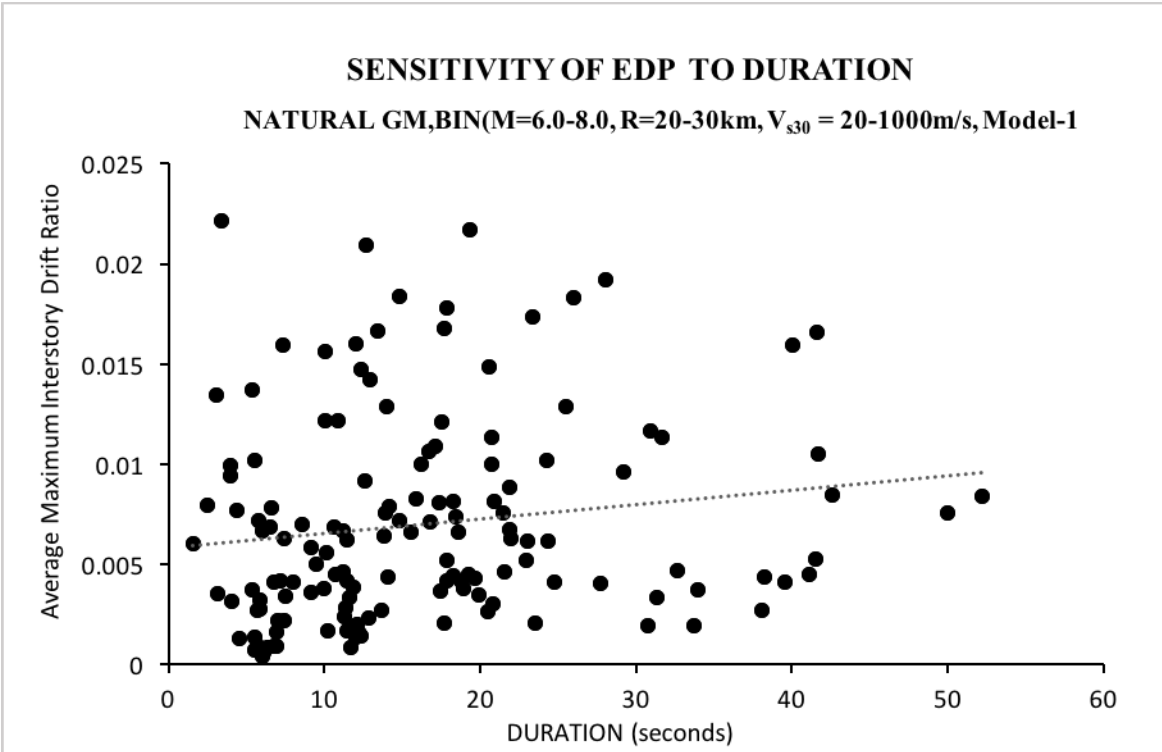

Figure 5.4: Sensitivity of EDP to Duration

5.4 Identification of Conditional Probability Distribution

As discussed in the above section, the sensitivity of parameter ω_{mid} is of interest. But, the experiment was carried out using a set of ground motions taken from the database are those which are already recorded, it is not possible to find ground motions with constant values of ω_{mid}. This is due to the lack of number of recorded motions available. To address this issue, simulated ground motions are utilized at this point of the study. To generate these simulations for design scenario matching to that of recorded motions (Section 4.3), stochastic ground motion model (refer Chapter 2) is used but with the conditional probability distribution instead of normal probability distribution of the model parameters to fit them after predicted by the empirical equation 2.3.

Considering the statistical analysis on the four parameters (Arias Intensity (I_a, Duration,

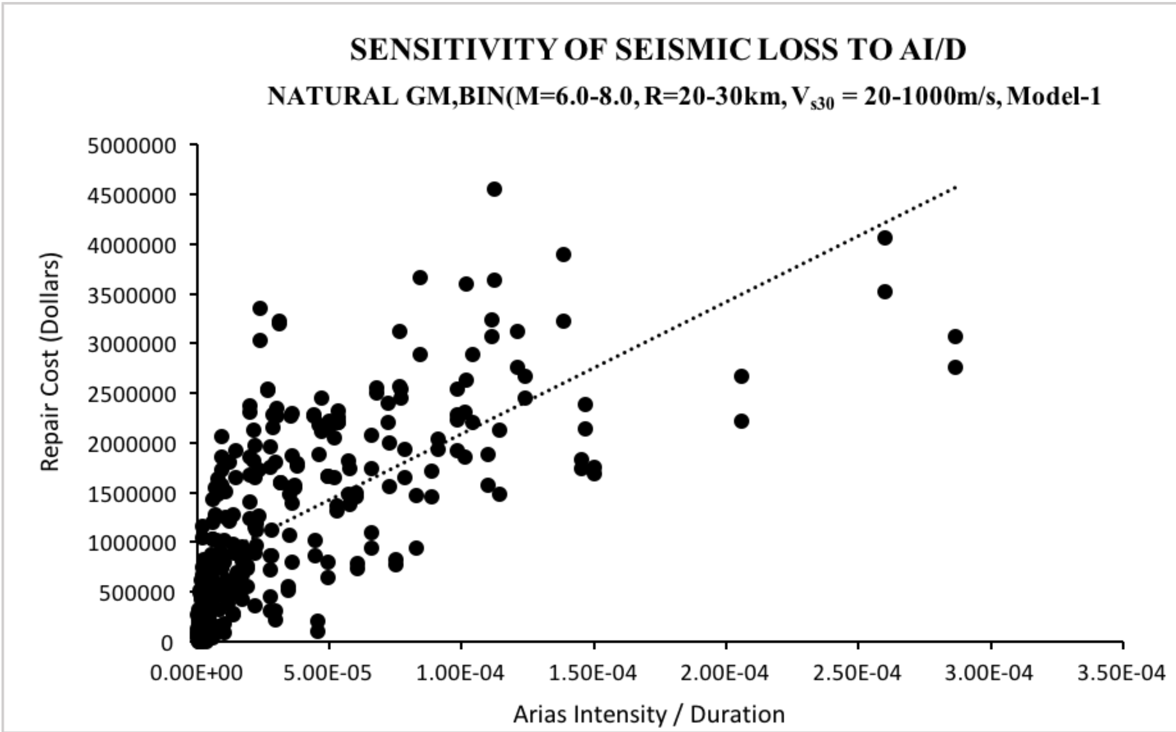

Figure 5.5: Sensitivity of Seismic Loss to I_a/D

Mid-frequency , I_a/D) by [25], the conditional probability can be derived. In this particular analysis, a database of ground motion from Pacific Earthquake Research Centre: Next Generation Attenuation (PEER NGA) and Campbell-Bozorgnia NGA ([7]). A total of 31 pairs of horizontal components from 12 earthquakes with strike-slip fault types, and 72 pairs of horizontal components from 7 earthquakes with reverse faults. For each ground motion, one set of these four parameters are identified and statistical characteristics, such as minimum and maximum, mean and standard deviation, and the fitting distribution for the data are generated.

To derive the mean and standard deviation of the conditional probability distribution for multivariate normal distribution, ([13]), provides the equations 5.2 and 5.3 respectively. Here,

$$Z = \begin{bmatrix} Y \\ X \end{bmatrix} \tag{5.1}$$

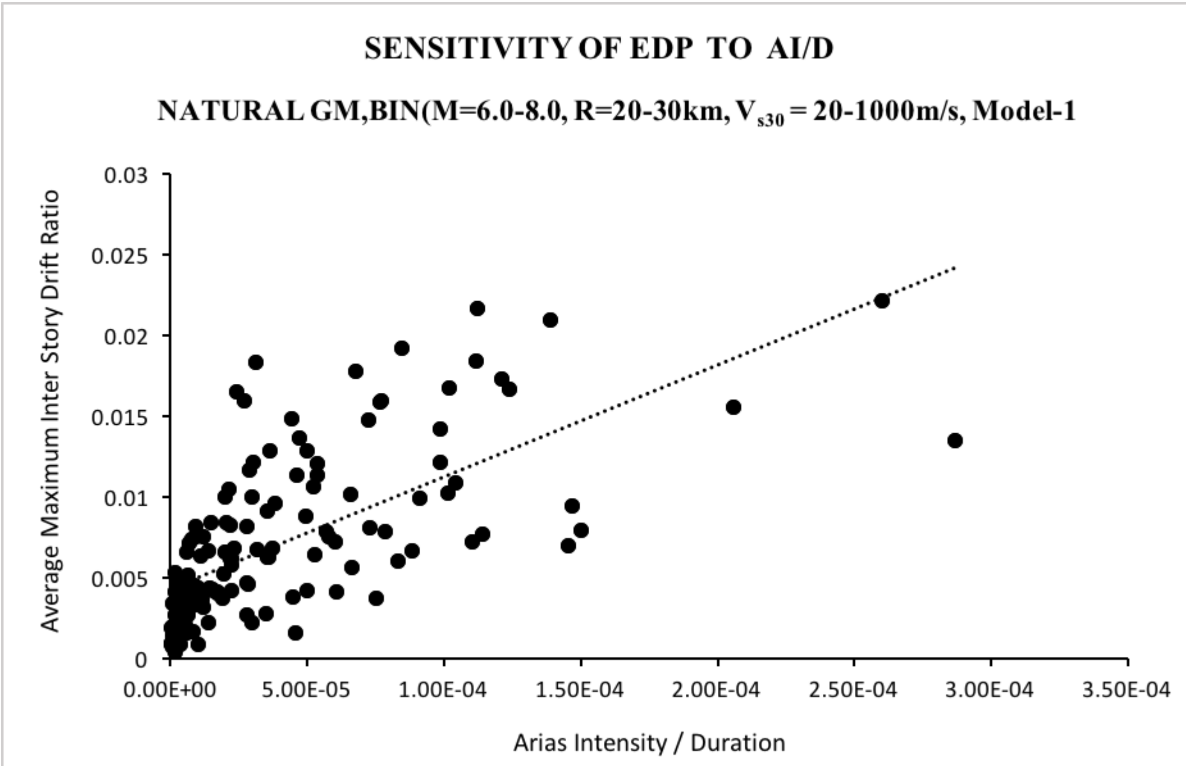

Figure 5.6: Sensitivity of EDP to I_a/D

wherein X is sub vector of one parameter with constant value and Y is sub vector of three parameters on which distribution is conditioned. μ_1 is the mean of sub vector of Y and μ_2 is the mean sub vector of X, and Σ_{11}, Σ_{12}, Σ_{21}, Σ_{22} are the partitions of covariance matrix Σ_z.

