EVALUATION OF INTENSITY MEASURES FOR GROUND MOTION SELECTION TO BE USED IN THE ANALYSIS OF HIGHWAY FLYOVER BRIDGES

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ABSTRACT

EVALUATION OF INTENSITY MEASURES FOR GROUND MOTION SELECTION TO BE USED IN THE ANALYSIS OF HIGHWAY FLYOVER BRIDGES

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Time history analysis that requires a proper ground motion selection is becoming popular as computational methods advance. It has been known that scaling any ground motion will not be the best fit to be used in the time history analysis. Over the years, scientists have studied recorded ground motion data by the help of a set of intensity measures to characterize the movement. The aim of this study is to compare intensity measures of ground motions with seismic demand parameters used in nonlinear time history analyses of four flyover intersection highway bridges with various natural periods varying between 0.84 s and 1.78 s. In this scope, nonlinear time history analyses have been performed on a total of forty-two ground motion records. Twenty-three intensity measures grouped as acceleration, velocity, displacement based and other categories have been researched to detect a correlation with column base seismic demand parameters consisting of axial, shear and moment forces. Traditionally, the peak ground acceleration has been used as the main measure between seismic hazard and structural analysis. However, the results showed that intensity measures such as Velocity Spectrum Intensity (cm), Sa(T1) (g) and Housner intensity (cm) have better correlations with seismic demand parameters compared to other intensity measures.

In general, the velocity-related intensity measures are the most appropriate intensity measures for the highway bridges analyzed.

Keywords: Intensity measure, correlation, flyover intersection highway bridge, seismic demand parameters, nonlinear time history analysis, ground motion

ÖZ

KARAYOLU KAVŞAK KÖPRÜLERİNİN ANALİZİNDE KULLANILACAK YER HAREKETİ SEÇİMİ İÇİN ŞİDDET ÖLÇÜLERİNİN DEĞERLENDİRİLMESİ

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Uygun bir yer hareketi seçimi gerektiren zaman tanım alanında hesap yöntemi analizi, hesaplama yöntemleri ilerledikçe daha yaygın olarak kullanılmaktadır. Herhangi bir yer hareketini ölçeklendirmenin, zaman tanım alanı analizinde kullanılacak en uygun yöntem olmadığı bilinmektedir. Yıllar boyunca, bilim adamları, hareketi karakterize etmek için bir dizi şiddet ölçüsü kullanarak kaydedilen yer hareketi verilerini incelediler. Bu çalışmanın odağı, 0.84 s ve 1.78 s arasında farklı doğal periyotlarda olan, doğrusal olmayan zaman tanım alanı analizlerinde kullanılacak dört farklı kavşak köprüsünün sismik kriterleri ile yer hareketlerinin şiddet ölçülerini karşılaştırmaktır. Bu kapsamda, toplam kırk iki yer hareketi kaydı kullanılarak doğrusal olmayan zaman tanımı analizleri yapılmıştır. Eksenel, kesme ve moment kuvvetlerinden oluşan kolon altı sismik kriterleri belirlemek için ivme, hız ve yer değiştirme esaslı ve diğer olmak üzere toplamda yirmi üç şiddet ölçüsü araştırılmıştır. Geleneksel olarak, en yüksek yer ivmesi, sismik tehlike ile yapısal analiz arasındaki ana ölçüm olarak kullanılmıştır. Bununla birlikte, sonuçlar, diğer şiddet ölçülerine kıyasla, Hız Spektrum Şiddeti (cm), Sa (T1) (g) ve Housner şiddeti (cm) gibi şiddet ölçülerinin sismik kriterlerle daha iyi ilişkilere sahip olduğunu göstermiştir. Genel

olarak, hıza bağlı şiddet ölçüleri analiz edilen otoyol köprüleri için en uygun şiddet ölçüleridir.

Anahtar Kelimeler: Şiddet ölçüsü, korelasyon, karayolu kavşak köprüsü, sismik kriterler, doğrusal olmayan zaman tanım analizi, yer hareketi

To my family who patiently and tirelessly gave me all kinds of support…

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LIST OF ABBREVIATIONS

ABBREVIATIONS

A95 : A95 parameter (g)

AI : Arias Intensity: (m/sec)

a_{RMS} : Root Mean Square of acceleration (g)

ASI : Acceleration Spectrum Intensity (g*sec)

CAV : Cumulative Absolute Velocity (cm/sec)

d_{RMS} : Root Mean Square of acceleration (cm)

EDA : Effective Design Acceleration (g)

FBM1 : Flyover Bridge Model 1

FBM2 : Flyover Bridge Model 2

FBM3 : Flyover Bridge Model 3

FBM4 : Flyover Bridge Model 4

GMIM : Ground Motion Intensity Measure

HI : Housner Intensity (cm)

IC : Characteristic Intensity (g3/2sec1/2)

MIV : Max Incremental Velocity (cm/sec)

PGA : Peak ground acceleration / Maximum acceleration (g)

PGD : Peak Ground Displacement / Max. Displacement (cm)

PGV : Peak ground velocity / Maximum velocity (cm/sec)

PSC: Pre-stressed Concrete

r= Pearson's Correlation Coefficient

RC: Reinforced Concrete

Sa (T1) : Spectral acceleration at the fundamental period of the structure (g)

Sa (T2) : Spectral acceleration at the period of the structure in second mode (g)

SED : Specific Energy Density (cm2/sec)

SMA : Sustained Maximum Acceleration (g)

SMV :Sustained Maximum Velocity (cm/sec)

T_m : Mean Period (sec)

T_p : Predominant Period (sec)

v_{RMS} : Root Mean Square of acceleration (cm/sec)

VSI : Velocity Spectrum Intensity (cm)

CHAPTER 1

INTRODUCTION

1.1. General

After fatal earthquakes in the past century, the importance of seismic vulnerability assessment become evident for highway bridges. Specifications have been developed based on experience gained in these past earthquakes. Thanks to developments in earthquake engineering, recent developments in computing methods, computer systems and programs, innovations in material technologies and knowledge gained from earthquakes and a better understanding of earthquake behavior, various methods have been developed to minimize the damages of the destructive effects of the earthquake on engineering structures. One of the most noticeable methods is the bearing application methods which can reduce the interaction between the substructure and superstructure and minimize the negative effects of the earthquake on highway bridges. Conventional methods are provided by increasing the load-bearing capacity, stiffness, ductility, stability, and elasticity of the structure. Bearing application methods; reducing the stiffness of the structure, increasing the period and the dampening of the structure provides the reduction of earthquake forces. The separation process performed by the elastomeric bearing elements is intended to limit the high values that will occur under the effect of an earthquake by extending the period of the structure. Highway bridges isolated with numerous kinds of bearings are commonly preferred. Scientists had been facing many problems to satisfy the minimum requirements in the seismic design of highway bridges for many years. Therefore, they needed to select accurate seismic measures in order not to have a false judgment in the seismic design of bridges.

Current specifications such as AASHTO Guide Specifications for LRFD Seismic Bridge Design , 2011 and Eurocode 8, Design provisions for earthquake resistance of structures, 1996 have referenced time history analysis as an alternative to the other methods in seismic analysis of highway bridges. The recorded time ground motions need to be input into time history analysis to simulate seismic response of the structure. Evaluation is conducted through different intensity measures in ground motion selection for seismic analysis of a flyover intersection highway bridges. The flyover superstructure, substructure, and connection details have also been determined to change the seismic response. The connections are supplied with elastomeric bearings. Effect of elastomeric bearing layout and stiffness have also been included in the seismic analysis.

The criteria used to select strong ground motion record in accordance with the design acceleration spectrum in a given region should include geological and seismological conditions. The magnitude of the earthquake, type of faulting, distance of the site to the fault, fault direction, the local ground conditions and the spectral content of the record constitute the most important of these conditions.

In seismic design specifications, the seismic hazard in an area is generally defined by the design acceleration spectrum. The acceleration records to be used in the earthquake calculations to be made in the time domain can be obtained from three sources: Design acceleration spectrum compatible with artificial records, simulated recordings and the acceleration records recorded during the earthquake. It is more preferable to use recorded motion records due to their superiority to other types of records. With increase in strong-motion databases, appropriate recorded motion data should be selected properly to meet the conditions specified in the regulations. The recorded earthquake recordings contain sound information about the nature and major characteristics of ground vibration such as amplitude, duration, phase characteristics and frequency content. It also reflects all factors such as the source, dispersion environment and ground that affect the records. Therefore, taking into account the seismological aspects of the field, the use of recorded ground motion data provides a

great advantage over other alternatives. Besides, the fact that the strong ground motion data banks have been enriched with each passing day and the access to them is getting easier with the advancing technology makes the use of acceleration records recorded in earthquakes widespread.

1.2. Object and Scope

In this study, general methods and criteria related to the selection of earthquake records are evaluated in detail. Ground motion records are usually selected based on either the design spectrum or the earthquake scenario with minimum measures such as size, distance and soil class to represent certain characteristics of ground motion. In seismic design regulations, the guidance on how to select the appropriate recorded data is mostly focused on the suitability of the response spectrum rather than all the seismological measures used in literature. The recordings should be selected to match a design response spectrum with the help of suitable ground motion intensity measures. In this scope, nonlinear time–history analyses of four reinforced concrete flyover highway bridges shall be performed under a set of forty-two ground motion records. The bridges are selected to represent features of different natural periods. The records contained in the ground motion database shall be compiled from recorded ground motions with the intention to represent a wide range of seismic demand parameters. Thus, by collecting the data, the main obje2ctive of this thesis is to compare seismic demand parameters with ground motion intensity measures through coefficients of correlation and determination, and consequently choosing best-correlated ground motion intensity measures to predict the severity of ground motions on analyzed flyover highway bridges.

CHAPTER 2

LITERATURE REVIEW

With the increase in use of time history analysis while implementing seismic design becoming more important and gaining reputation, obtaining ground motion data and using correct data in numerous structural analyses have a very important role for irregular structures. Hence, choosing appropriate data is required to estimate approximate relation between effects on structure and ground motion since there is very limited information about this problem design codes.

Structural seismic responses are typically computed utilizing Equivalent Static Earthquake Load Method and Mode Superposition Method in the recent past. As a result of rapid developments in the field of computational methods, calculation methods in time history have been widely used in the seismic analysis and design of structures.

Static analysis methods are suitable for regular medium to short span bridges where a higher degree of mode effects is not important. Advance dynamic analysis is typically required for structures with torsional irregularity and non-orthogonal structures. In the family of dynamic analysis methods, time history analysis is the most trusted way to determine structural response due to the inclusion of recorded earthquake effects on the structure per the characteristics of the structure and earthquake movement where dynamic analyses in the time domain can be realized as linear or nonlinear analysis (Hajali et al., 2018).

2.1. Time Series Selection in Current Codes

2.1.1. AASHTO Guide Specifications for LRFD Seismic Bridge Design

In Article 3.4.4 of AASHTO Guide Specifications for LRFD Seismic Bridge Design, 2011, it is desired to choose time histories recorded under conditions that are similar to site seismic conditions. However, because there are the limited data of time history records and multiple seismic environment properties are needed, ground motion intensity measures have a strong influence on response spectral content, response spectral shape, duration of strong shaking, and near-source ground motion characteristics, within reasonable ranges, selection of time histories with similar parameters such as earthquake magnitudes and distances are very important. In order to avoid using very large scaling factors with recorded motions and very large changes in spectral content in the spectrum-matching approach, it is desired recorded motions to be selected shall be somewhat similar in overall ground motion level and spectral shape to the design spectrum.

2.1.2. Eurocode 8 (Design provisions for earthquake resistance of structures)

Easily accessible waveform databases are available and evidence shows that only a relatively limited number of criteria has to be considered in selection and scaling to get an unbiased estimation of seismic demand. Like many codes worldwide, Eurocode 8, 1996 allows the use of ground-motion records for the seismic assessment of structures. The main condition to be satisfied by the chosen set is that the average elastic spectrum does not underestimate the code spectrum, with a 10% tolerance, in a broad range of periods depending on the structure's dynamic properties. The Eurocode 8 prescriptions seem to favor the use of spectrum matching records, obtained either by simulation or manipulation of records.

2.2. Time Series Selection in Previous Studies

- In order to minimize the approximate approach, several studies have been conducted by comparing intensity measures of ground motions with effects on structures. Pejović & Janković, 2015 compared several intensity measures of ground motions on reinforced concrete structures to estimate the most suitable intensity measures for flexible and stiff reinforced concrete systems. They concluded that widely used peak ground acceleration value may not be suitable for most cases and other intensity measures must be checked in order to estimate the most accurate effects.
- The most commonly used strong-motion intensity measure in seismic design is the acceleration response spectra. However, there is an increasing trend towards displacement and the use of energy spectra. Not dealing with force-based seismic design is due to the acknowledgment that structural damage cannot be controlled by acceleration during earthquakes, and therefore by controlling displacement or energy distribution, the damage can be more effectively limited. For spectrum-based design methods, the type of input is limited to the analysis method, but these new trends provide a better reflection of the destructive capacity of the movement. In time history analysis, it is important that the accelerogram programs used have appropriate those parameter values that are closely related to damage capacity. (Bommer & Martinez-Pereira, 2000)
- In some cases, for example for hazard compatibility, acceleration parameters should also be considered as an effective PGA. Padgett, Nielson & DesRoches, 2007 objected in their article to assess the the characteristics of optimal IMs for portfolios. They concluded that for relatively high frequency steel highway bridges with first mode periods ranging between 0.17 s and 0.32 s, PGA (peak ground acceleration) and spectral acceleration at the fundamental period, and for some cases with synthetic motions $S_{a\text{-}gm}$, is the optimal intensity measure on the basis of on the basis of hazard computability.

- Another study published by Song, Qian, Qian, Bao, & Lin, 2019 is about performing canonical correlation analysis for the selection of optimal ground motion intensity measures in the probabilistic seismic demand analysis of bridges with simple reinforced girders. Instead of looking for correlation between intensity measures and demand parameters by individual intensity measures, they concluded combining intensity measures by taking peak of some of them orby combining root mean square of some intensity measures give better results in terms of correlation. They also stated that, for the individual intensity measures, the velocity type of intensity measures such as PGV, SMV, HI, VSI, and v_{RMS}, were more proficient than acceleration and displacement types of intensity measures.
- In the report Selecting and Scaling Earthquake Ground Motions for Performing Response-History by NEHRP, 2011, choosing different intensity measure creates different question on scaling and selecting ground motions acknowledging that there is no intensity measure with perfect efficiency and sufficiency. For example, scale may be 2 for PGA (g) while 4 for AI (m/s).

2.3. Time History Record Definitions

2.3.1. Time History Record Types

- Artificially Produced Earthquake Records

In a wide range of intervals, artificial records can be produced that are exactly the same as the spectrum of behavioral elastic design acceleration spectrum. These records can be generated by collecting sinusoidal signals with random phase angles and amplitudes obtained from the power spectral density function of the simplified behavior spectrum design acceleration spectrum (Rofooei, Mobarake, & Ahmadi, 2001). In this method, the scaling coefficient between the recorded response spectrum and the target design acceleration spectrum ordinates is calculated in the selected frequency range, and the power spectral density function is adjusted with the square of this scaling coefficient and the recording is corrected. As a result of this process, a

new movement is obtained. The biggest challenge in using artificial records is to try to obtain a single record that corresponds to the design acceleration spectrum that symbolizes the range of many recorded actions. Since the design acceleration spectrum is the result of a statistical analysis that takes into account the effect of many seismic sources simultaneously, the spectrum acceleration values corresponding to different periods may also be derived from earthquakes in different sources. In addition, the main problem in artificial records is that a large amount of unrecorded amount of energy is exposed as a result of the increase in the number of cycles in strong motion.

- Simulated Earthquake Records

Such records are obtained from seismological source models that take into account the dispersion environment and soil characteristics that are the biggest challenges to acquire. In the analyzes used to obtain physically simulated records of the source and wave dispersion characteristics, the scenario earthquake must be defined depending on the size and distance. In particular, where seismic design regulations are used, most of this information is usually not available. (Rofooei et al., 2001)

- Recorded Earthquakes

The recorded earthquakes contain sound information about the nature and major characteristics of the earth's vibration (amplitude, duration, phase characteristics, and frequency content). It also reflects all factors such as the source, propagation environment, and ground that affect the records. Therefore, taking into account the seismological parameters of the field, the use of recorded ground motions gives a great advantage over other alternatives. In addition, the fact that the strong ground motion data banks have been enriched with each passing day and the access to them is getting easier with the advancing technology makes the use of acceleration data recorded in earthquakes widespread.

2.3.2. Ground Motion Records- Intensity Measures

Parameters computed from the ground motion records and parameters calculated from the response spectra are the two groups of ground motion intensity parameters. While some of these intensity parameters are based on a single value and can be obtained directly from the ground motion record or the response spectra, other parameters can be computed through equations, and thus, involve some calculations (Yakut & Yılmaz, 2008). Definitions and calculations of some intensity measure parameters can be seen as follows;

- **Max. Acceleration (g)-** Peak Ground Acceleration, PGA
- **Max. Velocity (cm/sec)-** Peak Ground Velocity, PGV
- **Max. Displacement (cm)-** Peak Ground Displacement, PGD

  The parameters PGA, PGV, and PGD represent the maximum amplitudes of acceleration, velocity, and displacement of the records.
- **Vmax / Amax: (sec)-** Peak Velocity and Acceleration Ratio
- **Acceleration RMS: (g)-** Root Mean Square of acceleration, a_{RMS}

  The root mean square acceleration arms, is defined as in Equation 1.

$$a_{RMS} = \frac{1}{DS}\int_{t_1}^{t_2}[a(t)]^2\,dt \tag{1}$$

  The DS is determined from the Husid plot (Husid, 1969), based on the interval during which the 5 to 95% of the total Arias Intensity IA is accumulated.
- **Velocity RMS: (cm/sec)-** Root Mean Square of velocity, v_{RMS}
- **Displacement RMS: (cm)-** Root Mean Square of displacement, d_{RMS}
- **Arias Intensity: (m/sec),** IA

  The IA is computed as in Equation 2.

$$IA=\frac{\pi}{2g}\int_0^{t(tot)}[a(t)]^2dt \tag{2}$$

- **Characteristic Intensity ($g^{3/2}sec^{1/2}$),** IC

  The Characteristic Intensity IC is determined using the relation in Equation 3.

$$IC = {a_{RMS}}^{3/2} \sqrt{t_{tot}} \tag{3}$$

- **Specific Energy Density (cm2/sec),** SED

  The Specific Energy Density SED is defined in Equation 4.

$$SED = \int_0^{t_{tot}} [v(t)]^2 \, dt \tag{4}$$

- **Cumulative Absolute Velocity (cm/sec),** CAV

  The Cumulative Absolute Velocity CAV is computed as in Equation 5.

$$CAV = \int_0^{t_{tot}} a(t) \, dt \tag{5}$$

- **Acceleration Spectrum Intensity (g*sec),** ASI

  The area under the acceleration response spectrum between periods of 0.1 and 0.5 s is defined as the Acceleration Spectrum Intensity and computed as in Equation 6.

$$ASI = \int_{0.1}^{0.5} Sa(\xi = 0.05, T) \, dT \tag{6}$$

- **Housner Intensity (cm),** HI

  It is defined as the area under the pseudo-velocity response spectrum between periods of 0.1 and 2.5 s and computed as in Equation 7.

$$HI = \int_{0.1}^{2.5} PSV(\xi = 0.05, T) \, dT \tag{7}$$

- **Velocity Spectrum Intensity (cm),** VSI

  The Velocity Spectrum Intensity is obtained from the absolute velocity spectrum, for the same period range as Housner Intensity.

- **Sustained Maximum Acceleration (g),** SMA

  The Sustained Maximum Acceleration, SMA is the third or fifth highest absolute value of acceleration in the time-history.

- **Sustained Maximum Velocity (cm/sec),** SMV

  The Sustained Maximum Velocity, SMV is the third or fifth highest absolute value of velocity in the time-history

- **Effective Design Acceleration (g),** EDA

  Effective Design Acceleration, EDA is defined as the peak acceleration value found after low pass filtering the input time history with a cut-off frequency of 9 Hz.

- **A95 parameter (g)**

  The acceleration parameter A95 is based on the Arias Intensity which is related to seismic destructiveness. This appears to be a predictable parameter and therefore can serve many engineering requirements. The parameter A95 is chosen to be as close to the peak as possible. However, any other level can serve as a design acceleration. (Sarma & Yang, 1987)

- **Predominant Period (sec), Tp**

  It is the period at which the maximum spectral acceleration occurs in an acceleration response spectrum calculated at 5% damping. The predominant period is defined as the period vibration corresponding to the maximum value of the Fourier amplitude spectrum.

- **Mean Period (sec), Tm**

The mean period (Tm) utilizes the Fourier Amplitude Spectrum, averaging periods (over a specified frequency range) weighted by the Fourier amplitudes. (Ellen, Norman, & Bray, 1998)

- **Max Incremental Velocity (cm/sec)**

Bertero et al. (1976) computed area under velocity vs time graph and called maximum incremental velocity. As a result, the difference between net increase in ground velocity over a uniform segment of time and maximum ground velocity that may be the result of successive increases in high-frequency unilateral acceleration increases.