$$\mu = \mu_1 + \Sigma_{12}\Sigma_{22}^{-1}(X - \mu_2) \tag{5.2}$$

$$\Sigma = \Sigma_{11} - \Sigma_{12}\Sigma_{22}^{-1}\Sigma_{21} \tag{5.3}$$

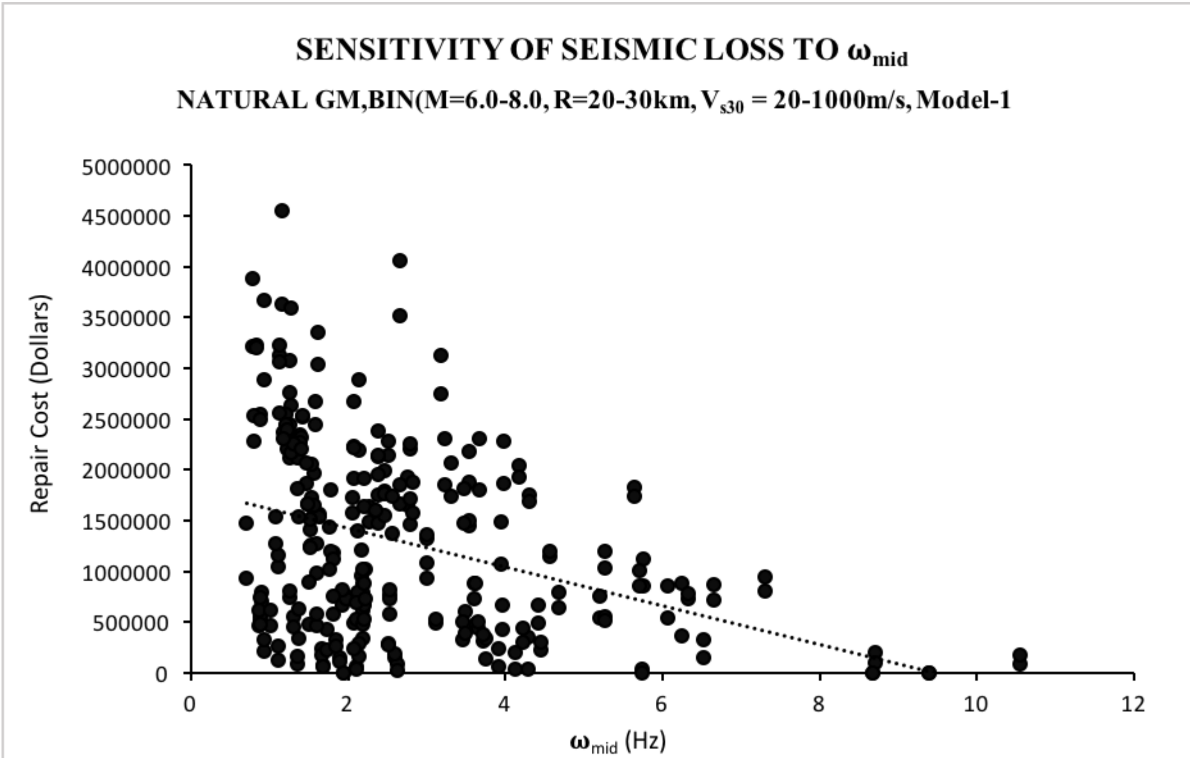

Figure 5.7: Sensitivity of Seismic Loss to ω_{mid}

5.5 Sensitivity of Seismic Response and Loss to ω_{mid}

From Figure 4.5 and 4.6, it can be observed that maximum drift and loss occurs at a value of $\omega_{mid} = 0.4$ and the trend gradually decreases as ω_{mid} increases. Therefore, for determining the conditional probability distribution, constant values starting from 0.4 to 1.4 is considered and also for a value of $\omega_{mid} = 0.2$ is evaluated. With help of this new probability distribution, suites of 148 simulated ground motion accelerations are generated equivalent to the number of recorded motions taken for the study. The structural and loss analysis is conducted for Model 1 and Model 2. Model 2 was considered to verify the effect of ω_{mid} and its effect on the building behavior during seismic activities. Figure 5.9,5.10,5.11 and 4.12 illustrates that loss and EDP increases as the ω_{mid} of the ground motion approaches the frequency of building and decreases beyond that value. So, it is evident that trend of the distribution of ω_{mid} that highest seismic response is observed ω_{mid} is close to the natural frequency of the

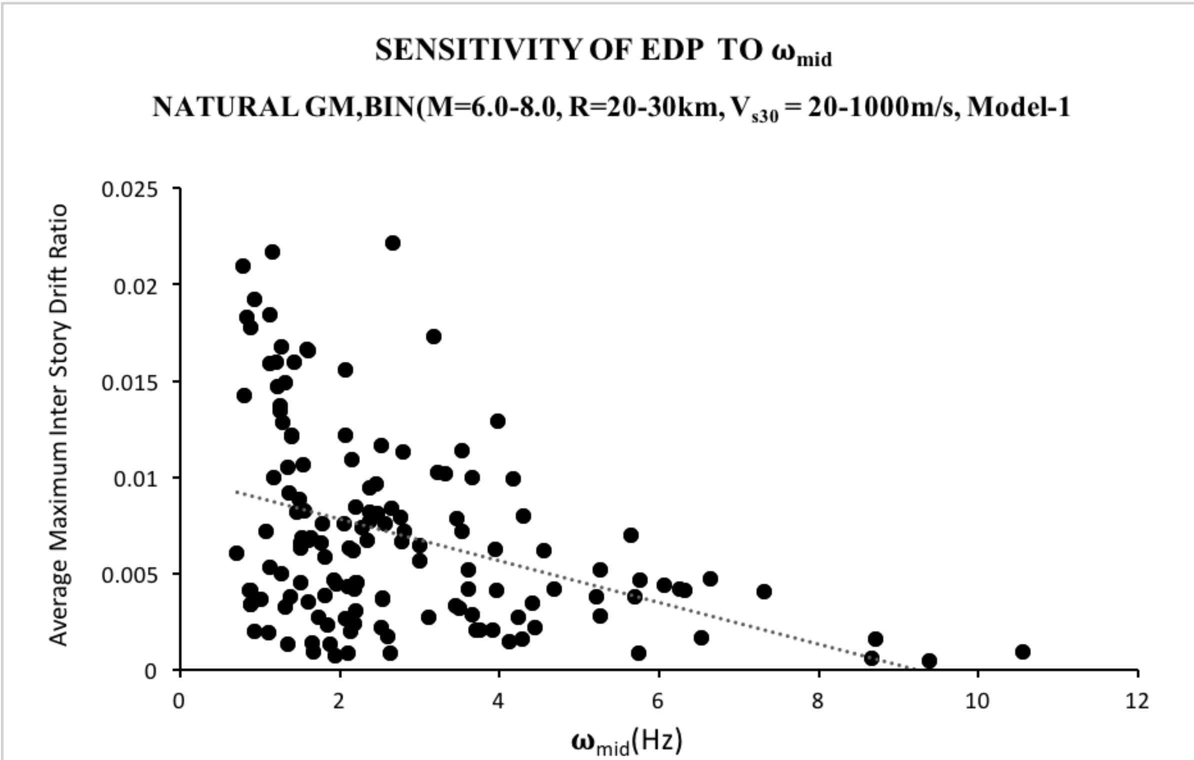

Figure 5.8: Sensitivity of EDP to ω_{mid}

building causing maximum trigger. For both the model structures examined, similar results have been seen and for further understanding, it can be inferred from the graph that there is a drop in the damage measure for ω_{mid} being lesser than the natural frequency of the building. So, the trend of gradual decrease observed in Section 4.3 follows the same concept discussed in this section. Also, another key factor is that the variation of losses the variation of the EDPs, i.e. inter story drift story as observed with other model parameters.

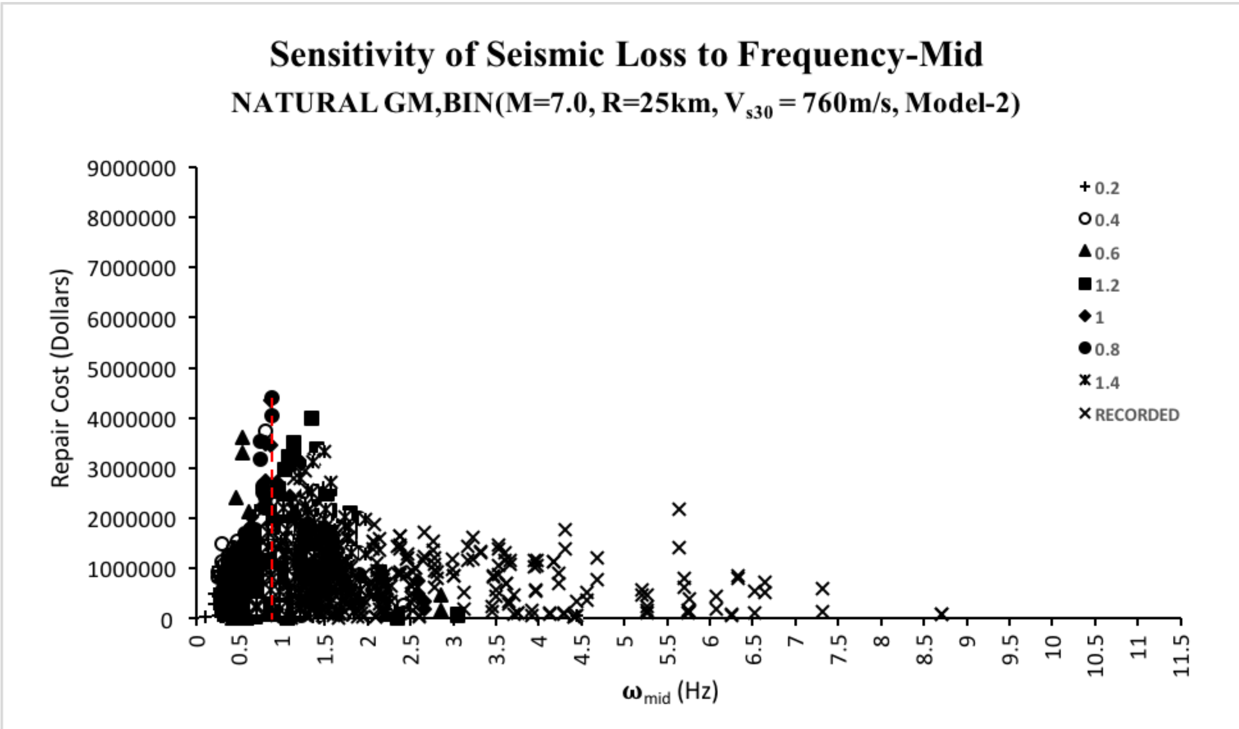

Figure 5.9: Sensitivity of Seismic Loss to ω_{mid}

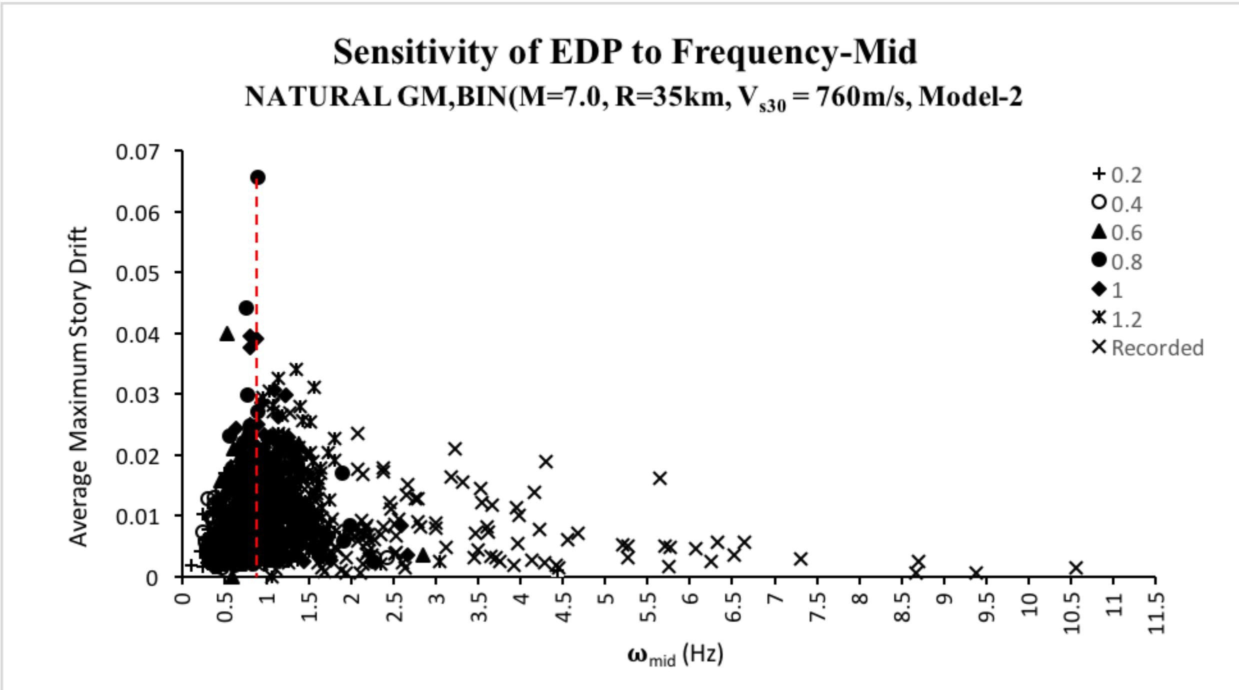

Figure 5.10: Sensitivity of EDP to $\omega_(mid)$

5.6 CASE STUDY: Sensitivity and Efficiency of Seismic Response and EDP to Model Parameters of Northridge Earthquake Motions

Now that we have discussed about the sensitivity of seismic loss and response to ground motion model parameters, a case study using real motions and simulated motions of 1994 Mw 6.7 Northridge earthquake,is conducted to analyse and validate a broadband ground motion simulation model([15]) generated simulations to validate the waveform propagation for near-field fault characteristics of the ground motions making it suitable to use in our case (see chapter 3). In our study, the efficiency of the ground motion simulation model can be derived by evaluating the sensitivity of seismic response and loss to model parameters. For this case study, Model 1 and 2 are used for structural and loss analysis to arrive at better understanding and comparison of the concepts discussed in above section.