- **Sa (T1) (g) -** Spectral acceleration at the fundamental period of the structure
- **Sa (T2) (g) -** Spectral acceleration at the period of the structure in second mode

2.4. Correlation Methods

The two methods are used to determine whether there is a relation between two series, and if so, the direction and severity of that relationship. Pearson's correlation coefficient and R-squared methods have been used in previous studies conducted in finding correlation between intensity measures and seismic demand parameters.

2.4.1. Pearson's Correlation Coefficient (r)

Pearson correlation coefficient is preferred if the data sets have a linear relation. If the correlation coefficient is negative, there is an inverse relationship between the two variables (Lin, 1989). If the correlation coefficient is positive, one of the variables increases as the other one increases. Pearson correlation coefficient varies between 1 and -1. If it is 1, there is an excellent positive relationship, and if it is -1 there is an excellent negative relationship. Illustrations of relationships between two different types of variables are shown in Figure 2-1 to Figure 2-3.

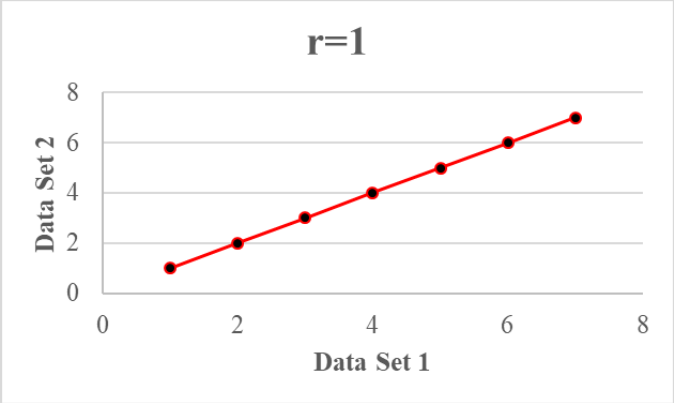


Figure 2-1: Graph showing perfectly positive correlation (Pearson's correlation coefficient = 1)

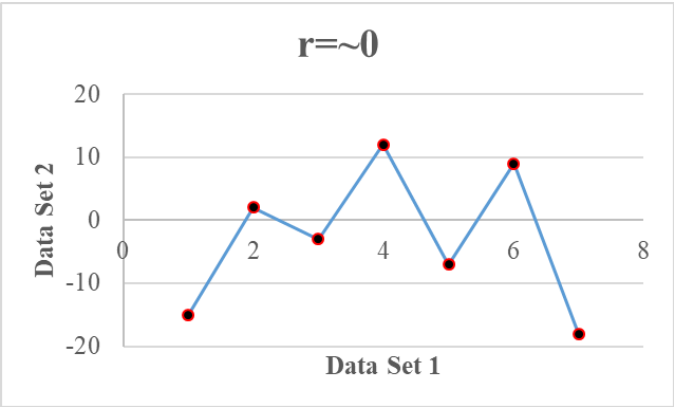


Figure 2-2: Graph showing no correlation (Pearson's correlation coefficient = 0)

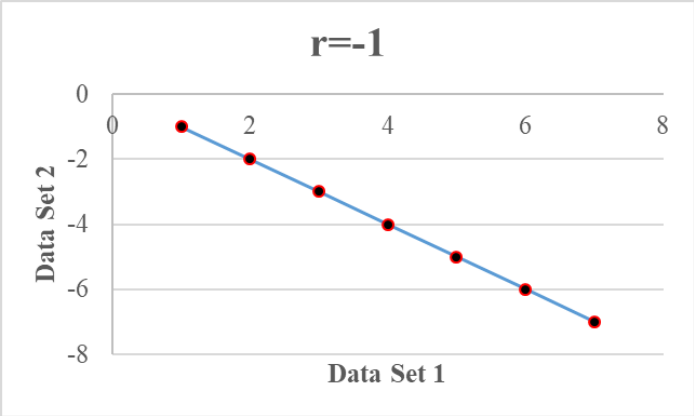


Figure 2-3: Graph showing perfectly negative correlation (Pearson's correlation coefficient = -1)

The Pearson's correlation coefficient formula between series can be seen in Equation 8.

$$r=\frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{\{[n\sum x^2-(\sum x^2)][n\sum y^2-(\sum y^2)]\}}} \quad (8)$$

where; n= number of the pairs of data sets, $\sum xy$ = sum of products of the paired data sets; $\sum x$ = sum of the x data sets; $\sum y$= sum of the y data sets; $\sum x^2$ = sum of the squared x data sets; $\sum y^2$ = sum of the squared y data sets

2.4.2. R-squared method (R^2)

Another way to find the correlation is R-squared method which can be defined basically as the square of Pearson's correlation coefficient. R-squared method was frequently used in previous studies in correlation between intensity measures and seismic demand parameters. In order to measure the success level of the regression equation, the statistical coefficient of determination (R^2) is used. It is a statistic that reflects the predictive power of the equation as well as measuring the success of the regression equation. It is the accuracy coefficient used to measure the accuracy of the model. It is a measure of the suitability of the model and can be computed by using Equation 9 (Cameron & Windmeijer, 1997).

$$R^2 = \frac{\Sigma_i^n (Y_{pi} - Y_m)^2}{\Sigma_i^n (Y_i - Y_m)^2} \tag{9}$$

where; Y_m is observations, Y_{pi} is observation mean, and Y_i is prediction.

CHAPTER 3

DYNAMIC ANALYSIS OF HIGHWAY BRIDGES IN TIME DOMAIN

3.1. Description of Bridges

Flyover type highway bridges shall be analyzed and discussed in this thesis since these types of bridges are commonly in use in intersections and reflect nonlinearity in geometry. For superstructure, while one pier in P2 axis is under equal loading on both sides with 12 prestresses girders, the other pier in P1 axis is loaded with one complete span with 12 prestressed girders and two separate spans that have 6 prestressed girders each. Each span length is varying between 24.5 m and 26.5 m among four bridges between the center of bearings. There are 5 axes and they are named A1-R, A1-L, P1, P2, and A2 respectively as seen in Figure 3-1 to Figure 3-3. A1-R, A1-L, A2 represents abutments while P1, P2 represents piers. Dimensions of the bridges are listed in Table 3-1 and Table 3-2.

As well as geometrical effects, the layout of elastomeric bearings can also be arranged. Elastomer bearings are typically used under each girder. For economical, construction and feasibility issues, less number of elastomeric bearings can be placed under transverse beams with construction joint connectivity at the ends of girders to each other. Four models are analyzed in this scope with same geometrically nonlinear superstructures, and different connectivity and substructure details. Hereafter, FBM1 represents flyover bridge model with total of 8 elastomeric bearings on cap beams with pier heights of 10 m, and with girders' clear span of 24.5 m, FBM2 represents flyover bridge model with total of 24 elastomeric bearings on cap beams with pier heights of 10 m, and with girders' clear span of 24.5 m, FBM3 represents flyover bridge model with total of 8 elastomeric bearings on cap beams with pier heights of 20 m, and with girders' clear span of 25.5 m and FBM4 represents flyover bridge

model with total of 8 elastomeric bearings on cap beams with pier heights of 40 m and with girders' clear span of 24.5 m. Dimension differences between four bridges are shown in Table 3-3. Plan view, profile view and cross section of pier axes region can be seen in Figure 3-6 to Figure 3-15.

Table 3-1: Dimensions in Axes of Bridges to be Analyzed

	Axes				
	A1-R	**A1-L**	**P1**	**P2**	**A2**
Skew angle (°)	15	15	0	0	0
Number of columns	0	0	2	2	0
Distances between center of RC columns (m)	-	-	6	6	-
RC Cap beam length (m)	-	-	11.9	11.9	-
RC Cap beam width (m)	-	-	1.5	1.5	-
Expansion joint on RC deck	Yes	Yes	No	No	Yes

Table 3-2: Dimensions Between the Axes of Bridges to be Analyzed

	Between Axes Of			
	A1-R/P1	**A1-L/P1**	**P1/P2**	**P2/A2**
RC Deck Width (m)	6.1	6.1	12.2	12.2
RC Deck Height (cm)	25	25	25	25
PSC Girder height (cm)	100	100	100	100
PSC girder cross section area (m^2)	0.4491	0.4491	0.4491	0.4491
Number of PSC girders	6	6	12	12

Table 3-3: Dimension Differences Between Bridge Models

	FBM1	FBM2	FBM3	FBM4
Column Heights (m)	10	10	20	40
Column Type	Oval	Oval	Circular	Box
Column Dimensions (m)	1.2x2.5	1.2x2.5	Ø2.1	2.5x2.5 (t=0.6 m)
Number of Bearings on Cap Beams	8	24	8	8
Clear Span of Girders (m)	24.5	24.5	25.5	26.5
Cap Beam Dimensions (m)	1.5x1.2	1.5x1.2	2.5x1.2	3x1.2

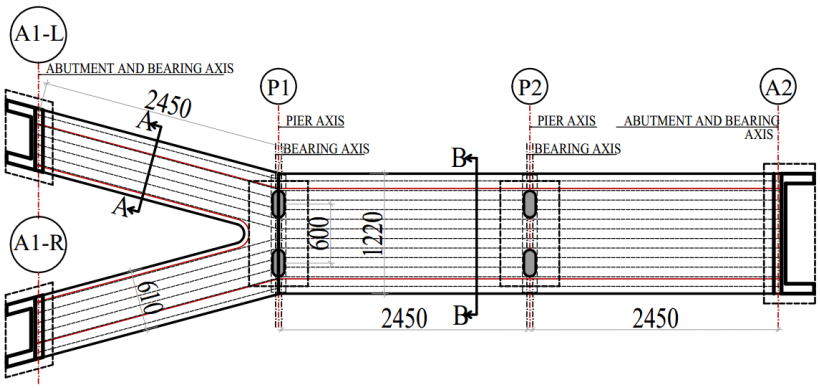


Figure 3-1: Plan View of FBM1 and FBM2

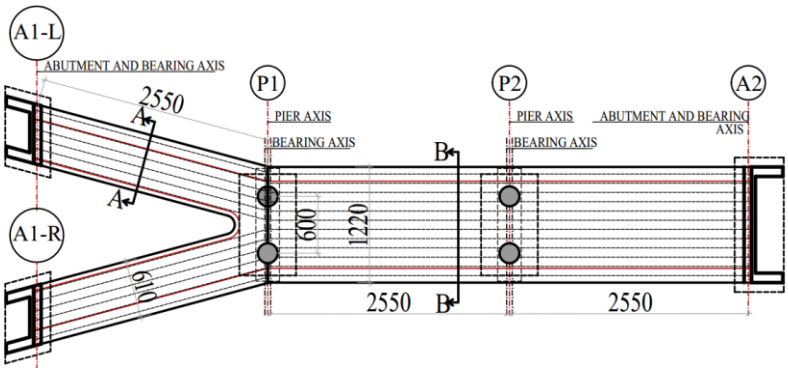


Figure 3-2: Plan View of FBM3

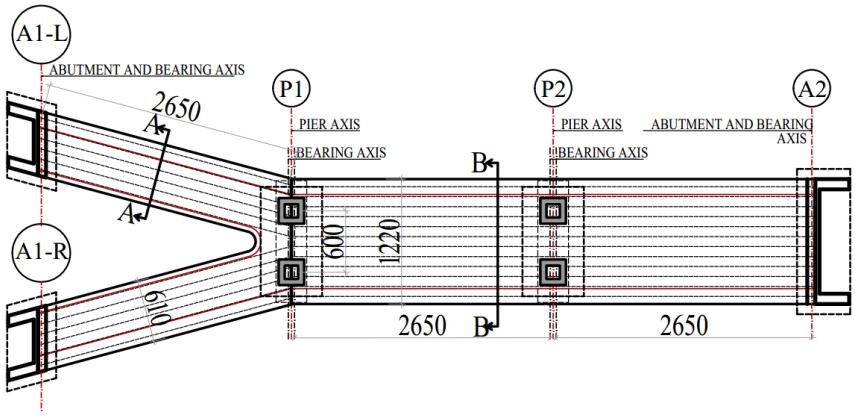


Figure 3-3: Plan View of FBM4

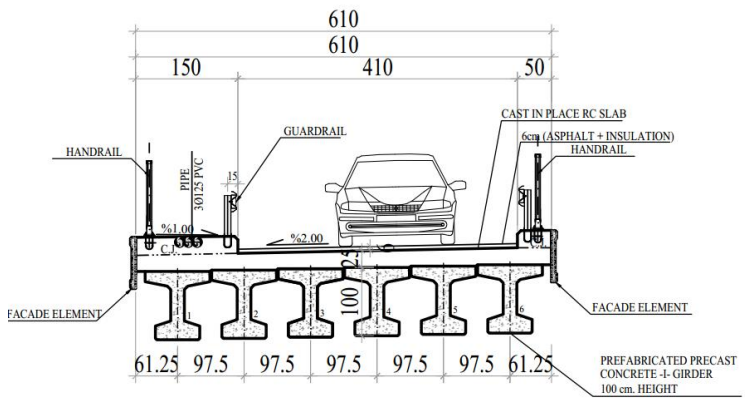


Figure 3-4: Superstructure Details between A1-P1 axis (Section A-A) (Units cm)

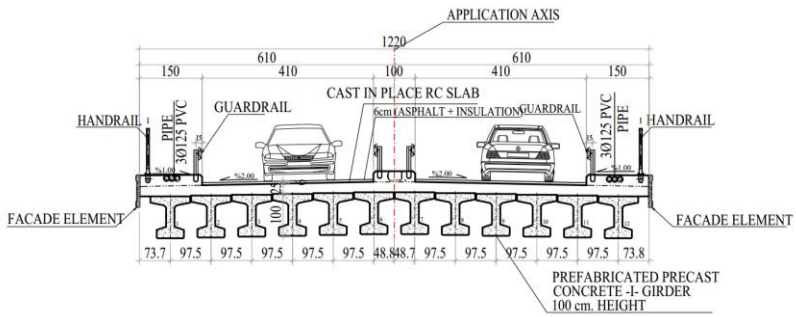


Figure 3-5: Superstructure Details between P1-A2 axis (Section B-B) (Units cm)