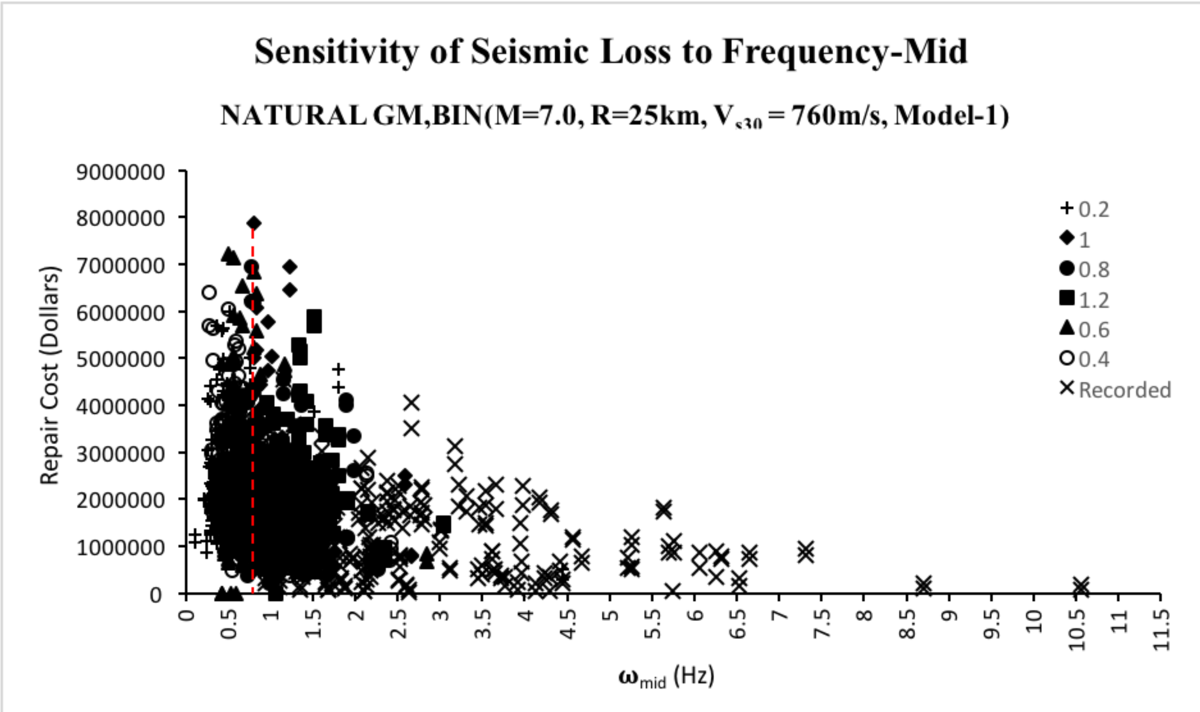

Figure 5.11: Sensitivity of Seismic Loss to ω_{mid}

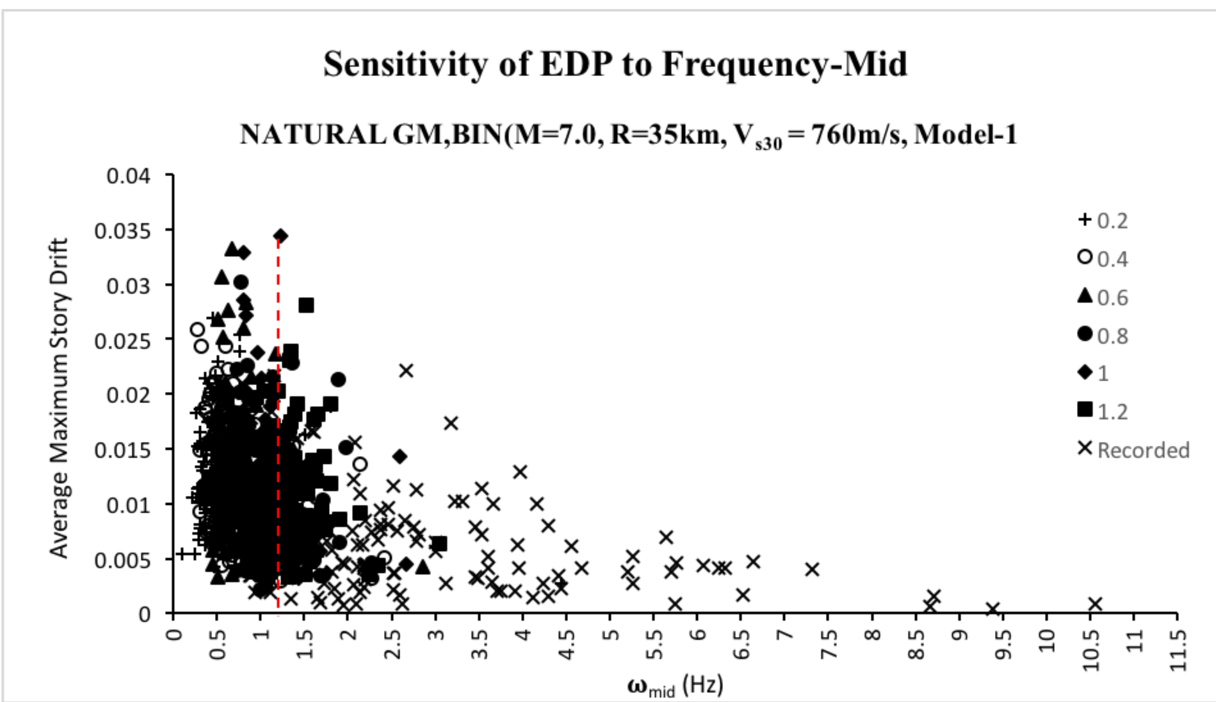

Figure 5.12: Sensitivity of EDP to ω_{mid}

The validation expresses the extent to which the simulation ground motion model can closely match the statistical characteristics of the waveform. Here, the sensitivity of seismic response and loss to model parameter are taken into consideration to validate against the real motions. Validation is conducted using both the model structures in order to study in detail the efficiency of the ground motion model. Figure 5.13 through Figure 5.28 illustrate the variation produced between the seismic responses and losses to the all four parameters when ground motions are experienced by Model 1 and 2. 'GP' refers to Graves and Pitarka ([16]) ground motions.

Now, to address the validity, along with the plots, table 5.29 gives the standard deviation of the sensitivity for all the ground motions. The correlation of recorded and simulation ground motion seismic response and loss to model parameters explains the validation of the ground motion simulation model. The variation in standard deviation shows the variation in simulated records when compared to real motions. Basically, the ratio of simulated to recorded parameters and seismic responses accounts for the matching and if the ground motion generated was accurate ground motion accelerations, correlation value of 1 should have been observed. Instead, here dispersion is visible, and the difference in standard deviation calculated between EDPs and losses with to all four parameters accounts for inefficiency in simulation.

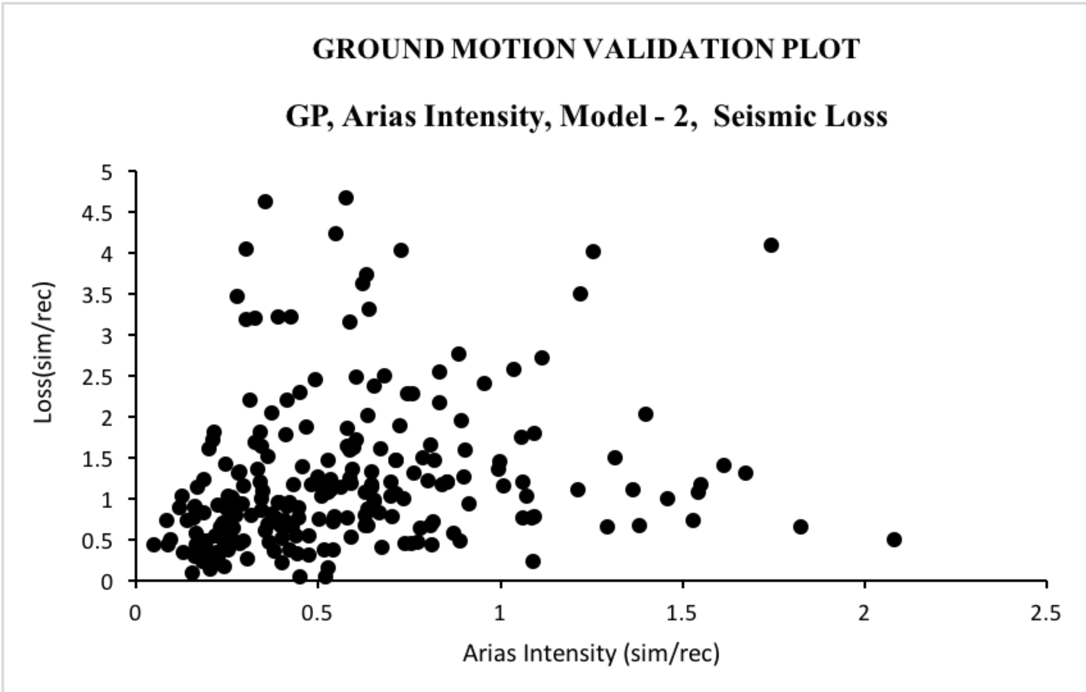

Figure 5.13: Ground Motion Validation Plot - Seismic Loss v/s Arias Intensity [Model-2]

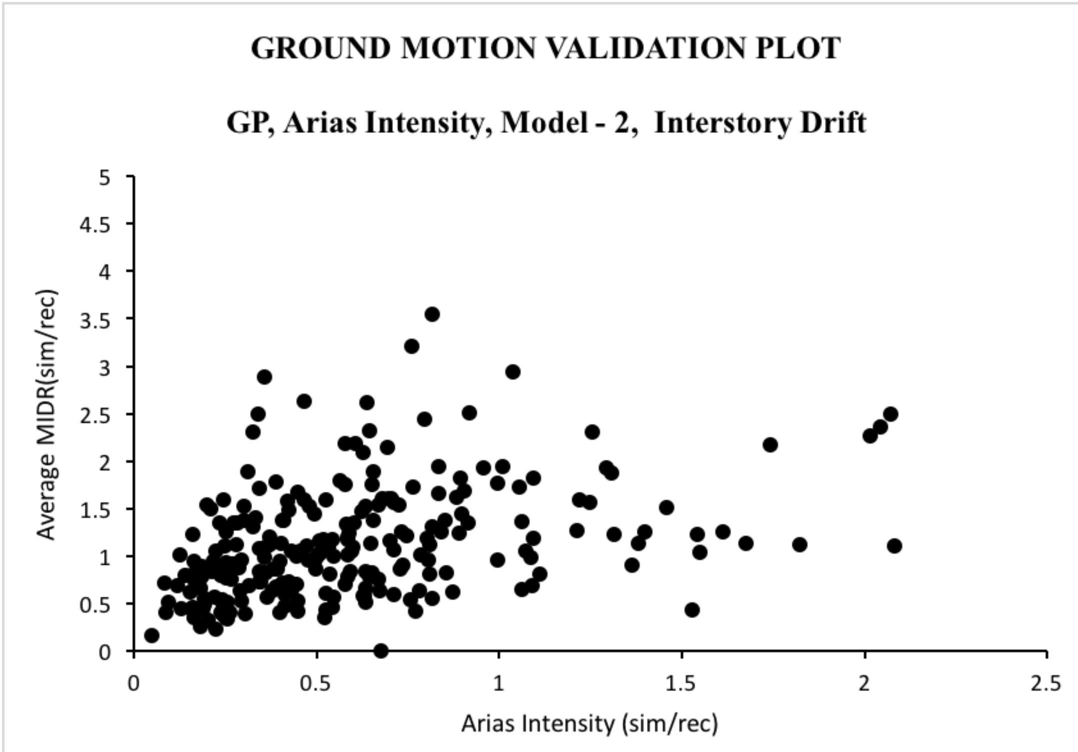

Figure 5.14: Ground Motion Validation Plot - Average Story Drift v/s Arias Intensity [Model-2]

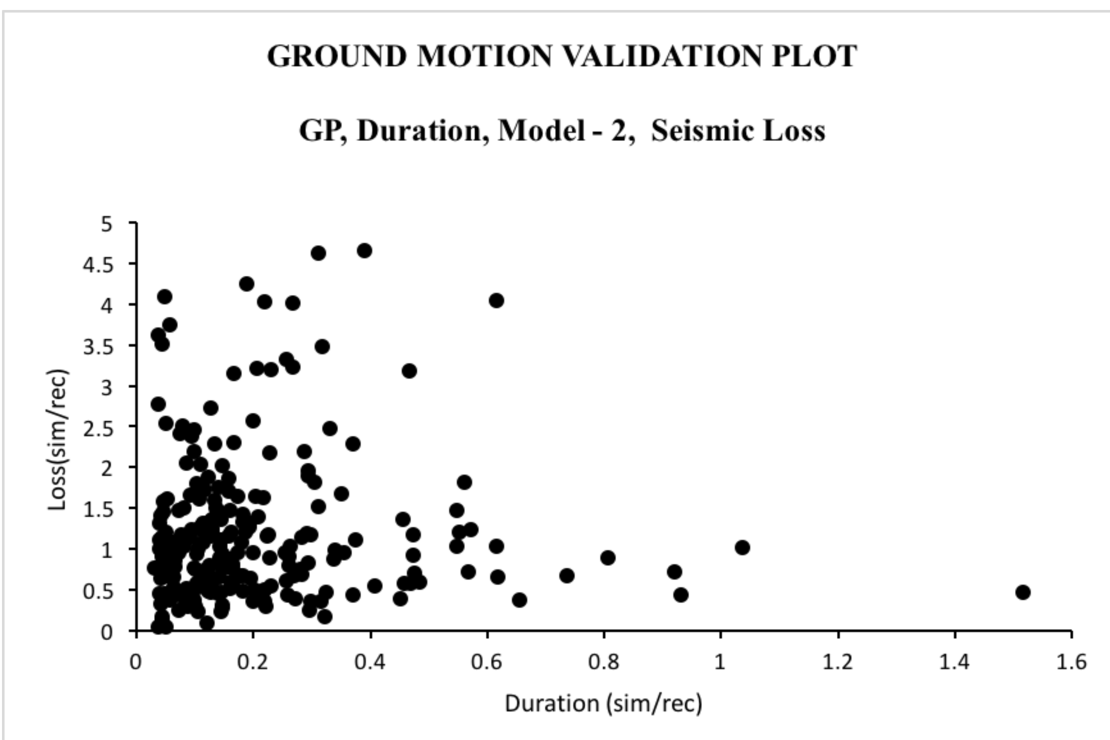

Figure 5.15: Ground Motion Validation Plot - Seismic Loss v/s Duration [Model-2]