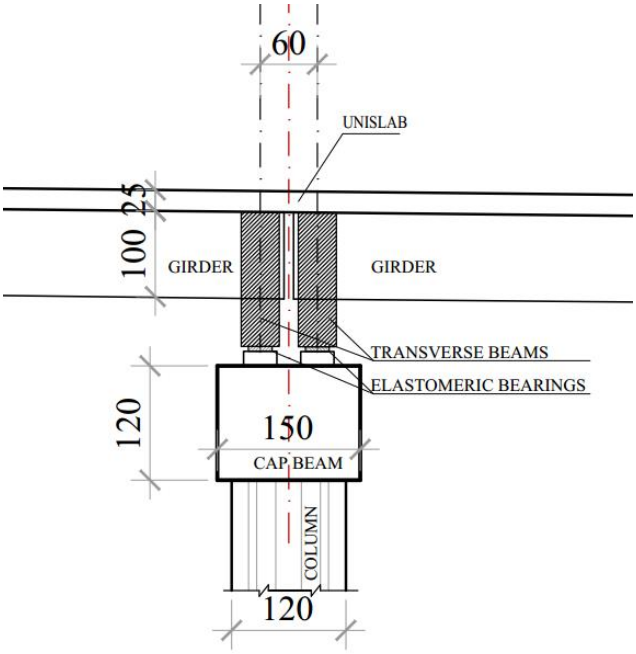


Figure 3-6: Profile view of pier axes region of FBM1

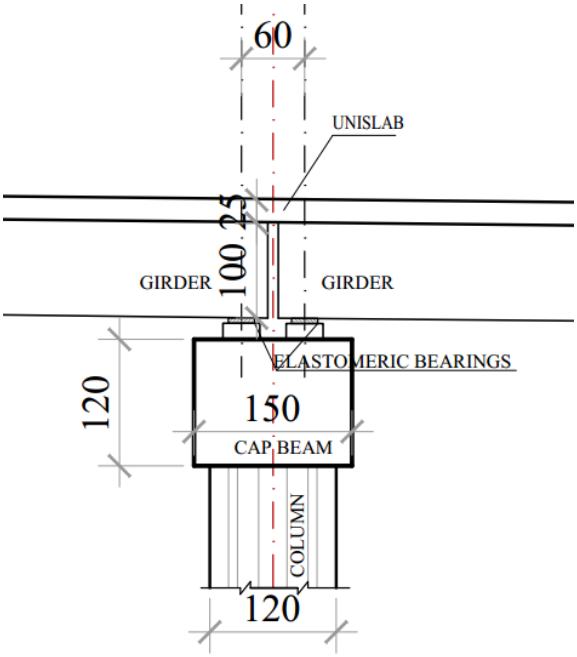


Figure 3-7:Profile view of pier axes region of FBM2

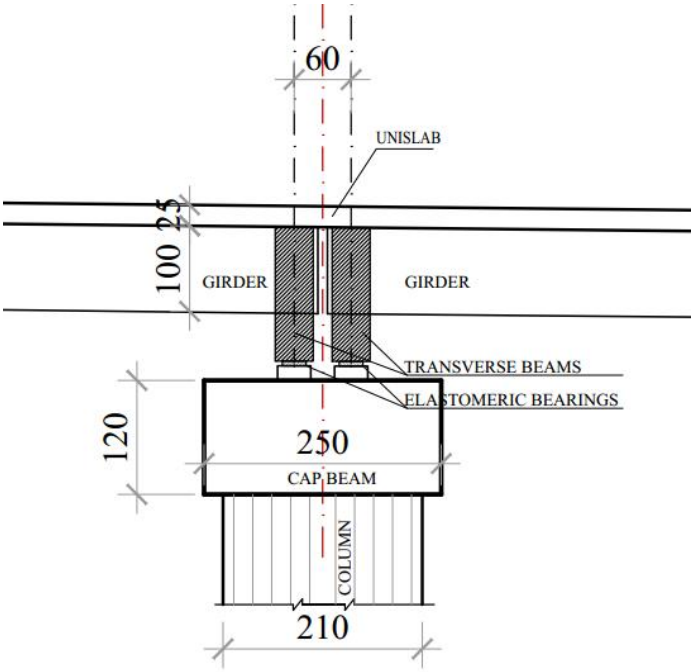


Figure 3-8: Profile view of pier axes region of FBM3

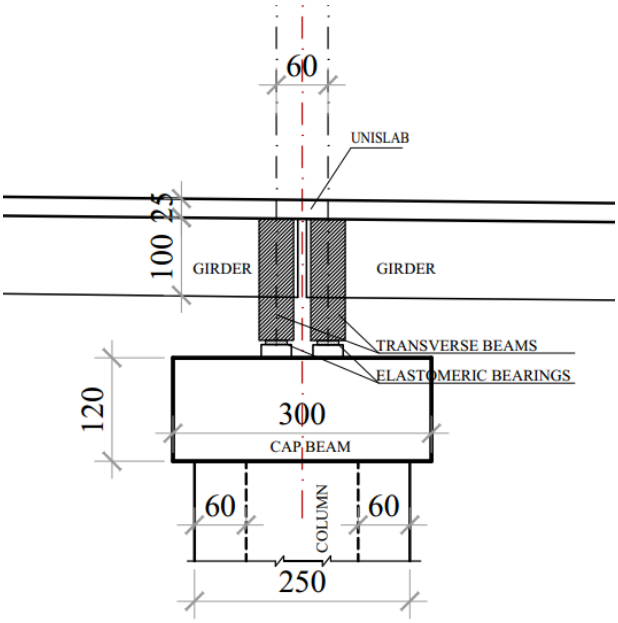


Figure 3-9: Profile view of pier axes region of FBM4

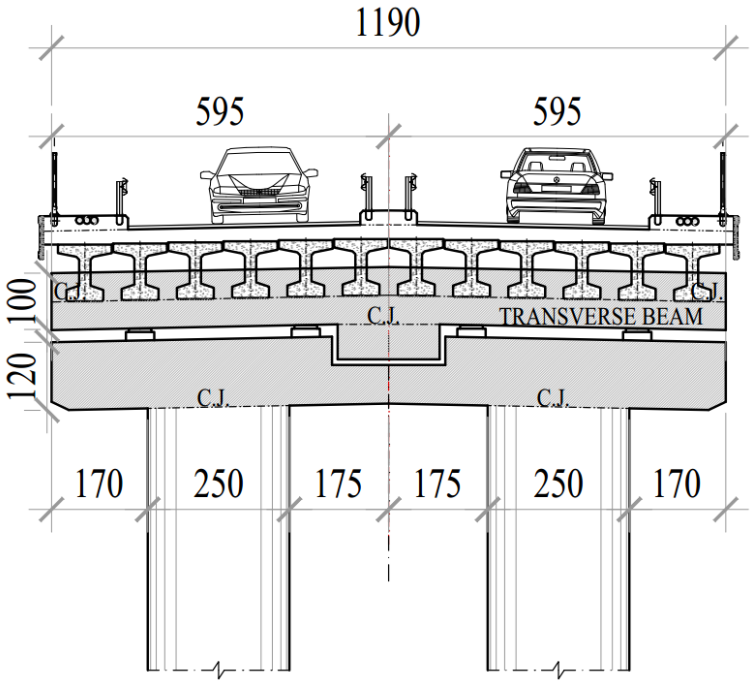


Figure 3-10: Cross section of pier axes region of FBM1

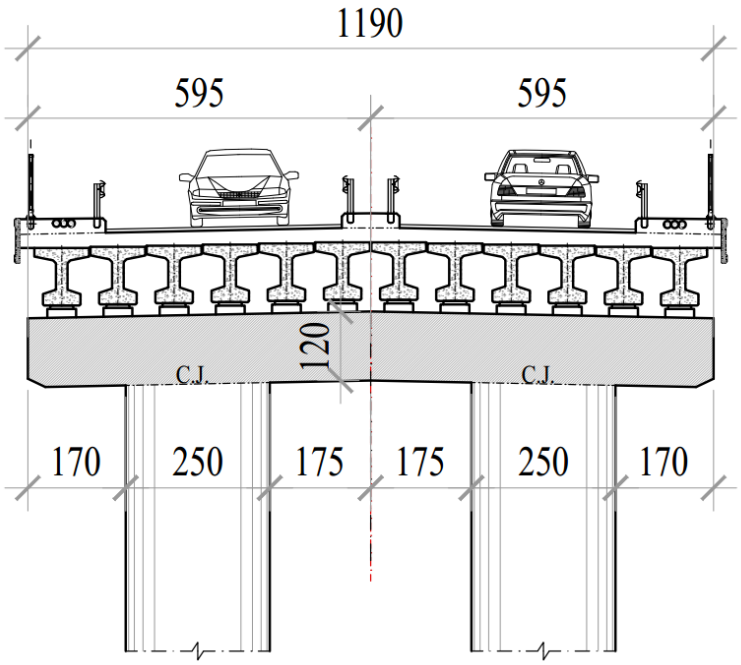


Figure 3-11: Cross section of pier axes region of FBM2

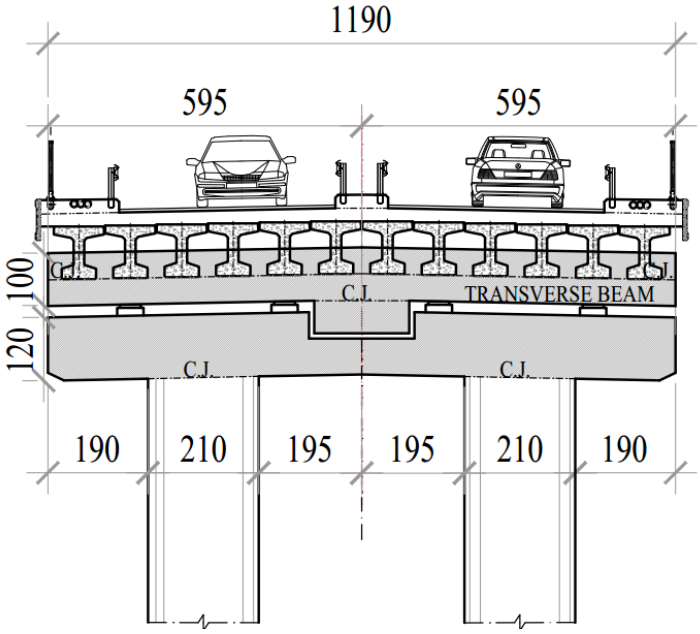


Figure 3-12: Cross section of pier axes region of FBM3

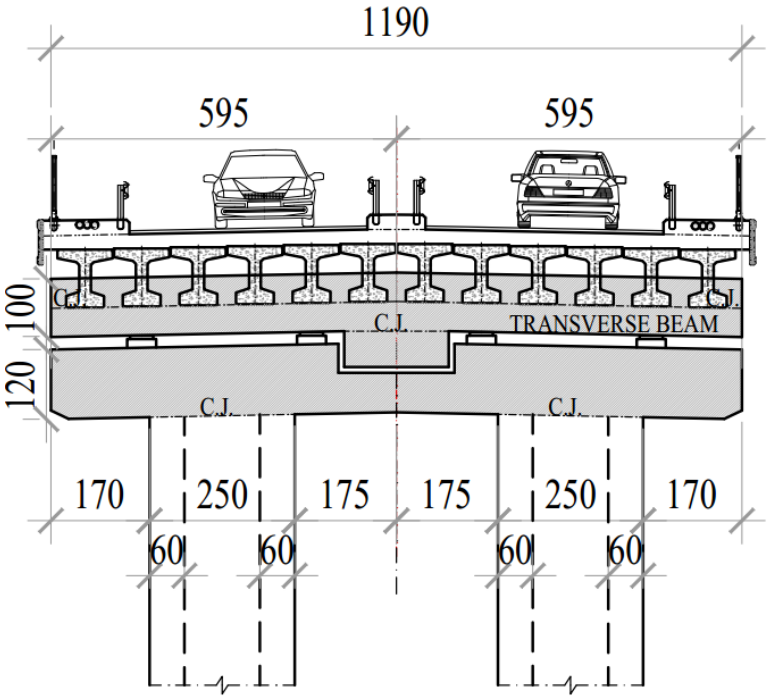


Figure 3-13: Cross section of pier axes region of FBM4

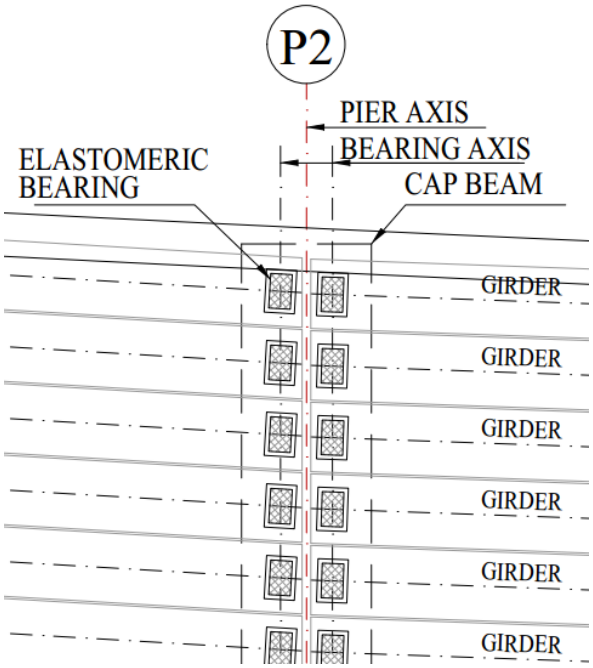


Figure 3-14: Plan view of P2 axis with girders and bearings with 24 elastomeric bearings

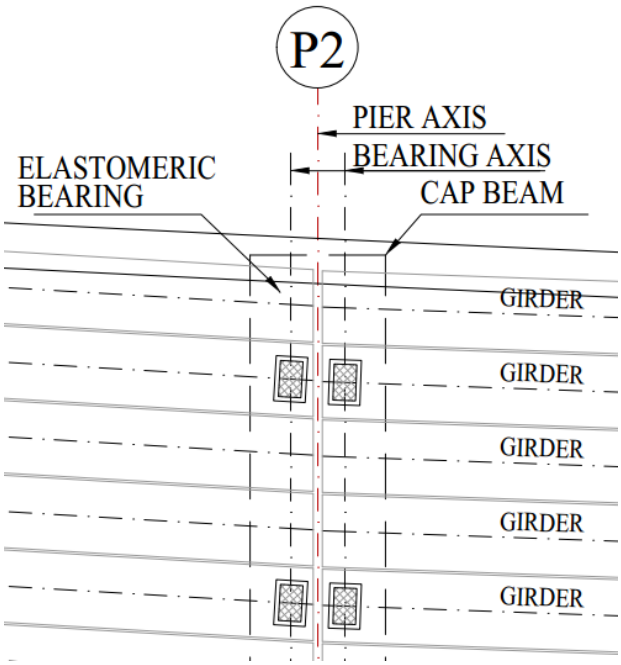


Figure 3-15: Plan view of P2 axis with girders and bearings with 8 elastomeric bearings

3.2. Bridge Analysis Models

Bridges including bearings analysis models ought to be established to calculate the seismic response of bearings underneath seismic effects. Global structural displacements, and member forces of bridge are analytically determined through mathematical models. Analytical bridge models are typically developed using acceptable assumptions and simplifications representing the entire system and its parts. Approximations sometimes result in enormous results. Analysis results can be checked by simple hand computations for verification purposes. The computer run time can be set to short run times so that errors can be detected easily and corrected. Usually, simple models of bridges can be used to estimate the seismic response.

3.2.1. Analysis Model

Since it is impossible to perform 3D bridge analysis manually in the time, a tool is needed for all the calculations and analyzes required. For this reason, four separate bridge models with geometric nonlinearities, whose geometries and features are mentioned in 3.1, are modeled as in Figure 3-16 to Figure 3-23 by using commercial software SAP2000 v14.2.2 (Computers & Structures Inc., 2016) by CSI. Complex models may be generated and meshed in the program. There are no nonlinearities in materials in the system.

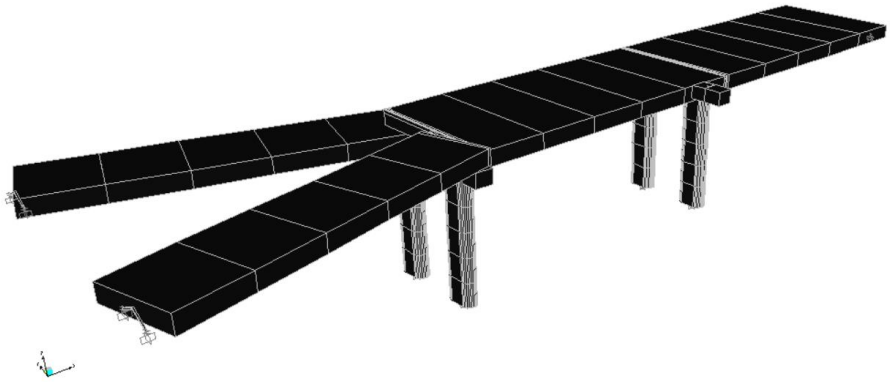


Figure 3-16: Extrude View of 3D Analysis Model of FBM1

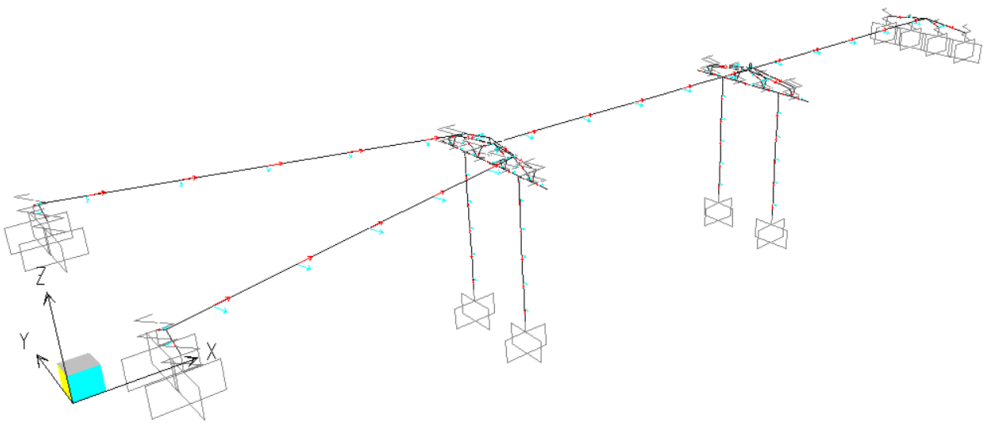


Figure 3-17: Standard View of 3D Analysis Model of FBM1

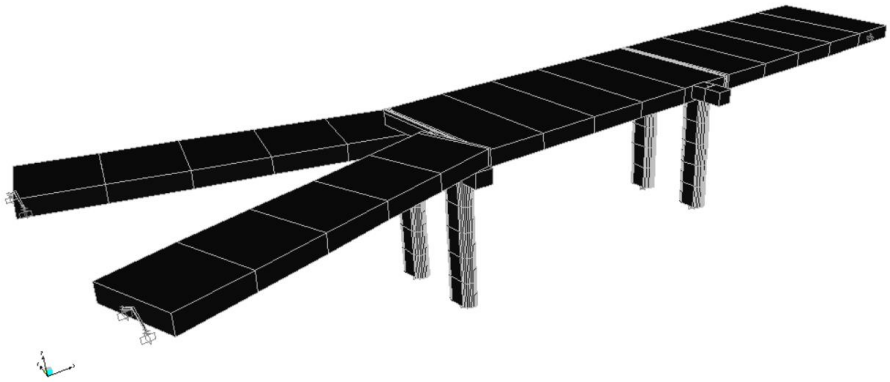


Figure 3-18: Extrude View of 3D Analysis Model of FBM2

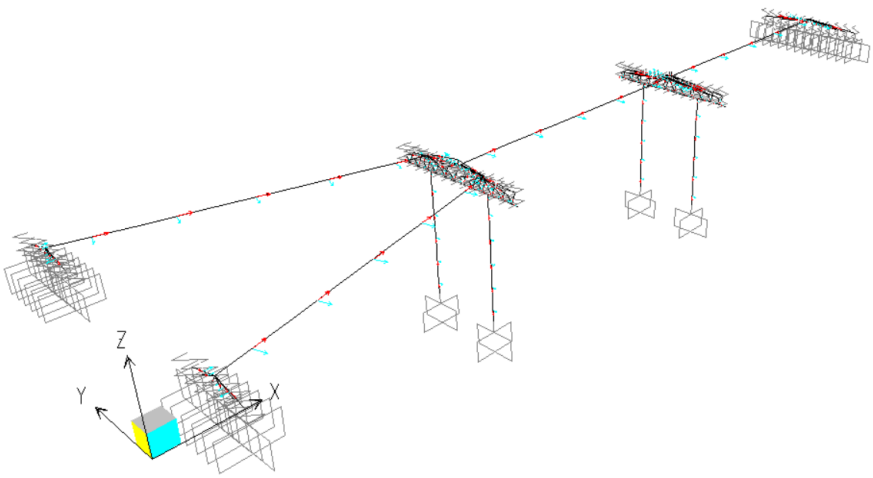


Figure 3-19: Standard View of 3D Analysis Model of FBM2

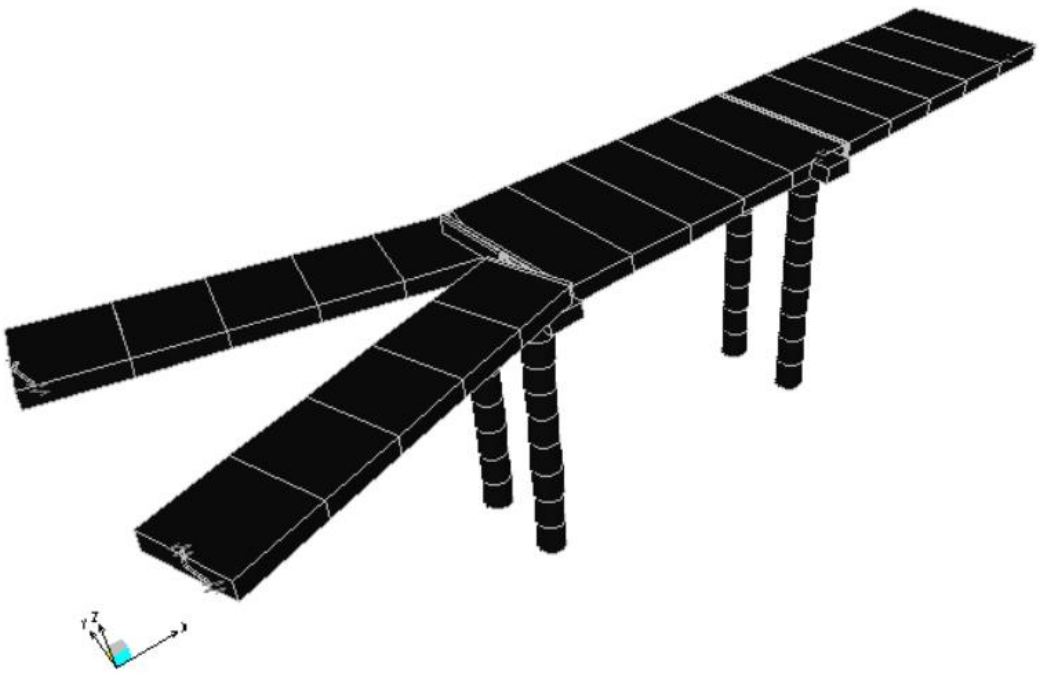


Figure 3-20: Extrude View of 3D Analysis Model of FBM3

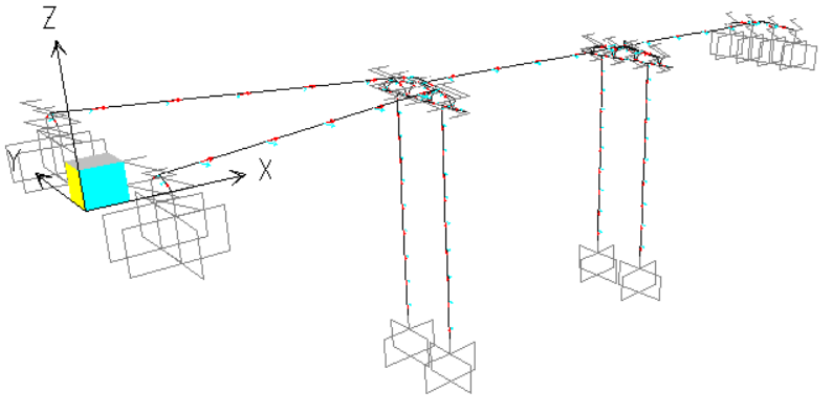


Figure 3-21: Standard View of 3D Analysis Model of FBM3

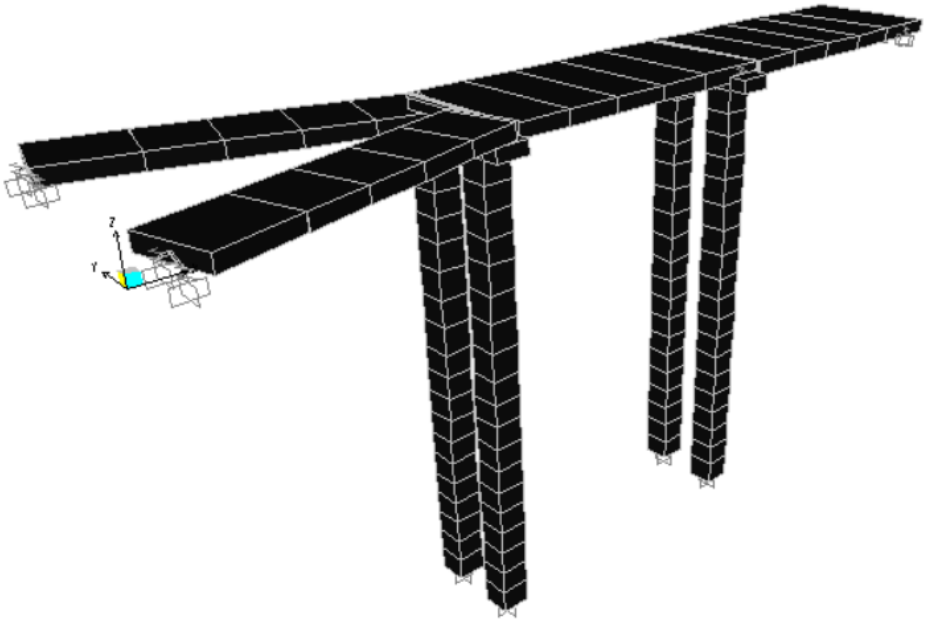


Figure 3-22: Extrude View of 3D Analysis Model of FBM4

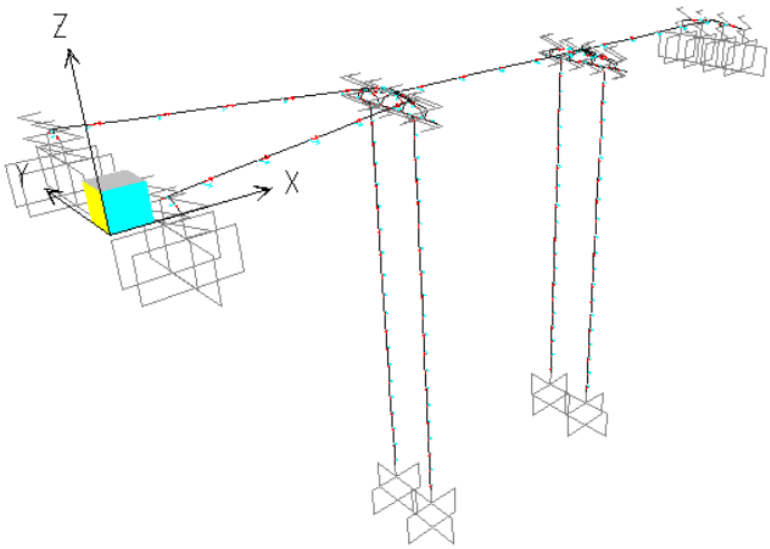


Figure 3-23: Standard View of 3D Analysis Model of FBM4

Analysis models of highway bridges can be constructed with mainly two structural components which are superstructure and substructure. Superstructure and substructure themselves and their connections play very important role on seismic effects so they must be modeled accurately. Modelling details are given in Figure 3-24 and Figure 3-25