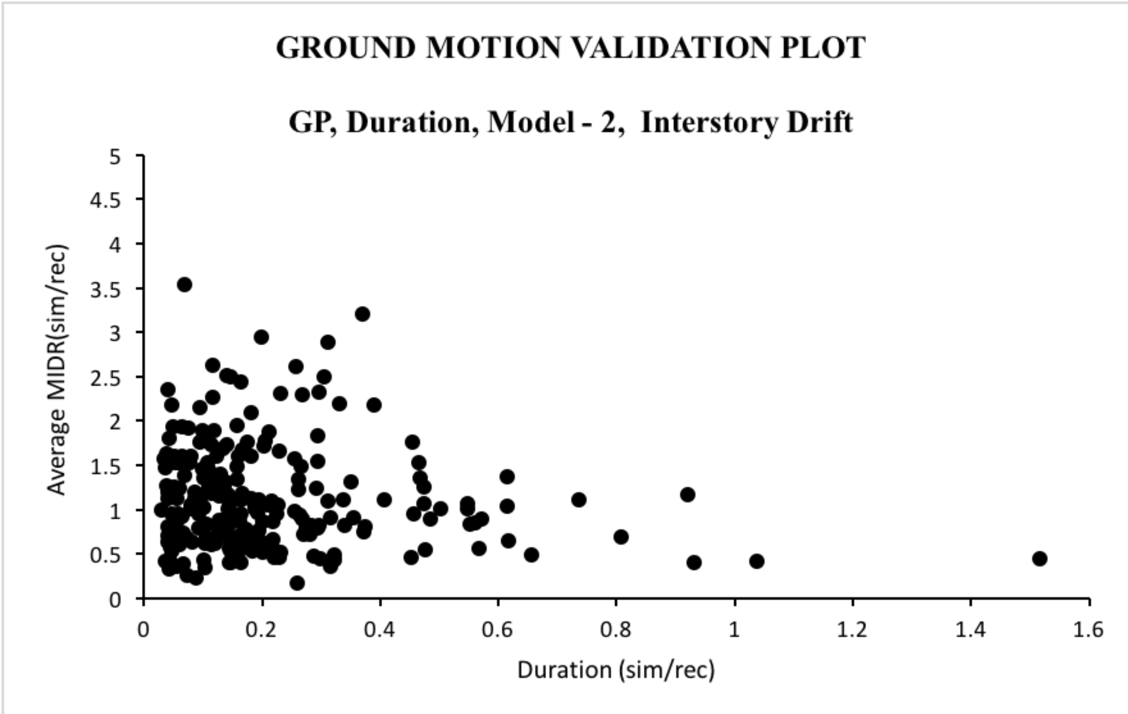

Figure 5.16: Ground Motion Validation Plot - Average Story Drift v/s Duration [Model-2]

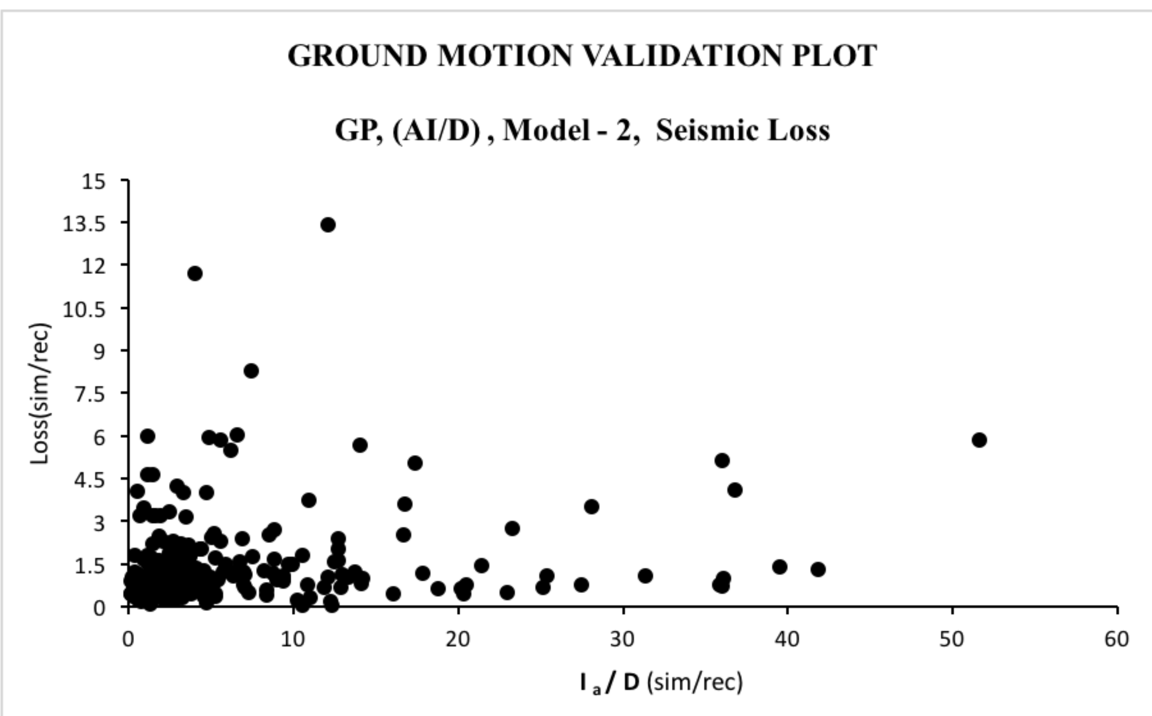

Figure 5.17: Ground Motion Validation Plot - Seismic Loss v/s I_a/D [Model-2]

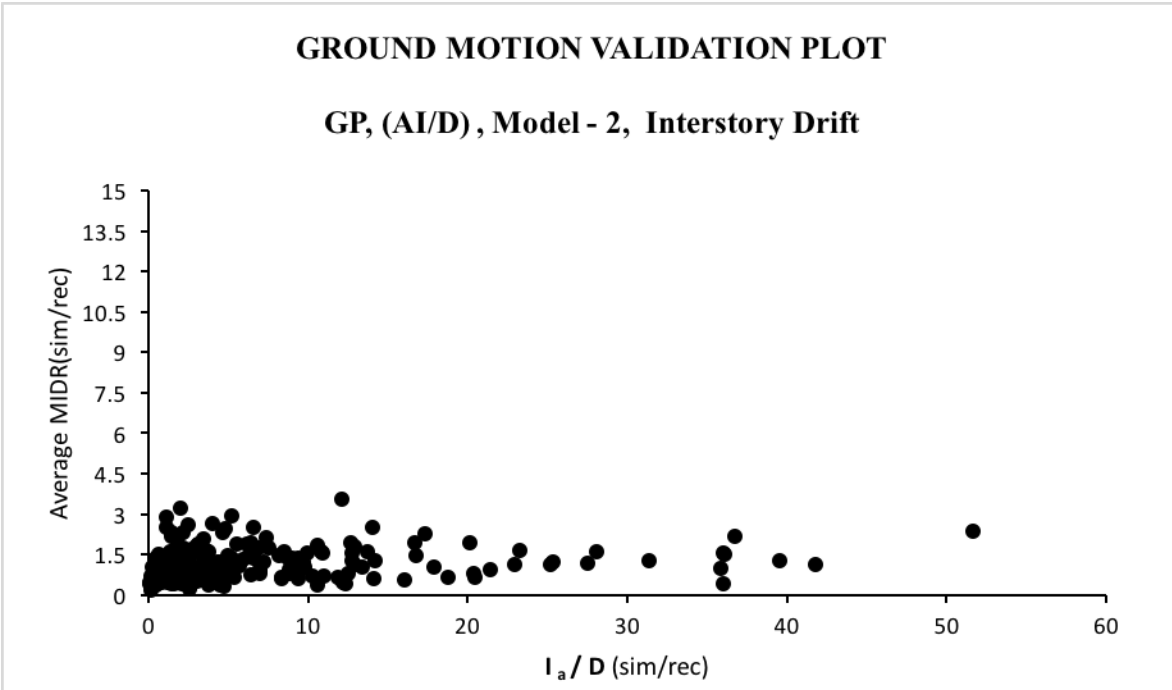

Figure 5.18: Ground Motion Validation Plot - Average Story Drift v/s I_a/D [Model-2]