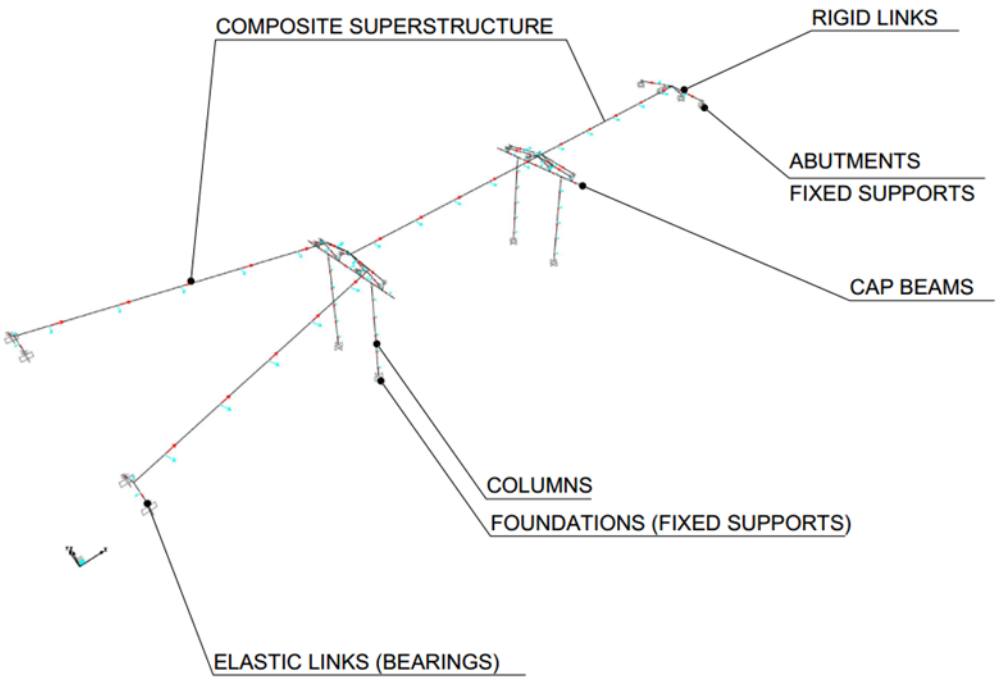


Figure 3-24: Model elements

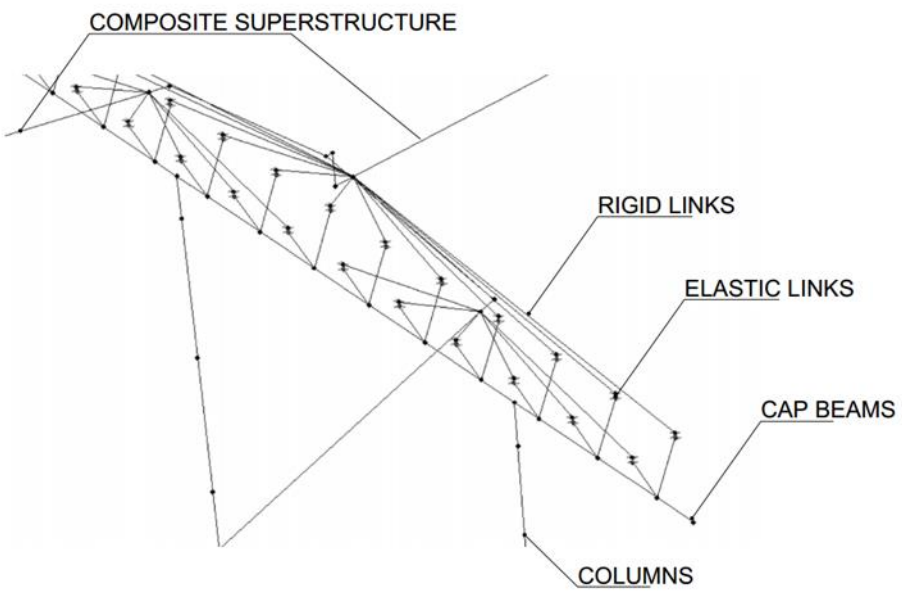


Figure 3-25:Model Elements (Zoomed in P1 Axis in FBM2)

3.2.1.1. Superstructure

Composite structure can be modeled as a frame element by combining prefabricated prestressed girders with in situ cast slab. The superstructure will be modeled so that each span has the five elements. The distributed mass of the span is agglomerated at points by means of a computer program. The dynamic behavior can be calculated with a sufficient number of points. In this case, five elements per span are sufficient to simulate mode shapes. The connection of the superstructure from the center of gravity to the support are provided with rigid elements.

The area and moment of inertia of the superstructure consisting of prefabricated concrete girder (C45/55) and cast-in-situ concrete slab (C30/37) shown in Figure 3-4 and Figure 3-5 are calculated from the section transformed to C45/55. The new unit density of the composite section and transformation can be calculated as in the following steps.

First, C30/37 in situ slab concrete is transformed to C45/55 by changing the dimensions. Only widths of slabs are changed by multiplying widths with square root of ratio between C30/37 and C45/55 class concretes' modulus of elasticities.

Slab width representing C45/55 concrete between P1-A2 axis: sqrt(30/45)*12.2 = 9.96 m.

Slab width representing C45/55 concrete between A1-P1 axis: sqrt(30/45)*6.1 = 4.98 m

Resulting C45/55 composite super structure sections can be seen in Figure 3-26 and Figure 3-27.

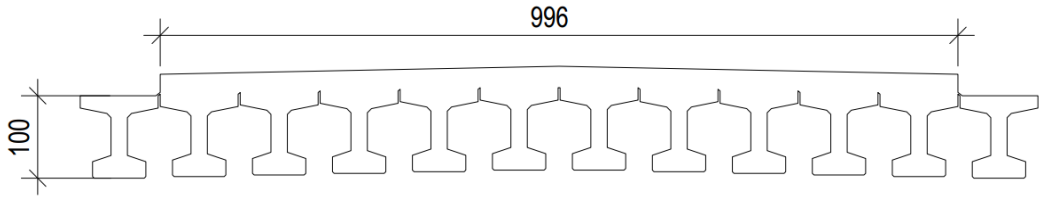


Figure 3-26: Composite Superstructure Details between P1-A2 axis (C45/55) (units in cm)

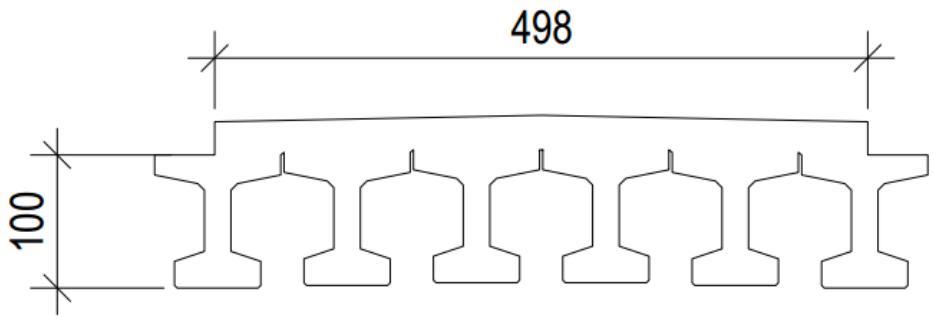


Figure 3-27: Composite Superstructure Details between A1-P1 axis (C45/55) (units in cm)

Superstructure is modeled using frame elements having properties of composite sections. To include super imposed dead loads, density of composite section has been increased. Super imposed dead loads can be calculated as below;

Super imposed dead loads between P1-A2 Axis:

- Asphalt: 0.06 x 8.2 x 24 = 11.81 kN/m
- Precast side panel: 2 x 0.08 x 0.7 x 25 = 2.80kN/m
- Pedestrian railing: 2 x 1.5 = 3.00 kN/m
- Guardrails: 4 x 0.5 = 2.00 kN/m
- Sideways: 1 x 4 x 0.25 x 25 = 25.00 kN/m

Total: 44.61 kN/m = 4.55 ton/m

Super imposed dead loads between A1-P1 Axis

- Asphalt: 0.06 x 4.1 x 24 = 5.90 kN/m
- Precast side panel: 2 x 0.08 x 0.7 x 25 = 2.80 kN/m
- Pedestrian railing: 2 x 1.5 = 3.00 kN/m
- Guardrails: 2 x 0.5 = 1.00 kN/m
- Sideways: 1 x 2 x 0.25 x 25 = 12.50 kN / m

Total : 25.20 kN/m = 2.57 ton/m

Composite superstructure area between P1-A2 axis: 7.82 m^2

Composite superstructure area between A1-P1 axis: 3.93 m^2

Super imposed dead loads as a unit density between P1-A2 axis: 4.55/7.82 = 0.58 ton/m^3

Super imposed dead loads as a unit density between A1-P1 axis: 2.57/3.93 = 0.65 ton/m^3

Considering concrete weight density is approximately 2.5 ton/m^3; weight density is modeled as 2.50+0.58=3.08 ton/m^3 between P1-A2 axis and as 2.50+0.65=3.15 ton/m^3 between A1-P1 axis.

Geometrical properties of superstructure assigned to model can be seen from figures between Figure 3-26 and Figure 3-31.

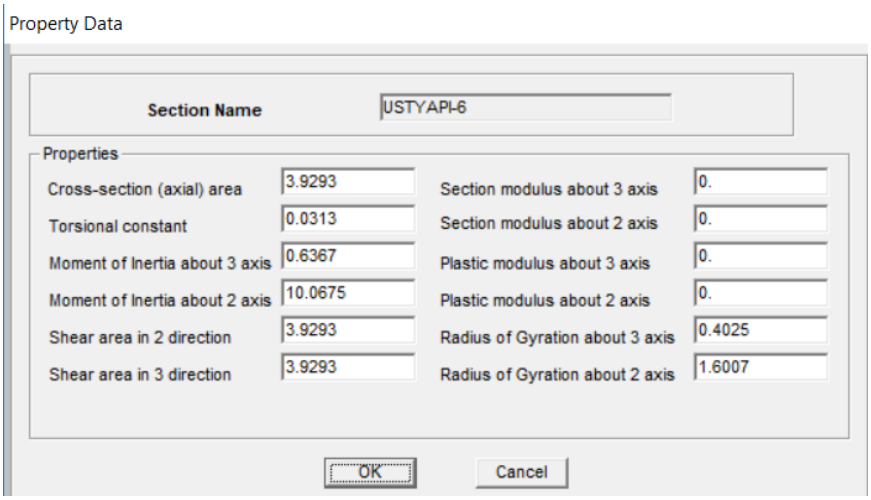


Figure 3-28: Composite Superstructure Geometrical Properties between A1-P1 axis

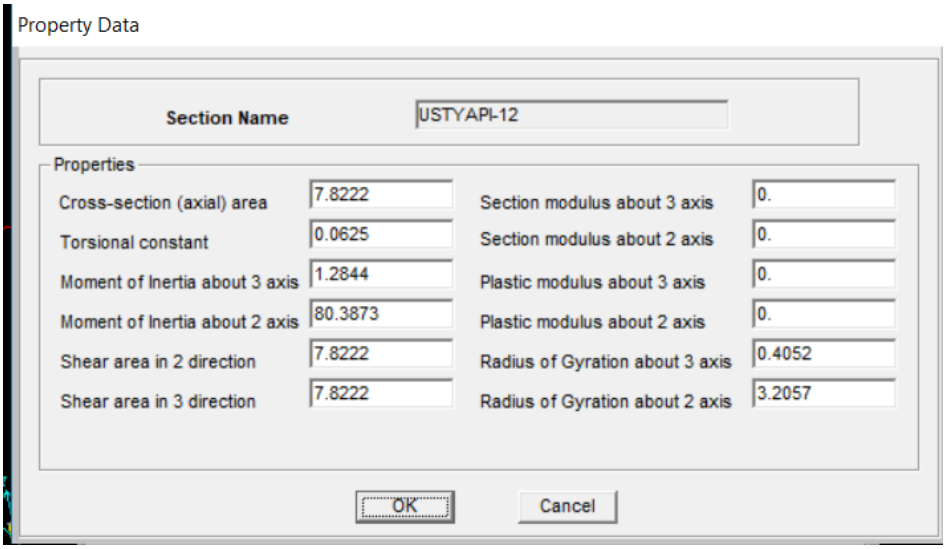


Figure 3-29: Composite Superstructure Geometrical Properties between P1-A2 axis

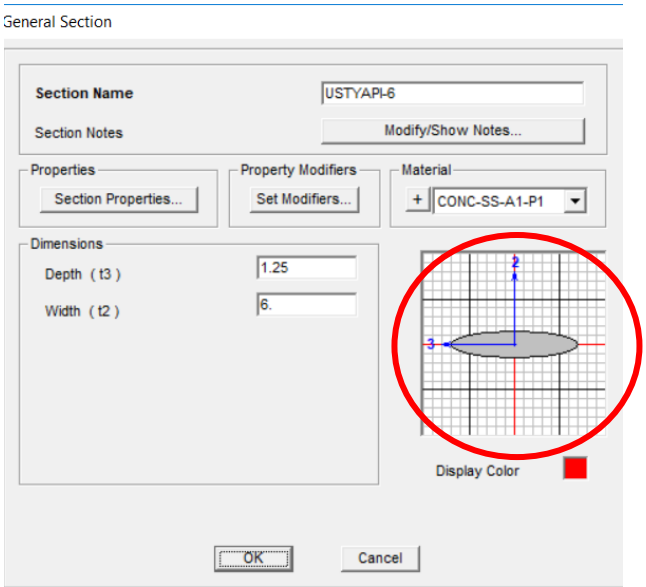


Figure 3-30: Composite Superstructure Local Axes between A1-P1 axis

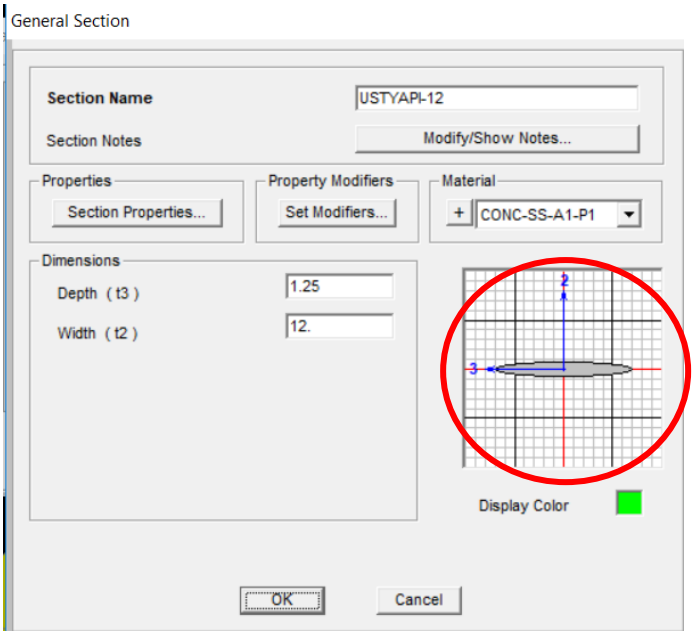


Figure 3-31: Composite Superstructure Local Axes between P1-A2 axis

Material properties assigned to superstructures can be seen from Figure 3-32 and Figure 3-33.

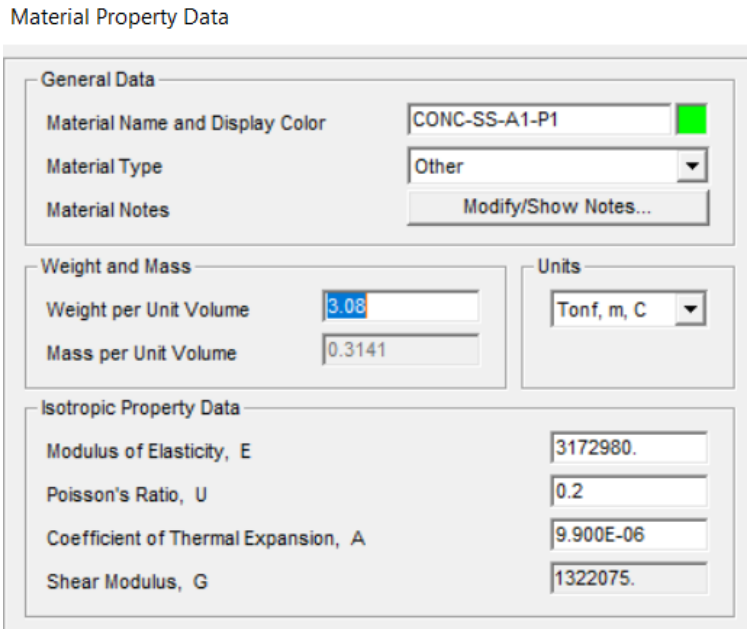


Figure 3-32:Material properties of superstructure between axes of A1-P1

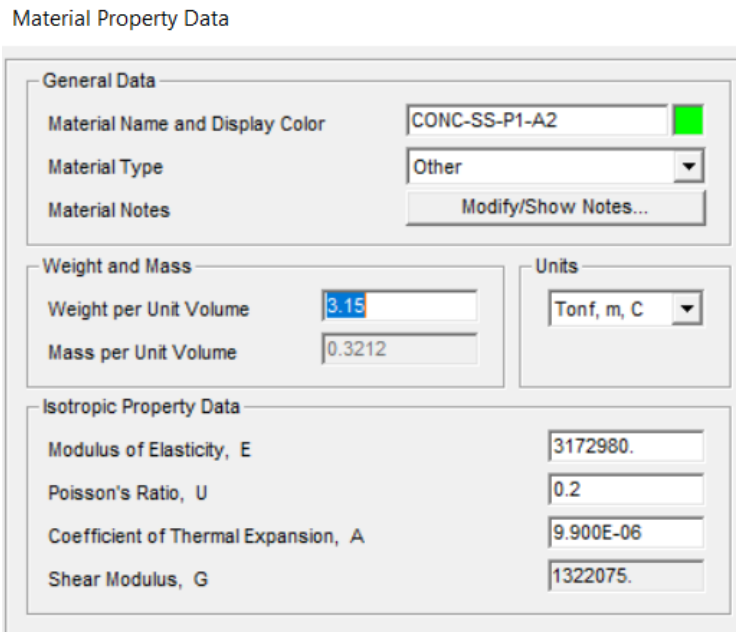


Figure 3-33: Material properties of superstructure between axes of P1-A2

3.2.1.2. Sub structure

- Abutments

Abutments are the earth-retaining structures that also support end of super structure. In engineering practice, abutment structures are either modeled by an equivalent spring or with a fixed support case. For simplicity, the abutments are assumed to be simulated by fixed supports in translation and rotation.

- Columns and Cap Beams

In order to see the direct effects of earthquakes on the whole structure, the dimensions of the columns and cap beams were selected not to have plastic response.

Geometrical properties of cap beam and column assigned to model can be seen in Figure 3-34 to Figure 3-37.

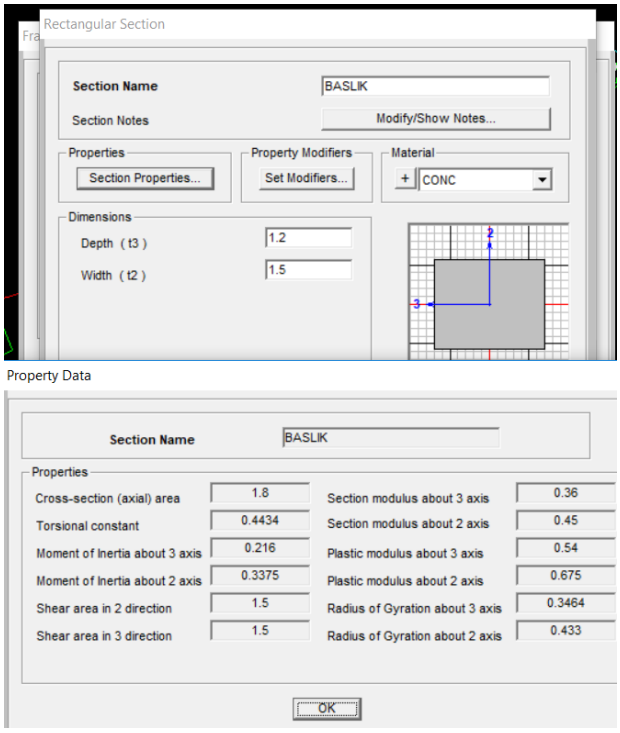


Figure 3-34: Cap Beam Geometrical Properties

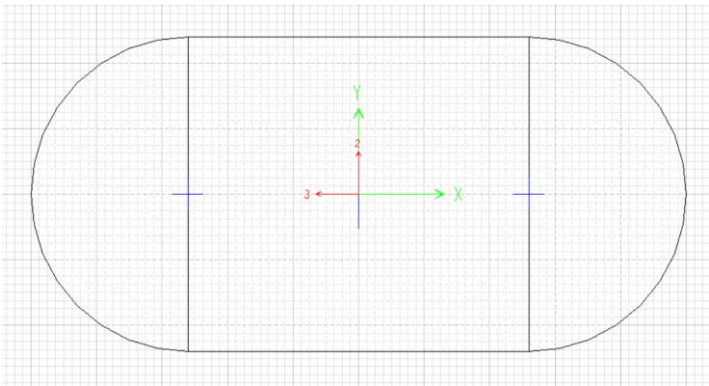
Column moment of inertias in both weak and strong way are decreased with the ratio of 0.5 to account for cracking.