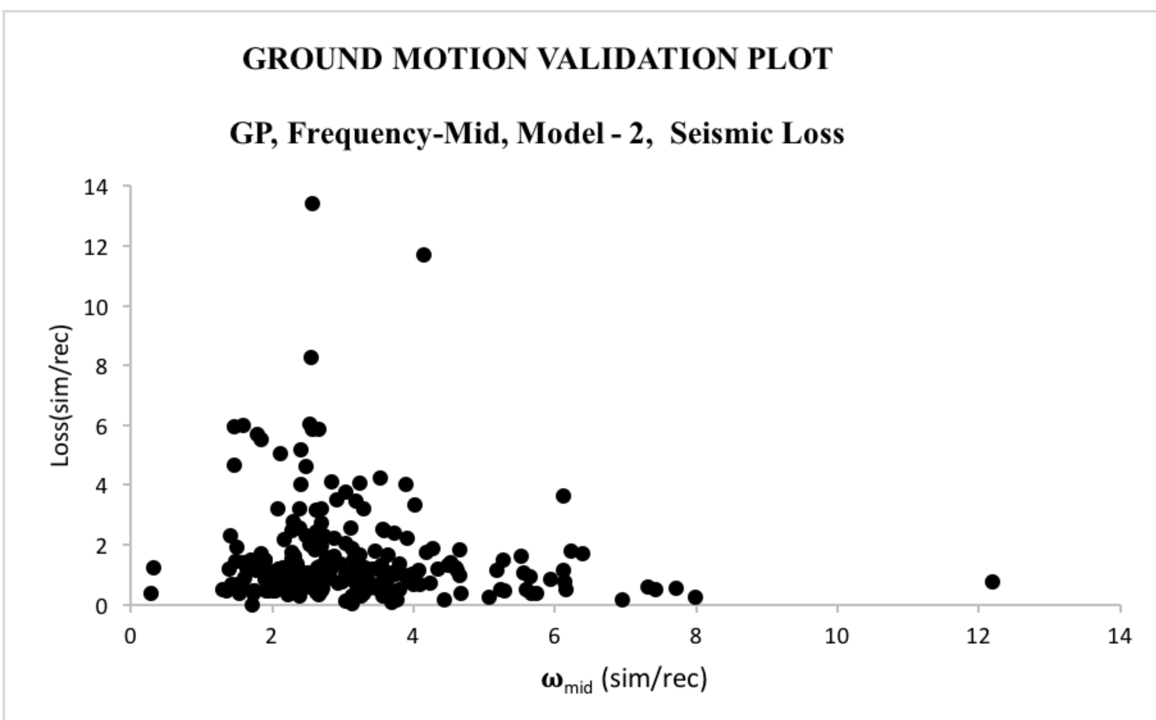

Figure 5.19: Ground Motion Validation Plot - Seismic Loss v/s $\omega_(mid)$ [Model-2]

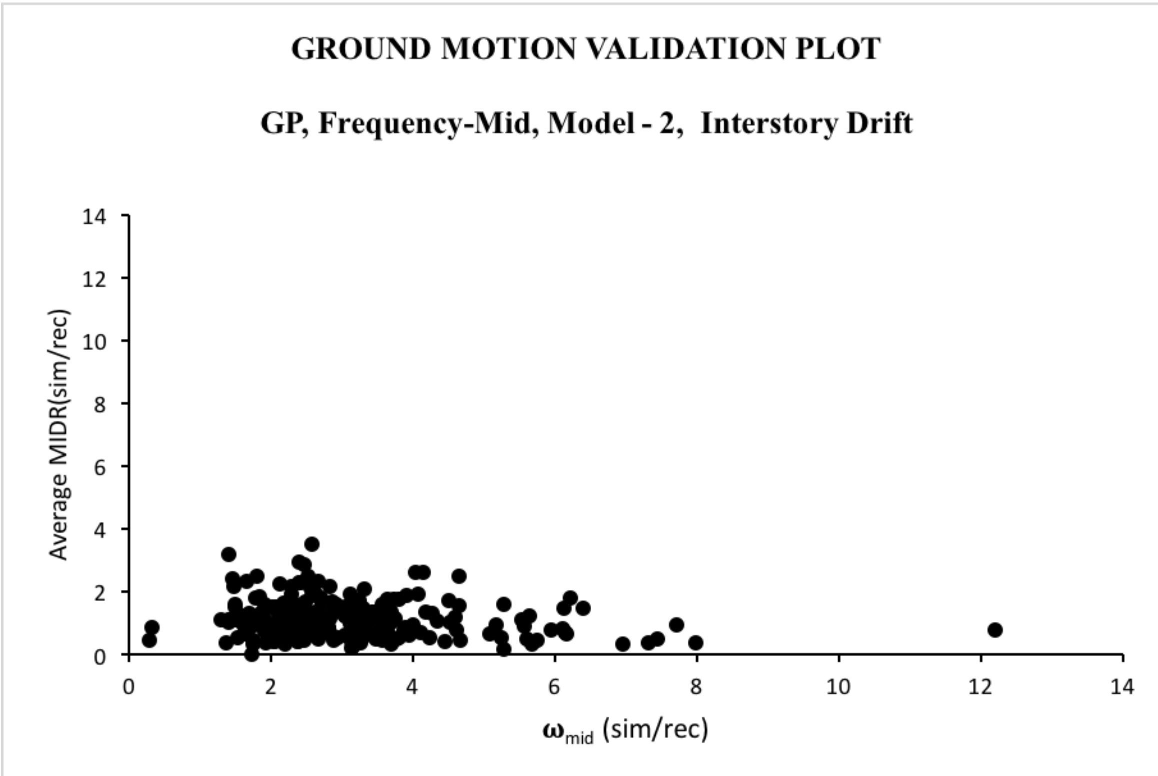

Figure 5.20: Ground Motion Validation Plot - Average Story Drift v/s ω_{mid} [Model-2]

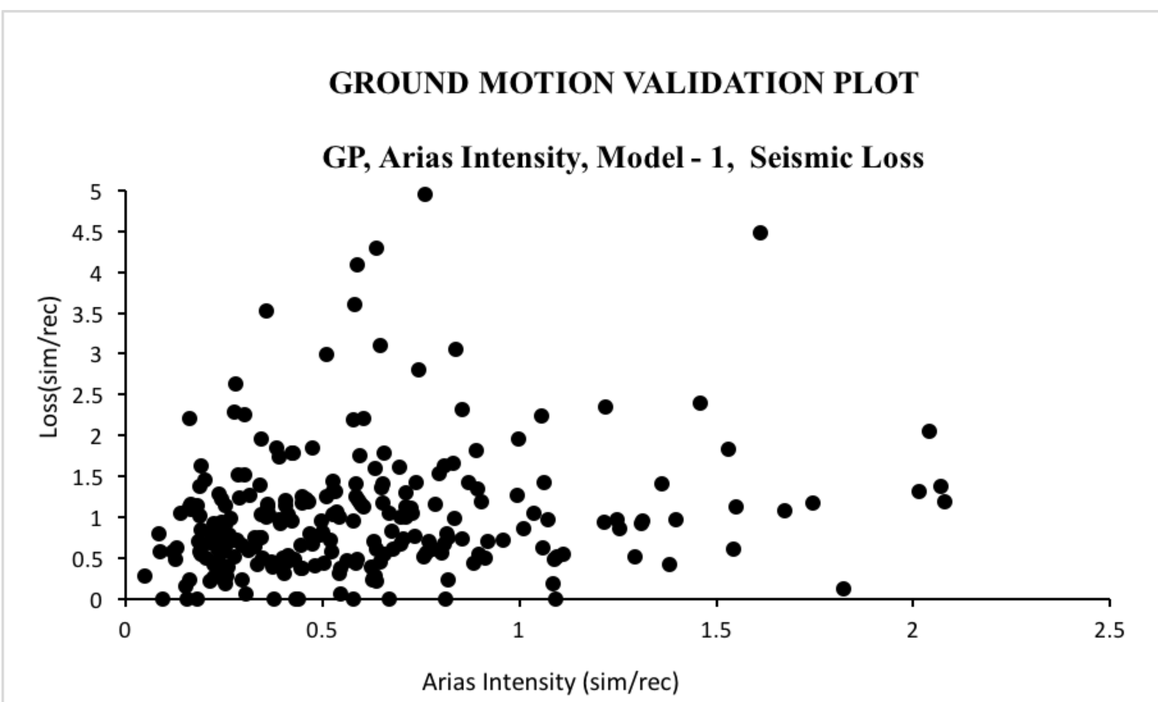

Figure 5.21: Ground Motion Validation Plot - Seismic Loss v/s Arias Intensity [Model-1]

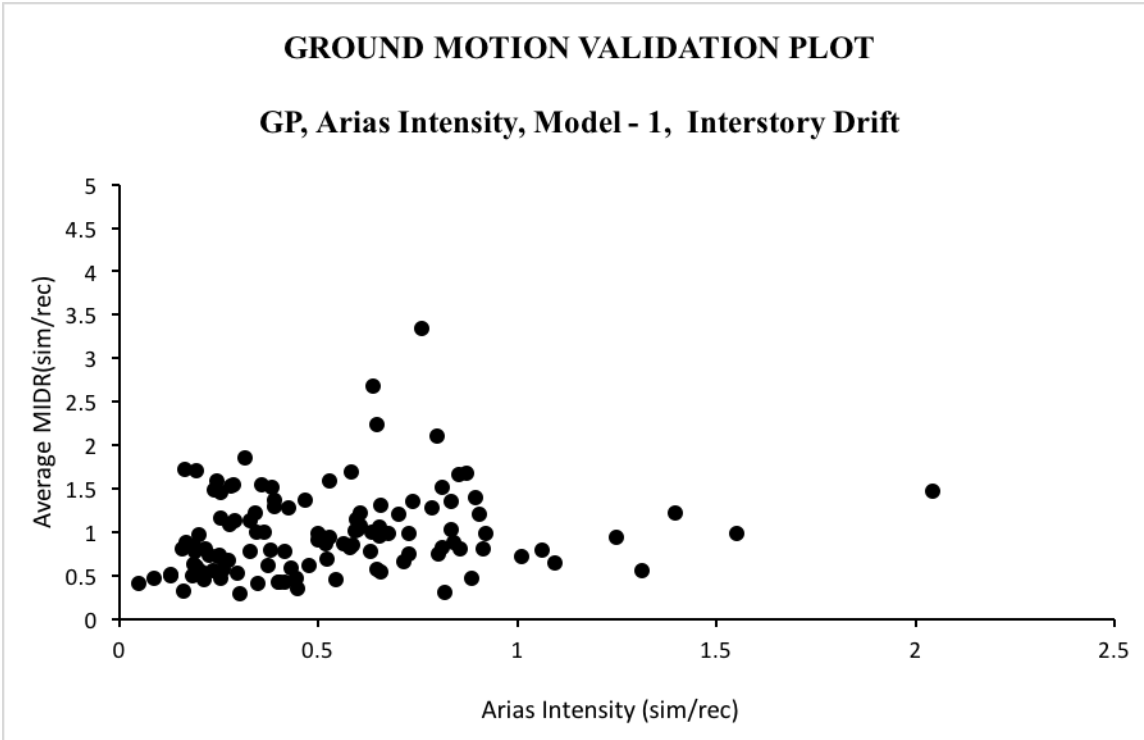

Figure 5.22: Ground Motion Validation Plot - Average Story Drift v/s Arias Intensity [Model-1]

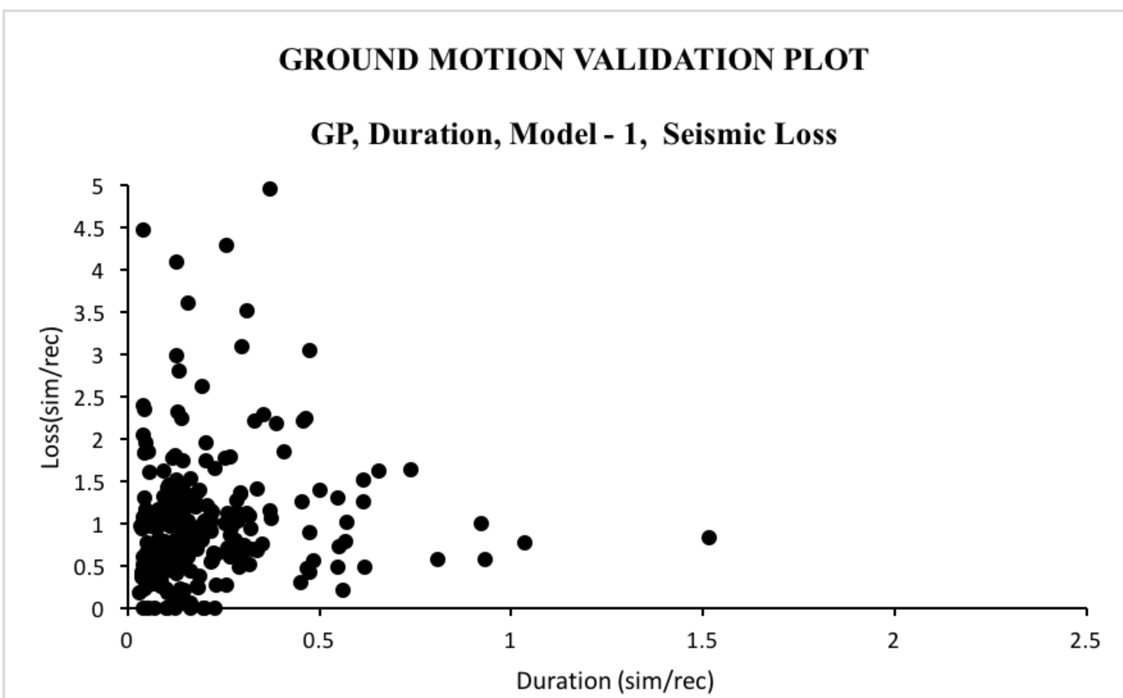

Figure 5.23: Ground Motion Validation Plot - Seismic Loss v/s Duration [Model-1]

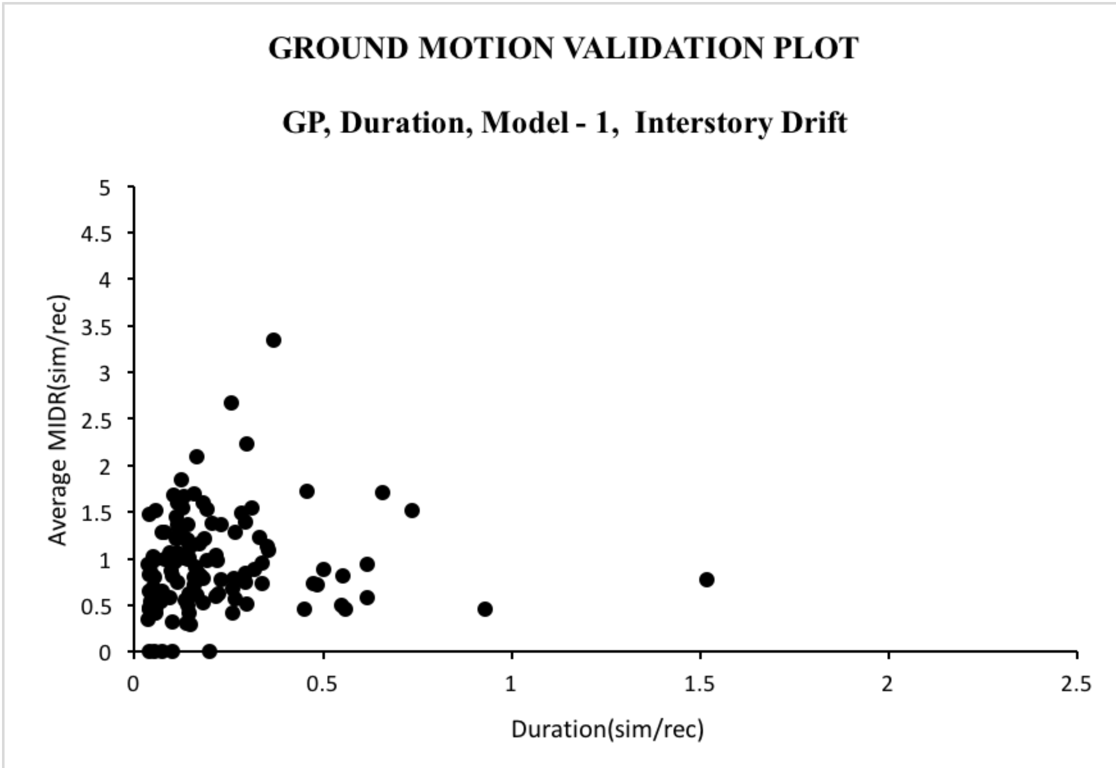

Figure 5.24: Ground Motion Validation Plot - Average Story Drift v/s Duration [Model-1]

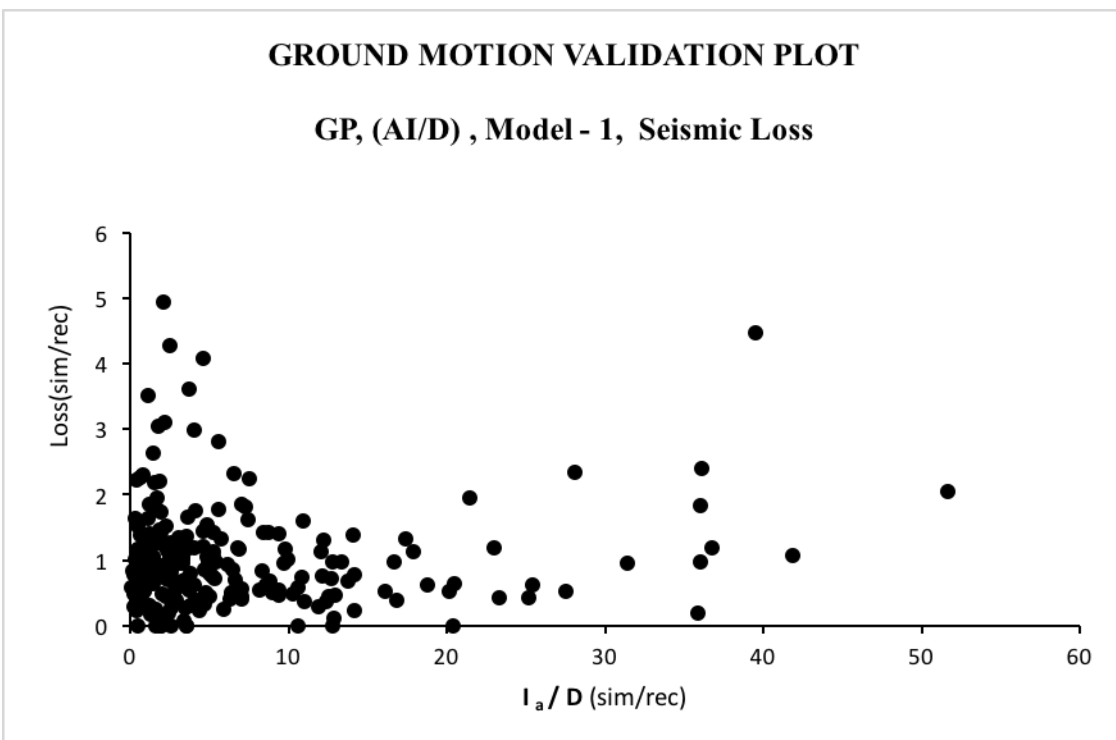

Figure 5.25: Ground Motion Validation Plot - Seismic Loss v/s I_a/D [Model-1]