Property Data

Section Name	KOLON

Properties

Cross-section (axial) area	2.6837	Section modulus about 3 axis	0.4795
Torsional constant	0.8924	Section modulus about 2 axis	0.9326
Moment of Inertia about 3 axis	0.2877	Plastic modulus about 3 axis	0.7532
Moment of Inertia about 2 axis	1.1658	Plastic modulus about 2 axis	1.5227
Shear area in 2 direction	2.3394	Radius of Gyration about 3 axis	0.3274
Shear area in 3 direction	2.3191	Radius of Gyration about 2 axis	0.6591



Frame Property/Stiffness Modification Factors

Property/Stiffness Modifiers for Analysis

Cross-section (axial) Area	1
Shear Area in 2 direction	1
Shear Area in 3 direction	1
Torsional Constant	1
Moment of Inertia about 2 axis	0.5
Moment of Inertia about 3 axis	0.5
Mass	1
Weight	1

Figure 3-35: FBM1 & FBM2 Column Geometrical Properties

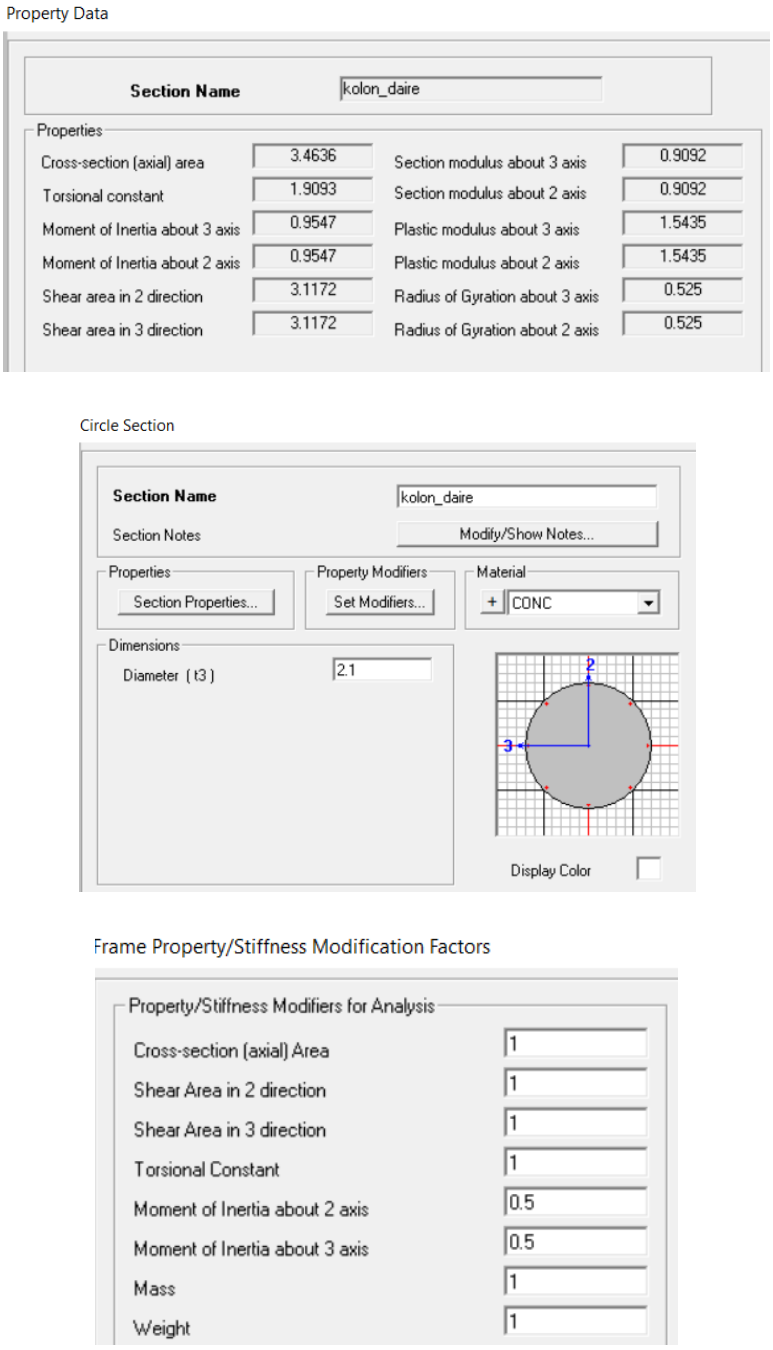
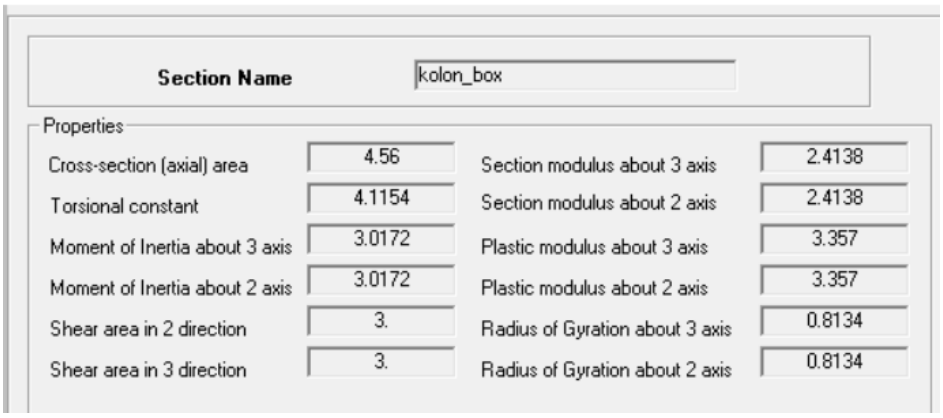
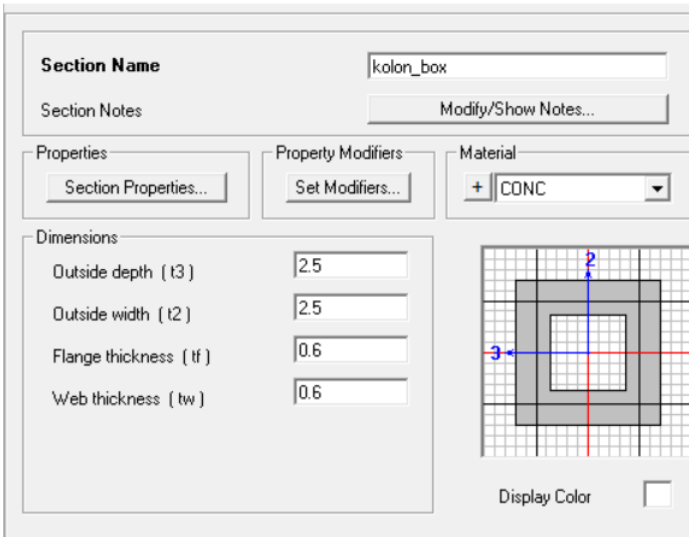


Figure 3-36: FBM3 Column Geometrical Properties

Property Data



Box/Tube Section



Frame Property/Stiffness Modification Factors

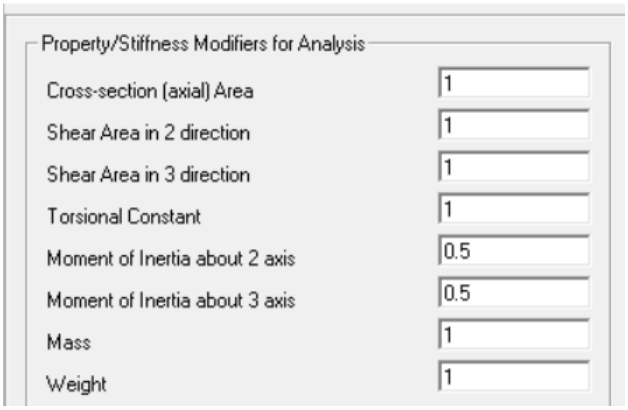


Figure 3-37: FBM4 Column Geometrical Properties

Since there are no expansion joints on the pier regions, slabs are identified in the model as a unifying element between composite superstructures. Slab geometrical properties can be seen from Figure 3-38.

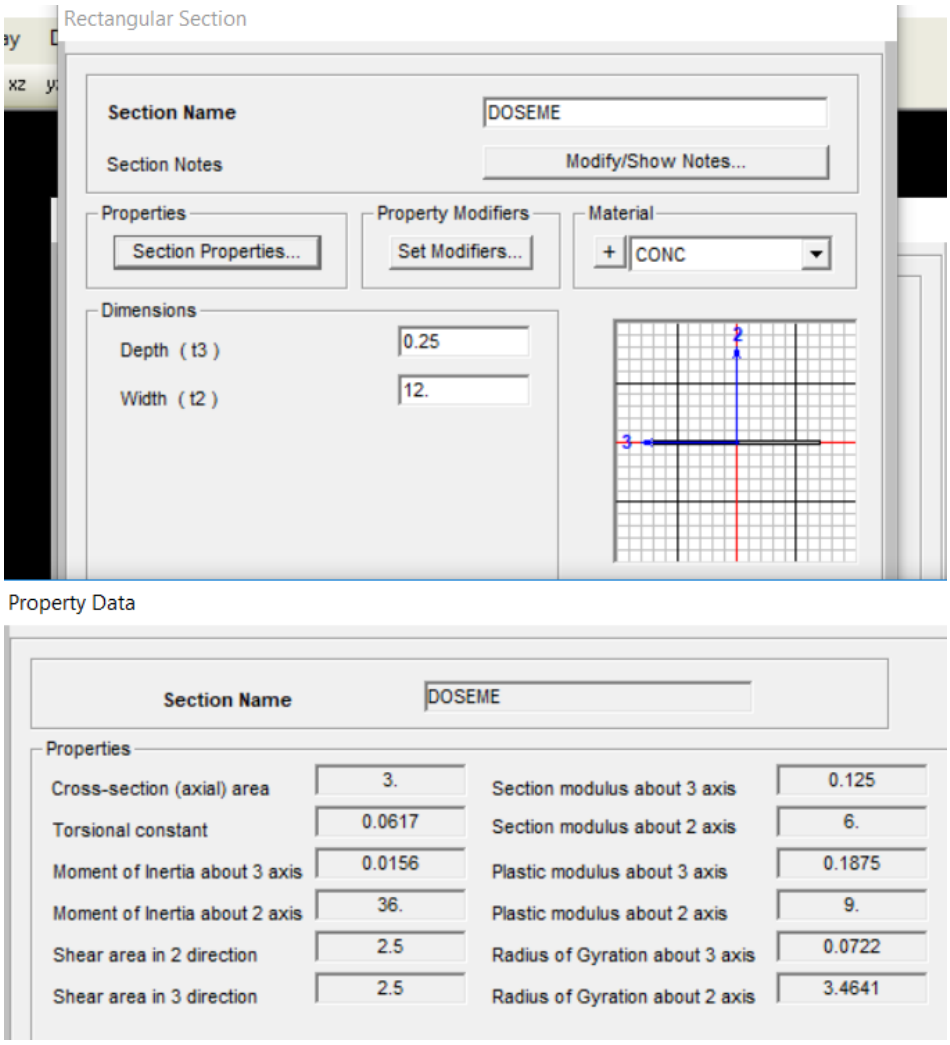


Figure 3-38: Slab Geometrical Properties

Material properties assigned to substructures can be seen from .

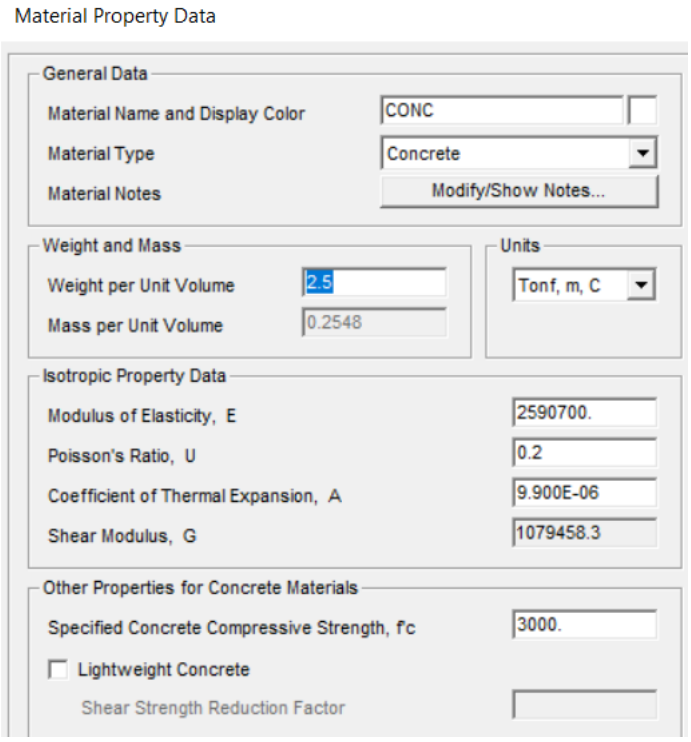


Figure 3-39: Material properties of substructures

3.2.1.3. Connections

Superstructure is connected to each elastomeric bearing with rigid links. Since superstructure is modeled with frame elements, and the load transfer to substructure are made through these rigid links. In order to transfer and distribute these effects, simple relatively rigid material is assumed. These rigid links also have no weight.

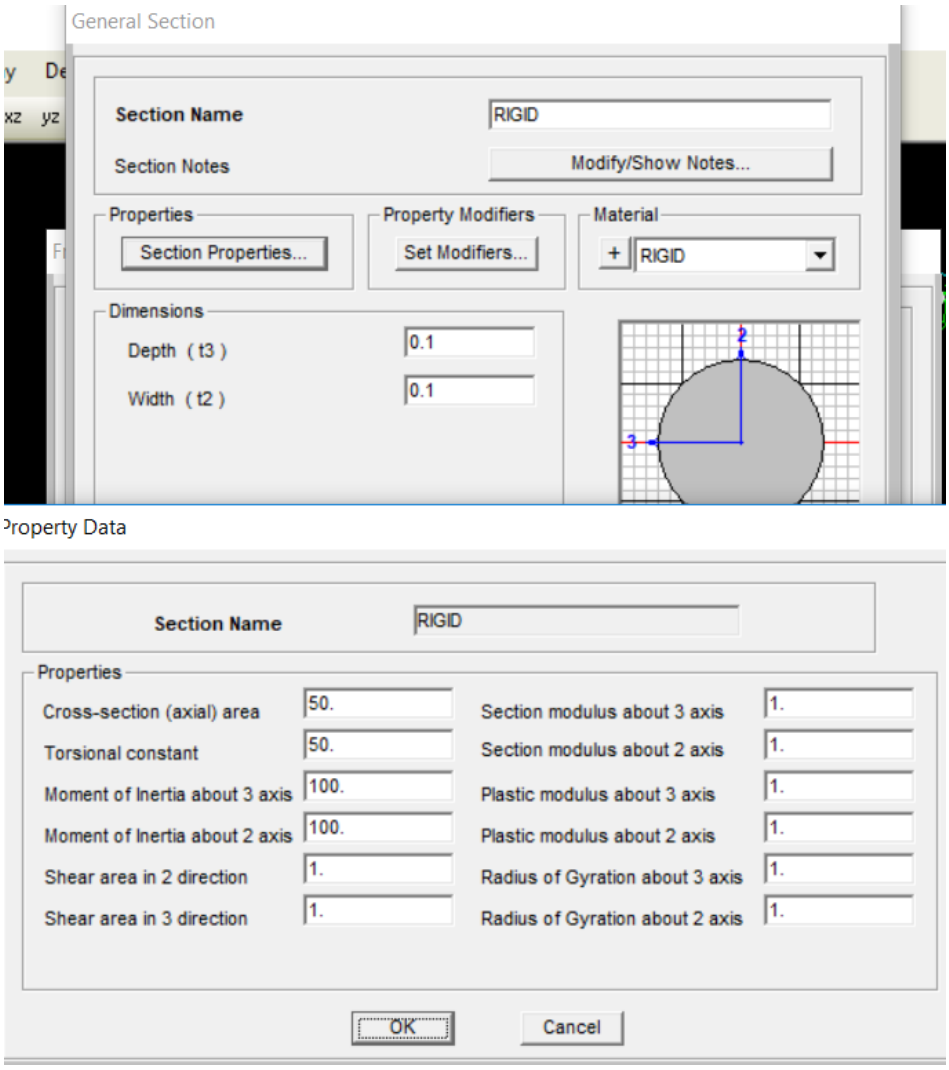


Figure 3-40: Rigid Link Geometrical Properties

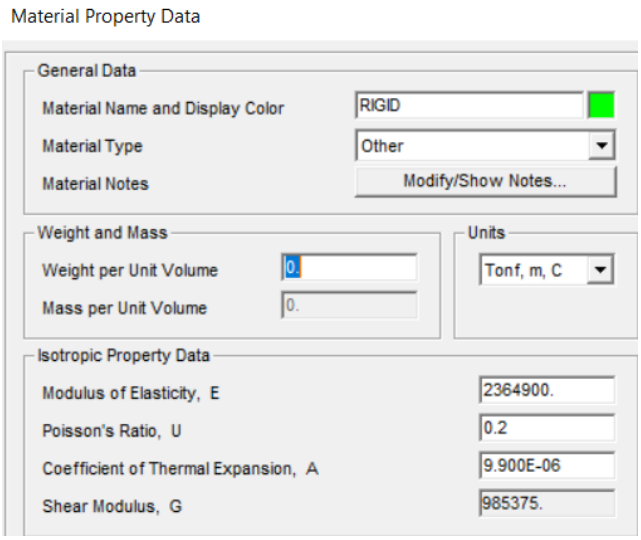


Figure 3-41: Rigid link material properties

In models of FBM1, FBM2, FBM3 and FBM4 bearing rigidities are considered to be equal. The collision to abutment will be avoided with proper gaps. Eventually, there are no nonlinearities in deformations or materials, but geometrical.

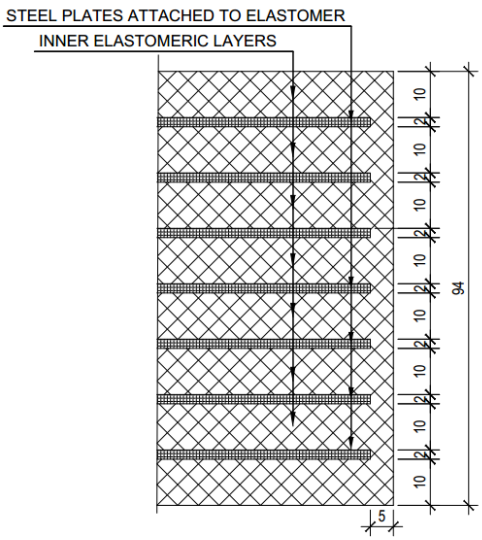


Figure 3-42: Elastomeric Bearing Dimensions in Profile view

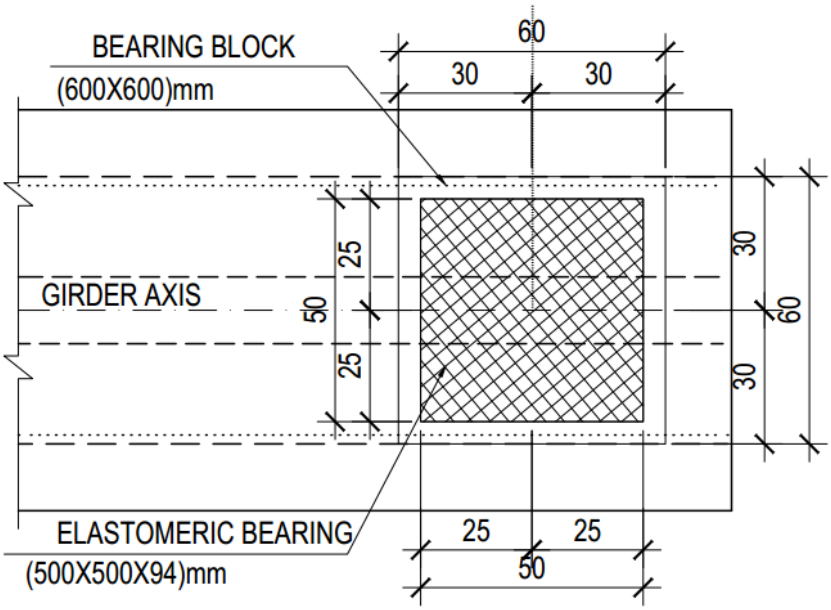


Figure 3-43: Elastomeric Bearing Dimensions in Plan view

Compressive stress, rotation, and stability check of elastomeric bearings can be found in Appendix D.