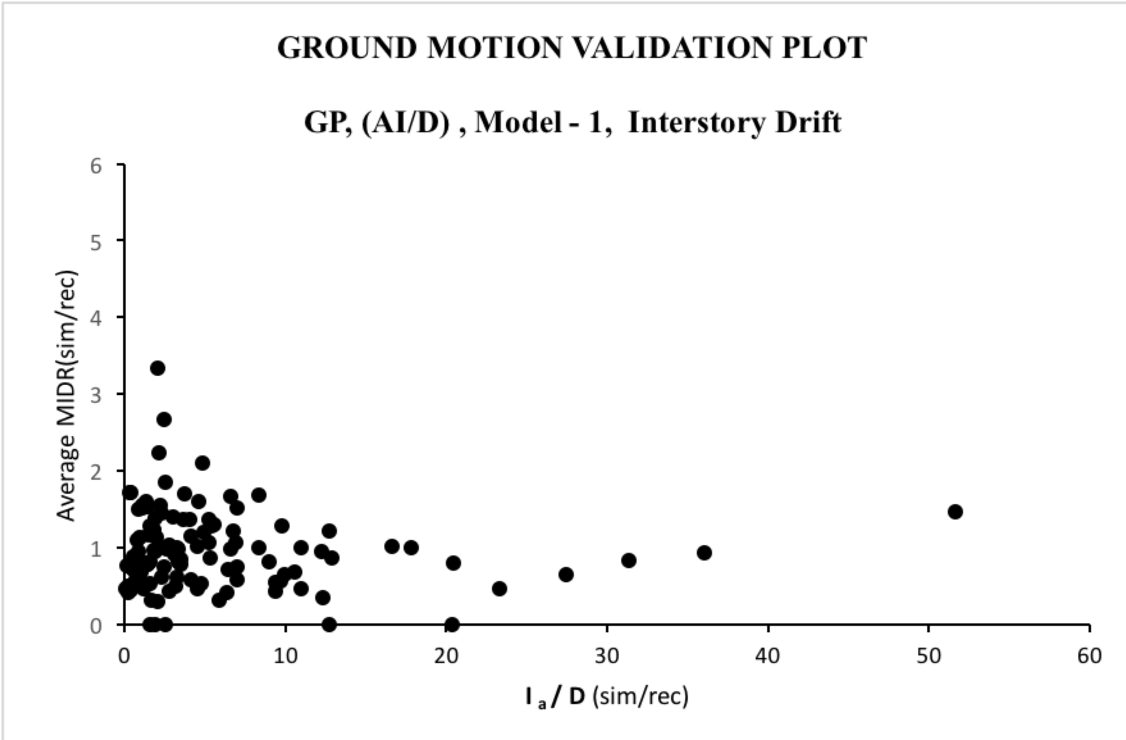

Figure 5.26: Ground Motion Validation Plot - Average Story Drift v/s I_a/D [Model-1]

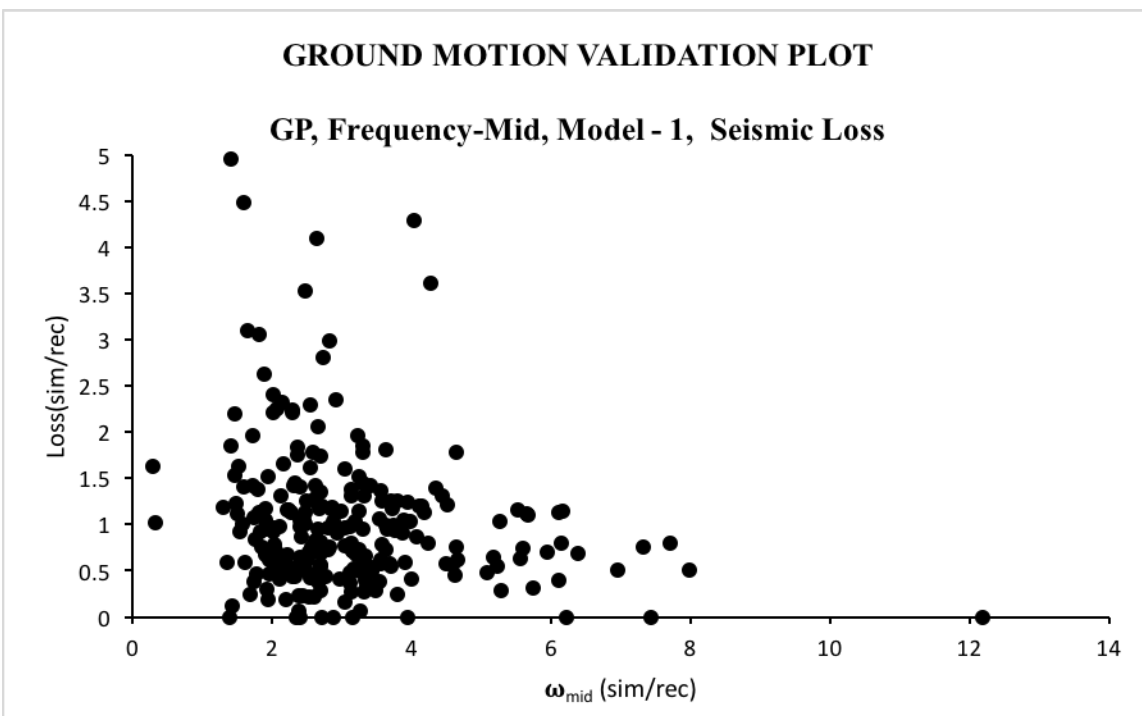

Figure 5.27: Ground Motion Validation Plot - Seismic Loss v/s ω_{mid} [Model-1]

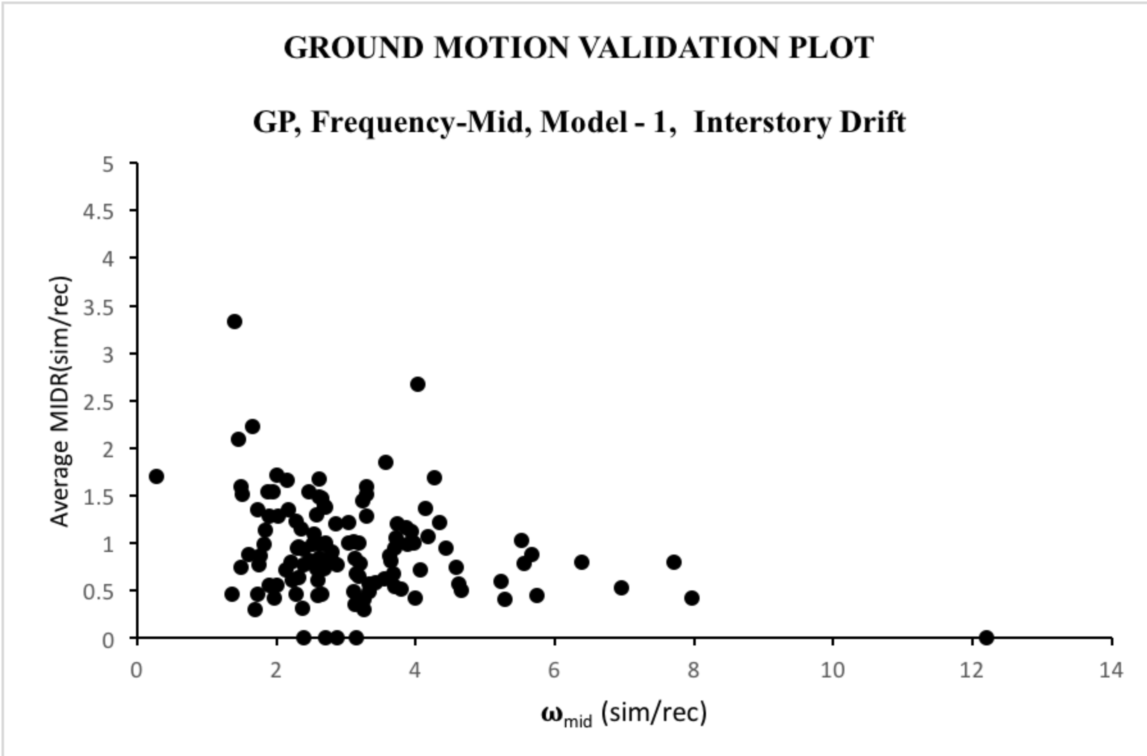

Figure 5.28: Ground Motion Validation Plot - Average Story Drift v/s ω_{mid} [Model-1]

Model-1:	**Standard Deviation**			
	Arias Intensity	**Duration**	**t_{mid}**	**ω_{mid}**
Loss $(\frac{sim}{rec})$	0.685	0.688	0.698	0.692
EDP $(\frac{sim}{rec})$	0.442	0.447	0.454	0.447
Model-2:				
	Arias Intensity	**Duration**	**t_{mid}**	**ω_{mid}**
Loss $(\frac{sim}{rec})$	0.784	0.846	0.834	0.846
EDP $(\frac{sim}{rec})$	0.464	0.527	0.507	0.527

Figure 5.29: Standard Deviation Chart

Chapter 6

Conclusion

The main interest of this study is to investigate the sensitivity of waveform parameters of ground motions in causing damage to the structures during a seismic events. A suite of recorded ground motions was initially taken to observe the sensitivity of seismic loss to the four model parameters : Arias Intensity, Duration , frequency at the middle of the strong shaking phase and rate of change of intensity along the duration of the ground motion. It was observed that except for ω_{mid} ,the rest of the three parameters showed relatively linear sensitivity. Hence, the further study was to examine the nature of ω_{mid} with the help of simulated ground motions generated from stochastic ground motion model. Upon conditioning the rest of the parameters on constant values of ω_{mid} , the seismic response increased as ω_{mid} reaches relatively closer to natural frequency of the buildings.In addition to this, validation of broadband based simulated ground motion using hybrid approach was carried out in terms of sensitivity of the seismic response and loss to model parameters. This led to the conclusion that the utilized ground motion model was not very efficient in matching the statistical characteristics of recorded ground motions. This interpretation can be used in future studies to take steps to develop more efficient broadband ground motion model.

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