3.2.2. Modal Analysis Results

In modal analysis of four bridges, modal periods and mass participation ratios in first 15 modes are given in Table 3-4 to Table 3-7.

Table 3-4: FBM1 Participating Mass Ratios

FBM1 Modal Participating Mass Ratios									
OutputCase	**StepType**	**StepNum**	**Period**	**UX**	**UY**	**UZ**	**SumUX**	**SumUY**	**SumUZ**
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless
MODAL	Mode	1	**1.25**	**0.92**	0.00	0.00	0.92	0.00	0.00
MODAL	Mode	2	**1.03**	0.00	**0.86**	0.00	0.92	0.86	0.00
MODAL	Mode	3	0.90	0.00	0.00	0.00	0.92	0.86	0.00
MODAL	Mode	4	0.31	0.00	0.00	0.07	0.92	0.86	0.07
MODAL	Mode	5	0.28	0.00	0.00	0.04	0.92	0.86	0.10
MODAL	Mode	6	0.25	0.00	0.00	0.00	0.92	0.86	0.11
MODAL	Mode	7	0.25	0.04	0.00	0.00	0.96	0.86	0.11
MODAL	Mode	8	0.24	0.00	0.00	0.56	0.96	0.86	0.67
MODAL	Mode	9	0.22	0.00	0.00	0.00	0.96	0.86	0.67
MODAL	Mode	10	0.22	0.00	0.00	0.00	0.96	0.86	0.67
MODAL	Mode	11	0.20	0.00	0.00	0.00	0.96	0.86	0.67
MODAL	Mode	12	0.13	0.00	0.10	0.00	0.96	0.96	0.67
MODAL	Mode	13	0.08	0.00	0.00	0.00	0.96	0.96	0.68
MODAL	Mode	14	0.08	0.00	0.00	0.00	0.96	0.96	0.68
MODAL	Mode	15	0.08	0.00	0.00	0.00	0.96	0.96	0.68

Table 3-5: FBM2 Participating Mass Ratios

FBM2 Modal Participating Mass Ratios									
OutputCase	**StepType**	**StepNum**	**Period**	**UX**	**UY**	**UZ**	**SumUX**	**SumUY**	**SumUZ**
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless
MODAL	Mode	1	**0.84**	**0.94**	0.00	0.00	0.94	0.00	0.00
MODAL	Mode	2	**0.50**	0.00	**0.91**	0.00	0.94	0.91	0.00
MODAL	Mode	3	0.39	0.00	0.00	0.00	0.94	0.91	0.00
MODAL	Mode	4	0.30	0.00	0.00	0.07	0.94	0.91	0.07
MODAL	Mode	5	0.28	0.00	0.00	0.03	0.94	0.91	0.09
MODAL	Mode	6	0.24	0.00	0.00	0.57	0.94	0.91	0.66
MODAL	Mode	7	0.22	0.00	0.00	0.00	0.94	0.91	0.66
MODAL	Mode	8	0.18	0.00	0.00	0.00	0.94	0.91	0.66
MODAL	Mode	9	0.18	0.00	0.00	0.00	0.94	0.91	0.66
MODAL	Mode	10	0.18	0.00	0.00	0.00	0.94	0.91	0.66
MODAL	Mode	11	0.17	0.02	0.00	0.00	0.96	0.91	0.66
MODAL	Mode	12	0.10	0.00	0.05	0.00	0.96	0.96	0.66
MODAL	Mode	13	0.09	0.00	0.00	0.00	0.96	0.96	0.66
MODAL	Mode	14	0.08	0.00	0.00	0.00	0.96	0.96	0.67
MODAL	Mode	15	0.08	0.00	0.00	0.00	0.96	0.96	0.67

Table 3-6: FBM3 Participating Mass Ratios

FBM3 Modal Participating Mass Ratios									
OutputCase	**StepType**	**StepNum**	**Period**	**UX**	**UY**	**UZ**	**SumUX**	**SumUY**	**SumUZ**
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless
MODAL	Mode	1	**1.47**	**0.87**	0.00	0.00	0.87	0.00	0.00
MODAL	Mode	2	**1.25**	0.00	**0.85**	0.00	0.87	0.85	0.00
MODAL	Mode	3	0.98	0.00	0.00	0.00	0.87	0.85	0.00
MODAL	Mode	4	0.44	0.00	0.00	0.00	0.87	0.85	0.00
MODAL	Mode	5	0.42	0.04	0.00	0.00	0.91	0.85	0.00
MODAL	Mode	6	0.39	0.00	0.00	0.00	0.91	0.85	0.00
MODAL	Mode	7	0.38	0.00	0.08	0.00	0.91	0.92	0.00
MODAL	Mode	8	0.32	0.00	0.00	0.06	0.91	0.92	0.06
MODAL	Mode	9	0.29	0.00	0.00	0.03	0.91	0.92	0.08
MODAL	Mode	10	0.25	0.00	0.00	0.46	0.91	0.92	0.54
MODAL	Mode	11	0.24	0.00	0.00	0.01	0.91	0.92	0.55
MODAL	Mode	12	0.23	0.00	0.00	0.00	0.91	0.92	0.55
MODAL	Mode	13	0.22	0.00	0.00	0.00	0.91	0.93	0.55
MODAL	Mode	14	0.12	0.05	0.00	0.00	0.96	0.93	0.55
MODAL	Mode	15	0.12	0.00	0.00	0.00	0.96	0.93	0.55

Table 3-7: FBM4 Participating Mass Ratios

FBM4 Modal Participating Mass Ratios									
OutputCase	**StepType**	**StepNum**	**Period**	**UX**	**UY**	**UZ**	**SumUX**	**SumUY**	**SumUZ**
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless	Unitless	Unitless	Unitless
MODAL	Mode	1	**1.78**	**0.80**	0.00	0.00	0.80	0.00	0.00
MODAL	Mode	2	**1.59**	0.00	**0.82**	0.00	0.80	0.82	0.00
MODAL	Mode	3	1.05	0.00	0.00	0.00	0.80	0.82	0.00
MODAL	Mode	4	0.70	0.00	0.00	0.00	0.80	0.82	0.00
MODAL	Mode	5	0.66	0.00	0.00	0.00	0.80	0.82	0.00
MODAL	Mode	6	0.63	0.00	0.04	0.00	0.80	0.86	0.00
MODAL	Mode	7	0.62	0.04	0.00	0.00	0.84	0.86	0.00
MODAL	Mode	8	0.36	0.00	0.00	0.04	0.84	0.86	0.04
MODAL	Mode	9	0.34	0.00	0.00	0.00	0.84	0.86	0.04
MODAL	Mode	10	0.33	0.00	0.00	0.02	0.84	0.86	0.06
MODAL	Mode	11	0.29	0.00	0.00	0.00	0.84	0.86	0.06
MODAL	Mode	12	0.27	0.03	0.00	0.14	0.87	0.86	0.20
MODAL	Mode	13	0.27	0.04	0.00	0.05	0.91	0.86	0.25
MODAL	Mode	14	0.27	0.00	0.00	0.16	0.91	0.86	0.41
MODAL	Mode	15	0.25	0.00	0.00	0.00	0.91	0.86	0.41

The mass participation ratios are about 90% in the first mode in bridge longitudinal direction.

First three mode shapes of four bridges are illustrated in Figure 3-44 to Figure 3-46.

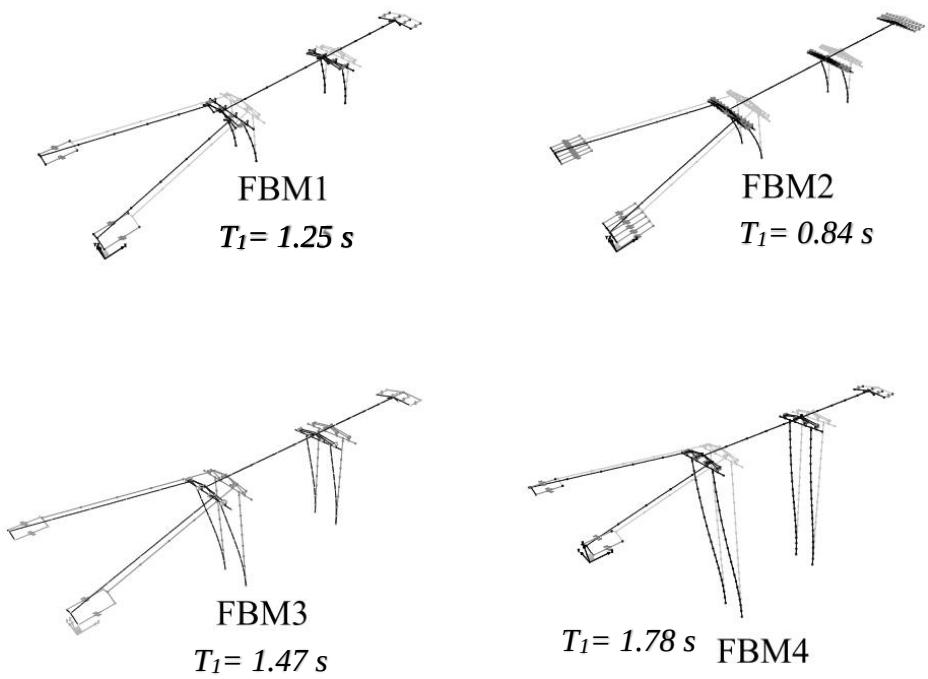


Figure 3-44: First mode shapes of bridges

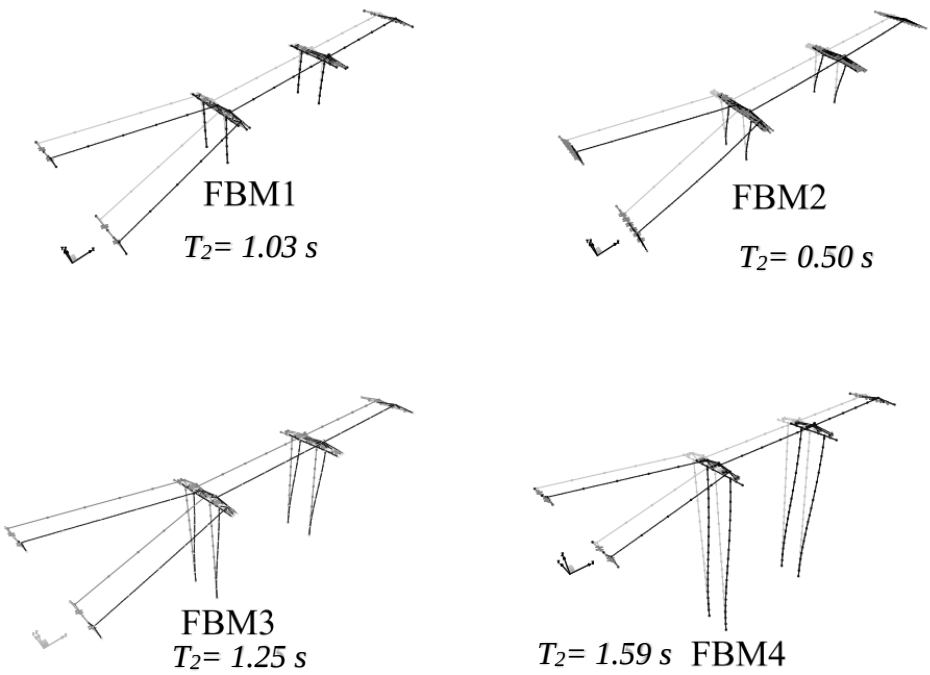


Figure 3-45: Second mode shapes of bridges

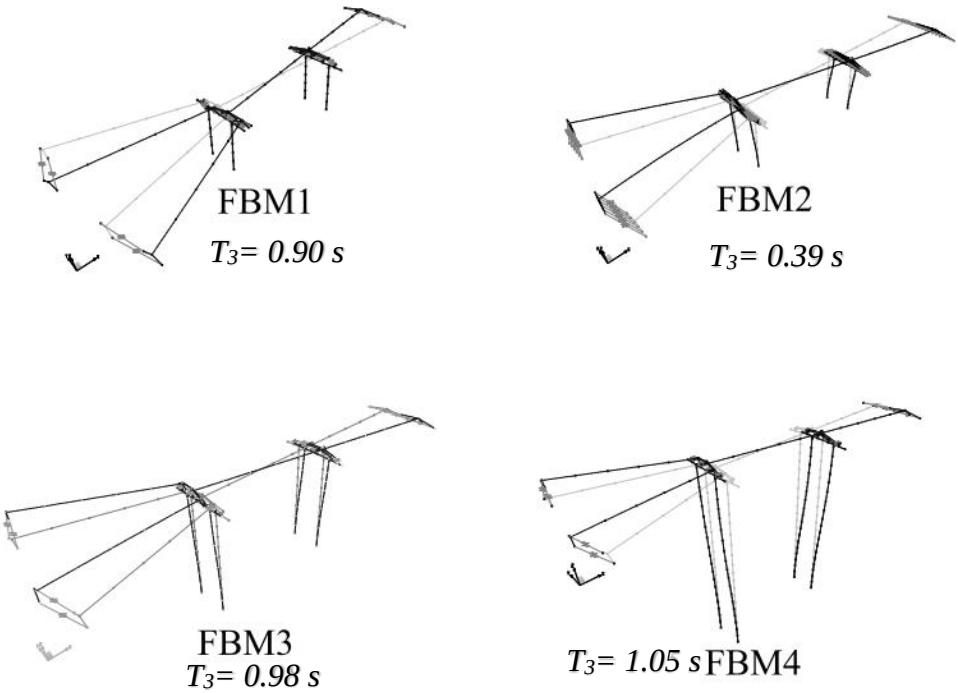


Figure 3-46: Third mode shapes of bridges

In addition to modal analysis, a new uniformly distributed unit loads are introduced to the system. As well as affecting natural periods, reduction in the number of bearings also affects the load distribution between abutments and columns. Each span is loaded with total force of 14000 tonf. The loads given can be seen in Figure 3-47 .

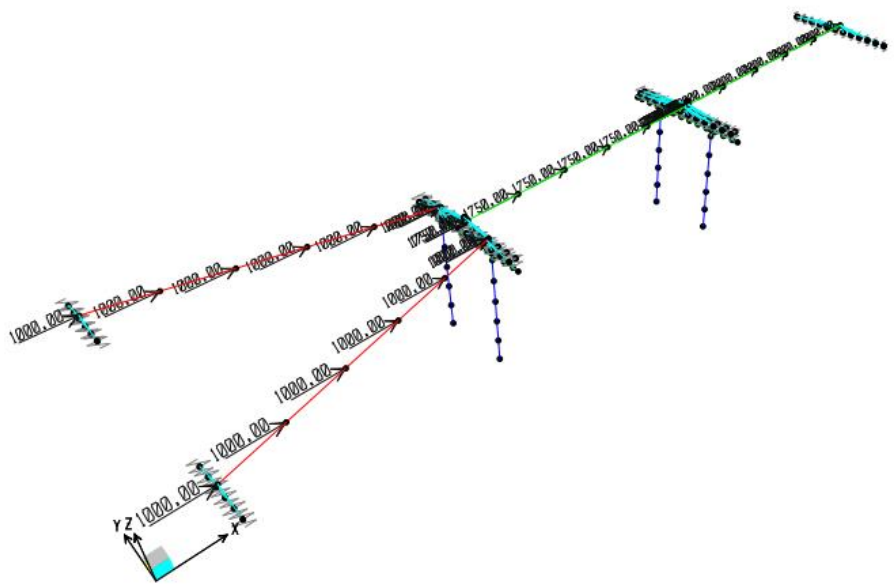


Figure 3-47: Uniformly distributed unit loads

In order to understand the load distribution between columns and abutments, base reactions resulted from a new uniformly distributed unit loads introduced to the system can be compared.

In FBM2, the total base reaction in P2 axis is 6522 tonf.

In FBM2, the total base reaction in A2 axis is 14616 tonf.

In FBM1, the total base reaction in P2 axis is 9548 tonf.

In FBM1, the total base reaction in A2 axis is 11590 tonf.

To conclude, not only number of bearings is affecting seismic effects on bridge, but number of bearings can also be arranged to optimize load distribution between bridge elements. This might be used for economical purposes.

When the damages in the bridge columns which are subjected to strong earthquake movements are examined, bearing conditions of the structures as well as the column rigidity and heights affect the behavior of these structures. The role of

bearings in the behavior of bridges can significantly influence the rigid superstructure behavior and thus the maximum behavior can vary greatly in addition to column rigidities and heights. The elasticity of elastomeric bearings, which have very low horizontal stiffness compared to vertical stiffness, gives the system a great flexibility in the horizontal direction.

3.3. Ground Motion Records

Using PEER NGA-West Database (Yang, Moehle, & Stojadinovic, 2009), forty-two earthquake records are selected classified for different soil classes, magnitudes, the distance between the source and fault mechanism. The earthquake records to be used in nonlinear time history analysis are usually selected based on either the design spectrum or the earthquake scenario by checking few parameters such as size, distance and ground class to represent certain characteristics of ground motion. In seismic design codes, the guidance on how to select the appropriate recorded data is mostly focused on the suitability of the response spectrum rather than seismological parameters. The records to be selected for a given region should be matched with the response spectrum generated by the Seismic Hazard Analysis and should provide geological and seismological conditions. Since the magnitude of the earthquake influences the frequency content and duration of the ground motion, it is very important to select the records of appropriate size.

It is possible to mention three different sources where earthquake records can be obtained. These are the design acceleration spectrum-matched recordings, source, and wave propagation characteristics, physically simulated recordings generated using artificial paths and recordings from recorded earthquakes.

The Pacific Earthquake Engineering Research Center accumulates the properties of earthquakes and acceleration records in a database. PEER's objective is to be included in the development of ultimate performance-based earthquake engineering applications. According to PEER official website, by May 2019, PEER

NGA-East database includes the two- and three-component ground-motion recordings from numerous selected events (M > 2.5, distances up to 1500 km) recorded in the Central and Eastern North America (CENA) region since 1988. The database contains over 29,000 records from 81 earthquake events and 1379 recording stations. The database includes time series and pseudo-spectral acceleration (PSA) for the 5%-damped elastic oscillators with periods ranging from 0.01 to 10 sec. Additionally, the NGA-East database includes Fourier amplitude spectra (FAS) of the processed ground motions. (Yang et al., 2009)

Ground motions from three different Richter's magnitudes intervals and two soil classes were chosen. Each combination forms a group meaning there shall be analyzed six different groups in this thesis. For each group, seven ground motions are determined. Each ground motion is labeled in terms of its group properties. In order not to have difficulties while selecting earthquake ground motion data, most common soil classes, magnitudes are preferred. Soil classes C-D and magnitudes of 6.0, 6.5 and 7.0 defined in Table 3-9 are selected by considering strike slip and far fault (between 15-30 km) behavior. 42 different earthquake records were selected with variety of magnitudes Mw = 6.0, 6.5 or 7.0, soil classes C and D defined in Table 3-8 whose shear wave velocities, Vs_{30} varies from to 180 m/sec to 540 m/sec by looking at common shear wave velocities map in Figure 3-48, and fault distances ranging between 15 and 30 kilometers. Magnitudes 6.0, 6.5 and 7.0 are named as 60, 65, 70 respectively. For instance, an earthquake record with label 60CI2 can be divided into four parts as 60(Mw=6.0), C (Soil class C), I (Intermediate far distance to fault), 2 (2nd earthquake records in the group). 42 earthquake records are listed in Table 3-10 and Table 3-11. Acceleration vs time graphs of 42 recorded ground motions can be found in Figure F- 1 to Figure F- 42.

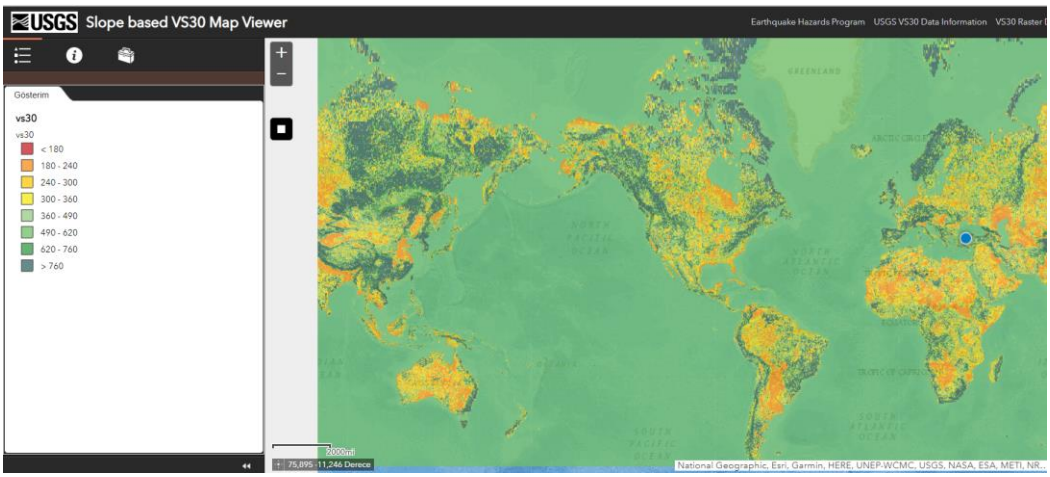


Figure 3-48: Shear wave velocities (Allen & Wald, 2007)

Table 3-8: Soil Types Classification (Building Seismic Safety Council, 2003)

Soil type NEHRP	**General description**	**Velocity to 30 m (m/s) Average shear wave**
A	Hard rock	> 1500
B	Rock	760 < Vs ≤ 1500
C	Very dense soil and soft rock	360 < Vs ≤ 760
D	Stiff soil 15 ≤ N ≤ 50 or 50 kPa ≤ Su ≤ 100 kPa	180 ≤ Vs≤ 360
E	Soil or any profile with more than 3 m of soft clay defiled as soil with PI > 20, w ≥ 40%, and Su < 25 kPa.	≤ 180
F	Soils requiring site-specific evaluations	

Table 3-9: Classification of earthquakes depending on magnitudes (Academy & Karlo, 1962)

Magnitude 2.5 or less (Minor)	They are very light and light earthquakes.
Magnitude 2.5 to 5.4 (Moderate)	Plasters are cracked and poured in buildings.
Magnitude 5.5 to 6.0 (Severe Earthquake)	Earthquake is felt inside and outside the building.
Magnitude 6.0 to 7.0 (Strong Earthquake)	Populated environments are under a lot of damage.
Magnitude 7.0 to 7.9 (Major Earthquake)	This type of earthquake causes serious damages.
Magnitude 8.0 or more (Great Earthquake)	Total destruction may happen around epicenter.

Table 3-10: Selected Ground Motions from PEER Database (1/2)

GM Label	Earthquake Name	Year	Station Name	Magnitude	Mechanism	Rjb (km)	Rrup (km)	Vs30 (m/sec)
60CI1	Joshua Tree_ CA	1992	Whitewater Trout Farm	6.1	Strike Slip	28.97	29.4	425.02
60CI2	Chalfant Valley-02	1986	Lake Crowley Shehorn Res.	6.19	Strike Slip	22.08	24.47	456.83
60CI3	Morgan Hill	1984	Corralitos	6.19	Strike Slip	23.23	23.24	462.24
60CI4	Chi-Chi_ Taiwan-04	1999	TCU122	6.2	Strike Slip	23.14	23.19	475.46
60CI5	Parkfield	1966	Temblor pre-1969	6.19	Strike Slip	15.96	15.96	527.92
60CI6	Mammoth Lakes-06	1980	Bishop Paradise Lodge	5.94	Strike Slip	18.85	23.86	585.12
60CI7	Basso Tirreno Italy	1978	Naso	6	Strike Slip	17.15	19.59	620.56
60DI1	Westmorland	1981	Niland Fire Station	5.9	Strike Slip	15.16	15.29	212
60DI2	Morgan Hill	1984	Hollister Differential Array #3	6.19	Strike Slip	26.42	26.43	215.54
60DI3	Parkfield-02_ CA	2004	Parkfield Gold Hill 6W	6	Strike Slip	15.45	15.79	232.44
60DI4	Morgan Hill	1984	Agnews State Hospital	6.19	Strike Slip	24.48	24.49	239.69
60DI5	Chi-Chi_ Taiwan-04	1999	CHY101	6.2	Strike Slip	21.62	21.67	258.89
60DI6	Joshua Tree_ CA	1992	Indio - Jackson Road	6.1	Strike Slip	25.04	25.53	292.12
60DI7	Chalfant Valley-01	1986	Bishop - LADWP South St	5.77	Strike Slip	23.38	23.47	303.47
65CI1	Imperial Valley-06	1979	Superstition Mtn Camera	6.53	Strike Slip	24.61	24.61	362.38
65CI2	Big Bear-01	1992	Highland Fire Station	6.46	Strike Slip	26.18	26.47	362.39
65CI3	Big Bear-01	1992	Morongo Valley Fire Station	6.46	Strike Slip	27.96	29.06	396.41
65CI4	Imperial Valley-06	1979	Cerro Prieto	6.53	Strike Slip	15.19	15.19	471.53
65CI5	Tottori_ Japan	2000	OKY004	6.61	Strike Slip	19.72	19.72	475.8
65CI6	Tottori_ Japan	2000	SMNH02	6.61	Strike Slip	23.64	23.64	502.66
65CI7	Tottori_ Japan	2000	OKYH09	6.61	Strike Slip	21.22	21.22	518.92

Table 3-11: Selected Ground Motions from PEER Database (2/2)

GM Label	Earthquake Name	Year	Station Name	Magnitude	Mechanism	Rjb (km)	Rrup (km)	Vs30 (m/sec)
65DI1	Superstition Hills-02	1987	El Centro Imp. Co. Cent	6.54	Strike Slip	18.2	18.2	192.05
65DI2	Imperial Valley-06	1979	El Centro Array #12	6.53	Strike Slip	17.94	17.94	196.88
65DI3	Superstition Hills-02	1987	Brawley Airport	6.54	Strike Slip	17.03	17.03	208.71
65DI4	Northern Calif-03	1954	Ferndale City Hall	6.5	Strike Slip	26.72	27.02	219.31
65DI5	Imperial Valley-06	1979	El Centro Array #1	6.53	Strike Slip	19.76	21.68	237.33
65DI6	Victoria_ Mexico	1980	Chihuahua	6.33	Strike Slip	18.53	18.96	242.05
65DI7	Tottori_ Japan	2000	OKY005	6.61	Strike Slip	28.81	28.82	293.37
70CI1	Landers	1992	Fun Valley	7.28	Strike Slip	25.02	25.02	388.63
70CI2	Darfield New Zealand	2010	SPFS	7	Strike Slip	29.86	29.86	389.54
70CI3	Landers	1992	Morongo Valley Fire Station	7.28	Strike Slip	17.36	17.36	396.41
70CI4	Darfield New Zealand	2010	Heathcote Valley Primary School	7	Strike Slip	24.36	24.47	422
70CI5	Landers	1992	Whitewater Trout Farm	7.28	Strike Slip	27.05	27.05	425.02
70CI6	Duzce_ Turkey	1999	Lamont 362	7.14	Strike Slip	23.41	23.41	517
70CI7	Darfield New Zealand	2010	LPCC	7	Strike Slip	25.21	25.67	649.67
70DI1	El Mayor-Cucapah Mexico	2010	Chihuahua	7.2	Strike Slip	18.21	19.47	242.05
70DI2	El Mayor-Cucapah Mexico	2010	TAMAULIPAS	7.2	Strike Slip	25.32	26.55	242.05
70DI3	Darfield New Zealand	2010	Styx Mill Transfer Station	7	Strike Slip	20.86	20.86	247.5
70DI4	Darfield New Zealand	2010	ADCS	7	Strike Slip	28.46	31.41	249.28
70DI5	Kobe_ Japan	1995	Abeno	6.9	Strike Slip	24.85	24.85	256
70DI6	Kobe_ Japan	1995	Fukushima	6.9	Strike Slip	17.85	17.85	256
70DI7	Kobe_ Japan	1995	Morigawachi	6.9	Strike Slip	24.78	24.78	256

3.4. Seismic Demand Parameters

Yılmaz & Caglayan, 2017 conducted a study about selection of intensity measure in probabilistic seismic risk assessment of a Turkish railway bridge and chose demand parameter as joint displacement in their bridges resulted from nonlinear time history analysis.

Yakut & Yılmaz, 2008 carried out a comprehensive study investigate the correlation between maximum inter story drift demand of frame structures and a number of widely used ground motion intensity parameters.

The seismic demand of bridges is described with the pier which is the key component of the bridge specifically in analyzing in terms of earthquake aspects. In this study, as alternative demand parameters to other studies, axial, shear and moment forces on the bottom of piers were used as the seismic demand parameters of corresponding components resulted from nonlinear time history analysis. The component seismic demands and the correlation coefficient between them were calculated based on the nonlinear time history analysis for the 4 bridge samples with 42 different ground motions.

Each ground motion has 3 components; East-West (H1), North-South (H2), and Vertical (U). The vertical component can be eliminated as it is the selected ground motions are far enough to faults. The remaining two components are introduced in two directions in analysis model as bridge longitudinal (U1) and transverse (U2) direction. This results for each ground motion to be analyzed 4 times in the comparison. For example, 60CI1 ground motion has 4 components labeled as 60CI1_H1_U1 60CI1_H1_U2, 60CI1_H2_U1, and 60CI1_H2_U2. This results in 168 different runs for 42 ground motions. The sketch of this application can be seen in Figure 3-49 .

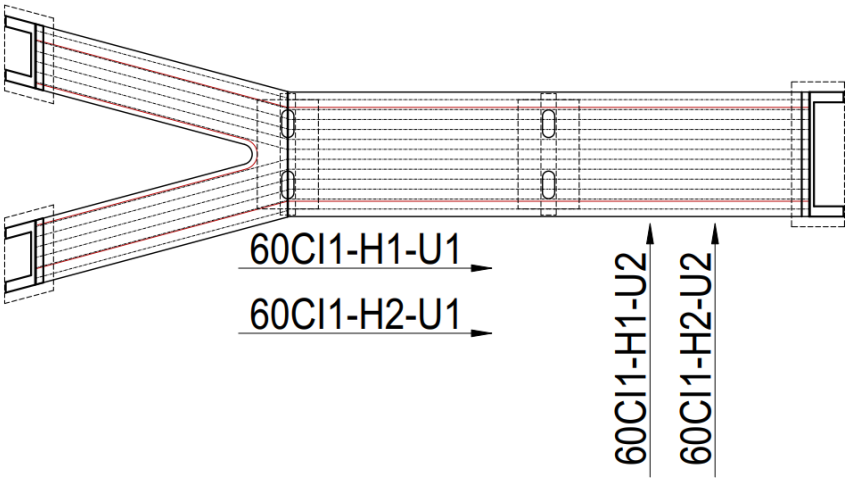


Figure 3-49: Ground motion different components application

During nonlinear time history analysis for each ground motion, response quantities are tracked at each time step. The demand quantities not explicitly tied to the transverse or longitudinal bridge direction are calculated at each time step using the square-root-sum-of-squares (SRSS) combination of the two lateral directions. For example, for 60CI1-H1 earthquake, demand parameter equation is resulted;

Resultant load of 60CI1-H1= A

Resultant load of 60CI1-H1-U1= B

Resultant load of 60CI1-H1-U2= C

$$A = \sqrt{(B^2+C^2)} \qquad (10)$$

A value in Equation 10 shall then be compared with ground motion intensity measures of relevant earthquake. *A* value in Equation 10 can be axial force, shear force or moment force.

For 60CI1_H1 earthquake, seismic demand parameters can be calculated by using seismic demand parameters in Figure 3-50 to Figure 3-54.

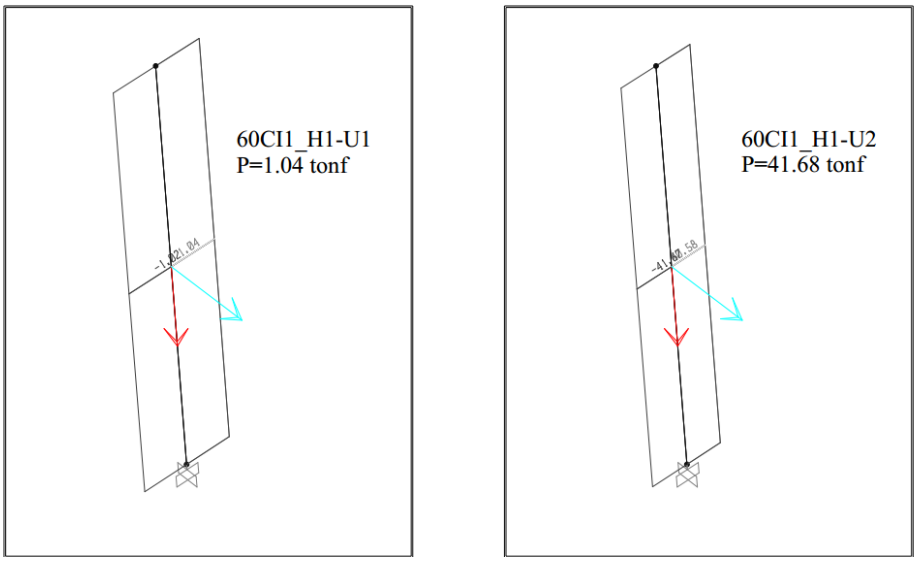


Figure 3-50: Axial force (P) at the bottom of right column in axis P1 in FBM1 in two directions of 60CI1_H1

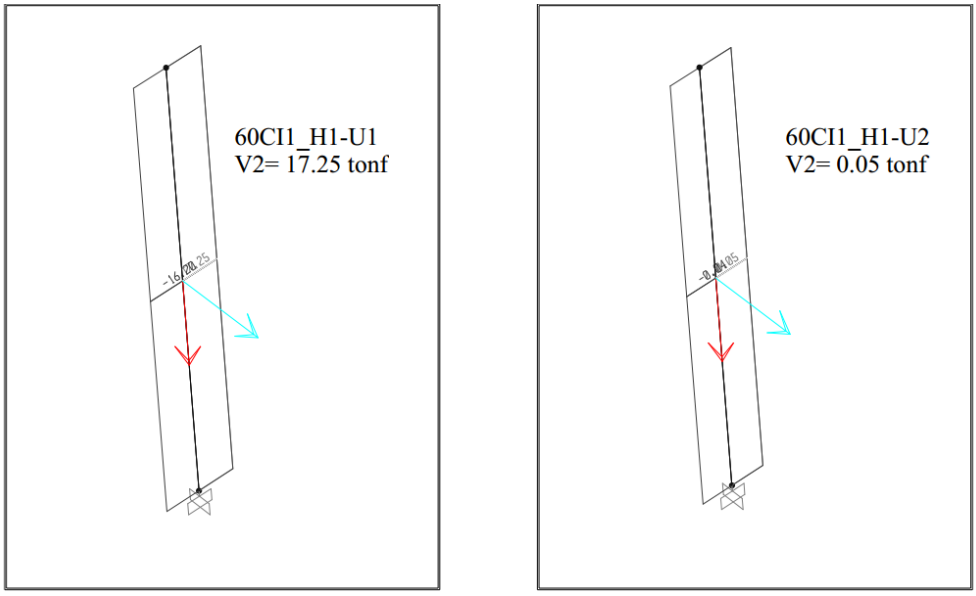


Figure 3-51: Shear force (V2) in bridge longitudinal direction at the bottom of right column in axis P1 in FBM1 in two directions of 60CI1_H1

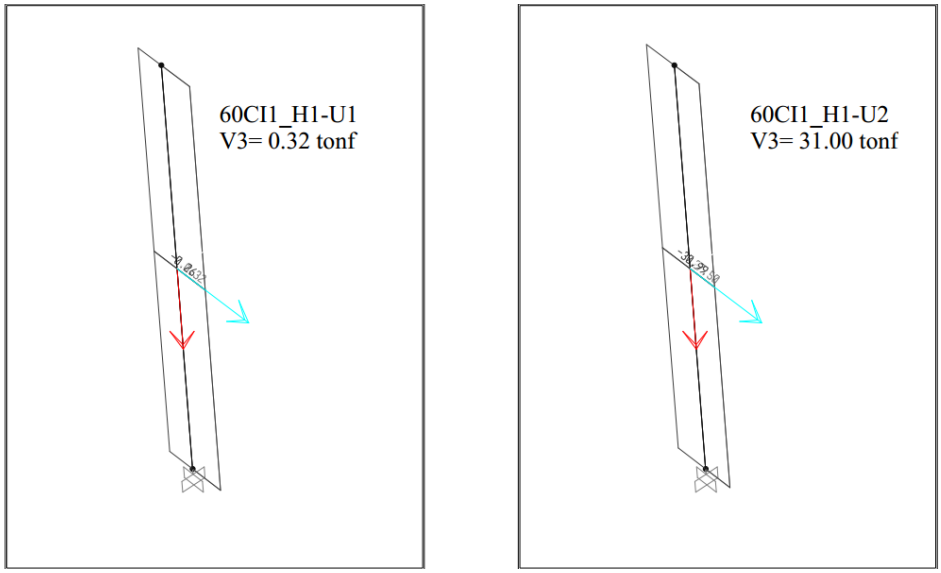


Figure 3-52: Shear force (V3) in bridge transverse direction at the bottom of right column in axis P1 in FBM1 in two directions of 60CI1_H1

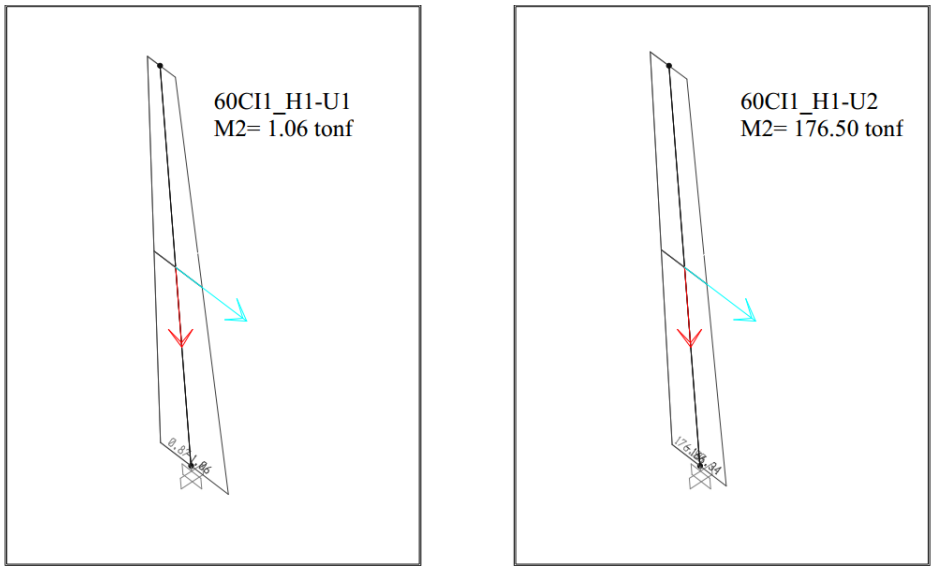


Figure 3-53: Moment force (M2) about bridge longitudinal direction at the bottom of right column in axis P1 in FBM1 in two directions of 60CI1_H1

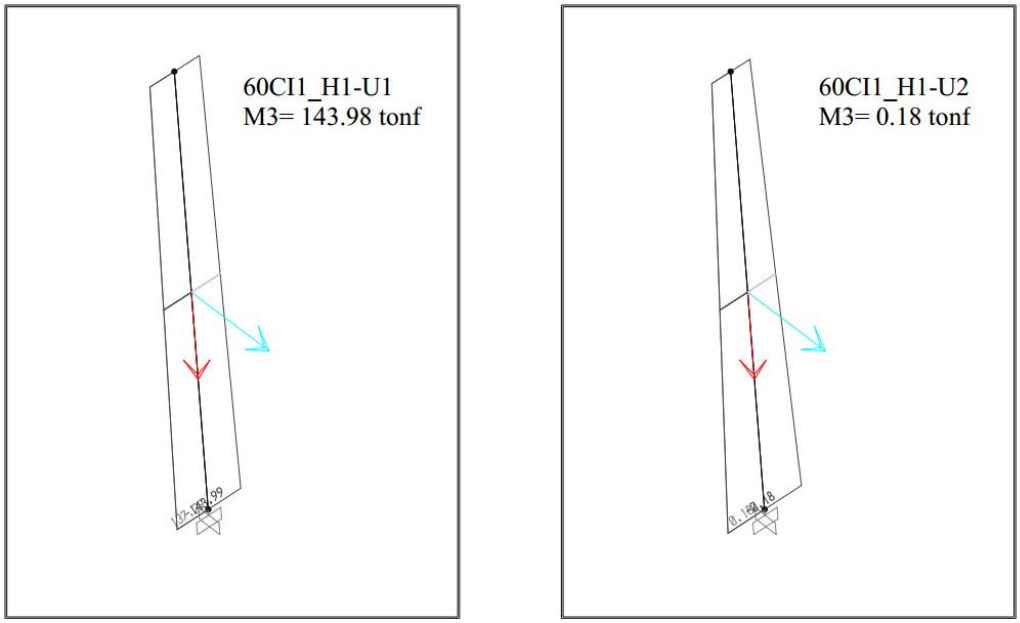


Figure 3-54: Moment force (M3) about bridge transverse direction at the bottom of right column in axis P1 in FBM1 in two directions of 60CI1_H1

From Figure 3-50 : Axial force (P) = $\sqrt{(1.04^2+41.68^2)}$=41.69 tonf

From Figure 3-51: Shear force (V2) = $\sqrt{(17.25^2+0.05^2)}$=17.25 tonf

From Figure 3-52: Shear force (V3) = $\sqrt{(0.32^2+31.00^2)}$=31.00 tonf

From Figure 3-53: Moment force (M2) = $\sqrt{(1.06^2+176.50^2)}$=176.50 tonf.m

From Figure 3-54: Moment force (M3) = $\sqrt{(143.99^2+0.18^2)}$=143.99 tonf.m

Seismic force directions of seismic demand parameters can be seen in Figure 3-55.

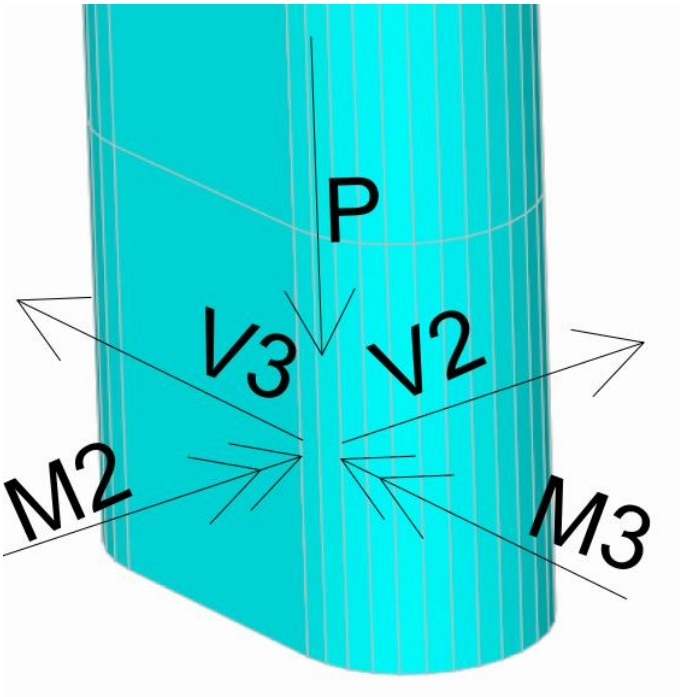


Figure 3-55: Direction of seismic demand parameters

Seismic demand parameters in different bridges resulted from by conducting nonlinear time history analysis using 42 ground motions can be seen in Table 3-12 to Table 3-19 .

Table 3-12:Seismic Demand Forces at Bottom of Right Column in Axis P1 in FBM1 (1/2)

	FBM1(tonf,m)				
	P(tonf)	V2(tonf)	V3(tonf)	M2(tonf.m)	M3(tonf.m)
GM Label	Axial Force	Shear force in Bridge Long. Direction	Shear force in Bridge Tran. Direction	Moment force about Bridge Long. Direction	Moment force about Bridge Tran. Direction
60CI1_H1	42.13	17.14	31.48	179.56	141.98
60CI1_H2	55.81	27.67	33.42	206.53	242.60
60CI2_H1	20.11	11.37	14.85	79.19	73.64
60CI2_H2	13.37	6.36	10.51	57.92	49.64
60CI3_H1	29.13	9.90	18.79	113.52	83.57
60CI3_H2	75.85	20.00	43.10	272.87	184.91
60CI4_H1	83.99	46.04	48.49	305.60	429.92
60CI4_H2	52.70	13.95	30.60	193.63	133.66
60CI5_H1	34.71	11.09	32.05	174.26	76.26
60CI5_H2	61.41	12.89	52.58	306.48	115.51
60CI6_H1	17.93	6.38	12.70	73.97	55.52
60CI6_H2	22.52	7.23	17.67	103.64	56.45
60CI7_H1	67.94	42.18	35.74	233.55	383.75
60CI7_H2	63.34	40.34	37.89	234.25	397.30
60DI1_H1	49.04	27.38	29.83	183.61	241.97
60DI1_H2	32.86	10.39	22.16	133.47	89.37
60DI2_H1	73.74	34.99	43.73	271.72	335.49
60DI2_H2	27.39	12.89	18.13	107.85	120.83
60DI3_H1	16.85	8.14	12.68	71.62	60.11
60DI3_H2	17.09	5.62	11.53	70.94	45.53
60DI4_H1	14.98	5.58	9.44	57.20	48.39
60DI4_H2	32.13	13.18	17.81	113.73	120.50
60DI5_H1	62.21	36.92	44.02	256.86	327.79
60DI5_H2	24.58	9.09	14.98	92.50	79.12
60DI6_H1	373.51	115.36	207.32	1328.05	1100.21
60DI6_H2	70.86	35.22	38.13	247.45	331.02
60DI7_H1	77.12	34.00	46.57	288.31	321.81
60DI7_H2	35.97	13.29	20.82	132.30	102.28
65CI1_H1	22.62	6.19	22.13	122.66	51.58
65CI1_H2	35.87	9.55	40.17	212.30	85.90
65CI2_H1	45.46	25.27	28.39	172.97	219.25
65CI2_H2	38.44	19.62	25.23	148.05	179.59
65CI3_H1	68.83	44.52	43.04	264.04	395.29
65CI3_H2	65.40	31.86	37.09	235.39	302.47
65CI4_H1	50.15	16.46	36.47	216.61	105.18
65CI4_H2	54.19	14.47	32.61	203.77	115.72
65CI5_H1	70.15	14.75	65.82	371.25	75.34
65CI5_H2	132.88	24.42	116.22	673.99	157.57
65CI6_H1	107.98	34.04	109.95	603.28	308.37
65CI6_H2	50.63	15.32	46.80	260.80	118.10
65CI7_H1	76.10	14.41	62.65	360.74	133.33
65CI7_H2	79.62	24.31	74.29	423.14	214.50

Table 3-13: Seismic Demand Forces at Bottom of Right Column in Axis P1 in FBM1 (2/2)

	FBM1(tonf,m)				
	P(tonf)	**V2(tonf)**	**V3(tonf)**	**M2(tonf.m)**	**M3(tonf.m)**
GM Label	**Axial Force**	**Shear force in Bridge Long. Direction**	**Shear force in Bridge Tran. Direction**	**Moment force about Bridge Long. Direction**	**Moment force about Bridge Tran. Direction**
65DI1_H1	195.89	103.46	117.15	732.29	1027.82
65DI1_H2	148.94	78.27	92.15	566.10	707.54
65DI2_H1	117.21	41.73	70.02	436.46	394.43
65DI2_H2	81.43	32.88	46.82	295.70	305.74
65DI3_H1	45.65	19.35	28.24	174.28	166.60
65DI3_H2	18.73	5.05	14.31	82.08	37.81
65DI4_H1	173.89	85.92	106.42	657.35	816.76
65DI4_H2	198.85	77.99	112.70	717.28	731.30
65DI5_H1	62.63	21.10	36.56	232.94	176.93
65DI5_H2	42.85	16.38	31.71	187.69	135.71
65DI6_H1	70.39	22.57	48.29	286.11	202.69
65DI6_H2	86.07	24.91	48.53	309.96	236.47
65DI7_H1	57.72	15.43	56.36	304.53	127.38
65DI7_H2	48.81	12.61	35.13	205.52	96.24
70CI1_H1	110.11	28.70	56.58	376.88	278.01
70CI1_H2	128.92	36.90	74.88	469.90	332.21
70CI2_H1	207.27	52.88	118.71	749.74	494.55
70CI2_H2	127.44	40.62	66.46	438.38	387.37
70CI3_H1	135.80	58.98	76.25	484.48	537.61
70CI3_H2	98.94	42.60	57.14	359.42	397.56
70CI4_H1	71.89	31.44	42.86	266.21	280.86
70CI4_H2	122.32	32.99	95.64	543.69	251.69
70CI5_H1	67.22	25.33	40.25	249.45	220.53
70CI5_H2	67.27	18.15	43.13	263.12	160.73
70CI6_H1	83.11	42.25	47.89	302.62	384.80
70CI6_H2	75.80	25.95	45.28	282.75	241.36
70CI7_H1	105.73	38.54	70.80	428.41	368.76
70CI7_H2	60.85	26.05	37.01	228.24	230.52
70DI1_H1	224.10	90.29	131.24	827.08	820.52
70DI1_H2	116.15	72.92	72.51	448.60	662.09
70DI2_H1	143.86	77.35	100.74	599.02	710.38
70DI2_H2	141.25	49.33	81.16	515.38	415.34
70DI3_H1	158.42	52.42	89.70	567.21	481.06
70DI3_H2	127.70	44.50	71.70	456.05	400.79
70DI4_H1	62.50	26.04	36.72	228.54	227.27
70DI4_H2	43.09	21.64	25.85	161.31	193.42
70DI5_H1	43.37	19.30	32.36	182.71	161.47
70DI5_H2	57.57	33.03	36.80	219.52	299.35
70DI6_H1	91.96	26.12	52.25	331.11	248.18
70DI6_H2	142.58	33.50	84.14	525.16	292.20
70DI7_H1	103.56	34.28	59.69	375.81	329.71
70DI7_H2	50.10	20.85	30.40	186.60	176.90

Table 3-14: Seismic Demand Forces at Bottom of Right Column in Axis P1 in FBM2 (1/2)

	FBM2(tonf,m)				
	P(tonf)	V2(tonf)	V3(tonf)	M2(tonf.m)	M3(tonf.m)
GM Label	Axial Force	Shear force in Bridge Long. Direction	Shear force in Bridge Tran. Direction	Moment force about Bridge Long. Direction	Moment force about Bridge Tran. Direction
60CI1_H1	175.20	30.49	100.23	623.26	264.43
60CI1_H2	61.69	16.97	36.85	225.25	139.40
60CI2_H1	80.78	10.66	46.63	288.92	92.83
60CI2_H2	135.54	5.67	74.91	473.20	46.96
60CI3_H1	105.58	10.86	58.07	366.93	102.58
60CI3_H2	144.63	31.30	79.80	503.67	277.86
60CI4_H1	90.87	29.52	51.27	319.92	264.56
60CI4_H2	67.81	20.84	38.55	240.87	176.86
60CI5_H1	93.35	15.93	49.39	307.59	100.94
60CI5_H2	57.01	14.64	32.68	201.21	102.10
60CI6_H1	18.82	9.97	10.38	63.31	79.59
60CI6_H2	34.59	6.98	21.87	132.25	54.64
60CI7_H1	252.08	34.87	141.35	888.96	301.85
60CI7_H2	180.45	22.30	98.60	626.06	212.90
60DI1_H1	58.17	11.87	34.73	213.33	94.88
60DI1_H2	109.95	12.37	63.93	397.96	105.61
60DI2_H1	82.90	25.60	47.36	295.02	218.34
60DI2_H2	103.22	12.30	58.10	363.45	107.42
60DI3_H1	40.87	4.85	21.07	136.09	29.79
60DI3_H2	27.49	4.81	14.90	90.21	34.83
60DI4_H1	14.64	4.10	7.78	49.13	33.79
60DI4_H2	37.10	14.62	22.10	135.49	131.98
60DI5_H1	190.11	23.30	108.76	678.07	209.70
60DI5_H2	44.41	10.39	26.40	163.30	88.20
60DI6_H1	337.34	117.31	200.36	1230.29	1048.35
60DI6_H2	168.68	27.24	92.75	587.38	233.66
60DI7_H1	89.96	25.60	48.11	304.77	236.65
60DI7_H2	74.71	17.47	40.27	251.93	146.57
65CI1_H1	41.34	5.10	25.72	154.90	45.39
65CI1_H2	68.83	9.86	36.28	232.89	68.72
65CI2_H1	66.84	14.72	40.13	245.87	120.06
65CI2_H2	84.08	23.78	48.60	302.36	212.81
65CI3_H1	187.52	26.97	102.82	648.57	227.04
65CI3_H2	103.55	57.94	60.73	370.22	510.46
65CI4_H1	50.74	15.67	29.64	185.28	118.06
65CI4_H2	156.67	20.13	86.25	543.50	164.32
65CI5_H1	56.52	11.10	45.00	267.75	51.85
65CI5_H2	108.60	19.78	81.54	459.88	136.48
65CI6_H1	182.12	43.55	98.31	619.86	283.13
65CI6_H2	106.11	17.33	59.64	376.00	104.81
65CI7_H1	75.18	15.80	43.49	270.21	139.95
65CI7_H2	58.12	16.25	35.93	218.40	132.12

Table 3-15: Seismic Demand Forces at Bottom of Right Column in Axis P1 in FBM2 (2/2)

	FBM2(tonf,m)				
	P(tonf)	V2(tonf)	V3(tonf)	M2(tonf.m)	M3(tonf.m)
GM Label	Axial Force	Shear force in Bridge Long. Direction	Shear force in Bridge Tran. Direction	Moment force about Bridge Long. Direction	Moment force about Bridge Tran. Direction
65DI1_H1	335.38	84.69	184.49	1164.51	742.87
65DI1_H2	307.68	31.33	170.41	1073.90	264.09
65DI2_H1	119.48	28.94	67.90	425.77	258.66
65DI2_H2	105.02	25.81	56.40	357.56	219.40
65DI3_H1	58.85	18.69	34.60	210.55	158.24
65DI3_H2	59.90	12.83	35.35	216.08	100.88
65DI4_H1	170.61	58.21	102.38	625.70	516.43
65DI4_H2	174.63	69.47	101.50	628.29	626.98
65DI5_H1	109.38	18.09	68.73	414.75	142.41
65DI5_H2	83.31	11.03	47.27	296.78	82.38
65DI6_H1	102.65	29.19	55.75	352.46	275.11
65DI6_H2	76.36	24.09	40.93	260.22	208.09
65DI7_H1	61.75	14.90	44.38	256.18	124.72
65DI7_H2	93.02	19.08	61.31	370.78	125.81
70CI1_H1	252.53	70.56	144.13	896.31	646.79
70CI1_H2	182.53	37.69	101.98	641.46	339.05
70CI2_H1	230.37	74.47	133.55	829.11	662.66
70CI2_H2	258.10	41.71	143.53	905.81	388.86
70CI3_H1	413.70	53.82	236.95	1476.22	482.93
70CI3_H2	203.54	41.35	117.85	731.49	352.99
70CI4_H1	72.42	26.05	37.71	244.30	224.35
70CI4_H2	198.65	30.97	110.42	655.22	240.59
70CI5_H1	101.26	42.36	60.11	367.74	377.09
70CI5_H2	99.51	15.42	57.96	357.27	128.91
70CI6_H1	99.43	20.83	57.53	358.07	170.93
70CI6_H2	112.27	33.06	65.47	404.88	299.44
70CI7_H1	150.63	33.83	88.38	545.10	253.84
70CI7_H2	49.85	15.67	30.58	185.54	127.56
70DI1_H1	332.33	82.00	188.57	1177.39	738.08
70DI1_H2	295.98	66.83	162.32	1025.16	584.78
70DI2_H1	152.73	46.67	84.31	531.59	422.32
70DI2_H2	145.64	64.24	84.56	527.31	579.38
70DI3_H1	235.70	58.36	133.10	832.34	514.86
70DI3_H2	196.51	48.10	112.40	699.84	409.59
70DI4_H1	132.02	18.01	71.43	454.15	166.83
70DI4_H2	60.60	10.61	32.63	207.24	90.56
70DI5_H1	183.45	14.60	101.63	638.99	111.55
70DI5_H2	94.63	18.81	54.43	345.30	156.80
70DI6_H1	467.69	48.73	260.20	1639.11	442.02
70DI6_H2	276.48	43.18	154.72	973.90	396.50
70DI7_H1	341.57	28.42	192.74	1208.15	258.84
70DI7_H2	173.27	20.87	97.64	609.10	172.16

Table 3-16: Seismic Demand Forces at Bottom of Right Column in Axis P1 in FBM3 (1/2)

	FBM3(tonf,m)				
	P(tonf)	V2(tonf)	V3(tonf)	M2(tonf.m)	M3(tonf.m)
GM Label	Axial Force	Shear force in Bridge Long. Direction	Shear force in Bridge Tran. Direction	Moment force about Bridge Long. Direction	Moment force about Bridge Tran. Direction
60CI1_H1	84.66	23.80	39.66	345.64	206.22
60CI1_H2	116.05	28.32	43.10	423.30	437.35
60CI2_H1	29.72	10.94	8.64	95.42	79.47
60CI2_H2	23.87	11.47	14.73	131.13	88.62
60CI3_H1	46.15	7.82	16.17	166.09	99.37
60CI3_H2	96.93	18.12	36.24	352.91	273.74
60CI4_H1	206.57	31.89	60.18	651.04	563.34
60CI4_H2	65.00	9.78	17.87	197.46	129.73
60CI5_H1	28.89	27.62	17.86	119.43	161.54
60CI5_H2	46.49	31.25	23.27	145.75	213.53
60CI6_H1	30.48	8.65	9.37	91.26	95.31
60CI6_H2	26.28	12.87	12.01	102.91	126.99
60CI7_H1	186.97	40.99	66.53	667.62	664.09
60CI7_H2	209.99	44.63	68.21	693.37	731.77
60DI1_H1	109.52	26.06	37.04	372.28	412.49
60DI1_H2	35.82	13.50	13.22	114.79	111.06
60DI2_H1	156.62	25.09	44.14	475.89	466.64
60DI2_H2	59.48	11.75	23.90	232.34	133.51
60DI3_H1	39.61	9.14	16.53	144.51	81.29
60DI3_H2	32.90	5.68	13.08	120.76	53.73
60DI4_H1	25.40	4.00	7.97	83.93	70.96
60DI4_H2	60.35	13.69	19.34	199.01	224.42
60DI5_H1	146.11	58.37	49.86	498.25	998.78
60DI5_H2	38.67	11.07	15.62	149.66	152.21
60DI6_H1	508.41	81.48	151.79	1616.40	1425.01
60DI6_H2	155.76	41.91	47.37	500.49	711.16
60DI7_H1	149.11	21.52	42.90	461.58	326.77
60DI7_H2	45.45	12.57	14.58	154.19	150.66
65CI1_H1	23.95	15.52	11.10	82.79	100.65
65CI1_H2	49.57	24.55	21.68	194.78	160.65
65CI2_H1	100.31	40.92	39.45	381.08	636.71
65CI2_H2	73.55	20.00	25.57	243.61	218.43
65CI3_H1	167.74	45.52	64.08	624.33	720.88
65CI3_H2	152.03	31.74	51.89	488.13	519.45
65CI4_H1	52.46	18.71	20.04	186.42	195.98
65CI4_H2	62.05	26.62	31.89	260.23	204.27
65CI5_H1	66.67	45.47	52.40	238.84	275.02
65CI5_H2	160.39	79.72	93.47	481.17	425.33
65CI6_H1	155.95	75.44	65.86	591.93	627.09
65CI6_H2	45.81	36.90	28.78	225.11	270.69
65CI7_H1	60.08	40.43	26.57	232.29	265.73
65CI7_H2	103.06	55.98	38.19	371.25	426.51

Table 3-17: Seismic Demand Forces at Bottom of Right Column in Axis P1 in FBM3 (2/2)

	FBM3(tonf,m)				
	P(tonf)	V2(tonf)	V3(tonf)	M2(tonf.m)	M3(tonf.m)
GM Label	Axial Force	Shear force in Bridge Long. Direction	Shear force in Bridge Tran. Direction	Moment force about Bridge Long. Direction	Moment force about Bridge Tran. Direction
65DI1_H1	495.01	83.22	137.43	1442.25	1282.12
65DI1_H2	340.06	95.78	106.57	1109.75	1459.04
65DI2_H1	207.25	38.09	66.46	699.07	661.38
65DI2_H2	149.83	36.48	46.72	491.21	541.04
65DI3_H1	82.09	21.31	27.44	276.63	314.43
65DI3_H2	21.49	11.35	11.64	89.98	93.96
65DI4_H1	392.42	95.22	121.71	1274.05	1657.26
65DI4_H2	346.55	66.90	105.44	1077.74	1189.36
65DI5_H1	86.77	27.98	31.83	282.16	334.39
65DI5_H2	61.71	22.84	22.91	219.31	275.61
65DI6_H1	106.55	24.18	32.91	358.89	272.92
65DI6_H2	115.51	21.61	33.35	355.77	365.33
65DI7_H1	61.93	35.13	29.92	234.07	253.99
65DI7_H2	79.91	19.35	33.87	274.03	178.15
70CI1_H1	134.59	24.59	43.11	451.08	364.92
70CI1_H2	148.29	38.25	48.85	492.76	613.22
70CI2_H1	229.76	49.08	74.17	755.12	788.40
70CI2_H2	177.80	30.43	58.49	584.84	483.06
70CI3_H1	252.48	72.43	96.32	927.30	1240.18
70CI3_H2	196.67	62.55	56.07	604.35	1002.00
70CI4_H1	138.70	31.78	54.47	530.86	467.21
70CI4_H2	154.84	46.55	65.86	580.94	388.24
70CI5_H1	99.77	26.60	37.39	364.68	401.55
70CI5_H2	76.02	24.80	23.89	249.61	387.13
70CI6_H1	186.75	50.21	63.62	638.98	852.95
70CI6_H2	108.76	29.88	37.52	374.06	459.39
70CI7_H1	182.72	41.89	59.48	565.96	385.04
70CI7_H2	109.26	28.09	39.31	387.98	431.81
70DI1_H1	391.86	71.99	136.63	1375.02	1174.17
70DI1_H2	327.09	67.57	114.42	1133.64	1003.75
70DI2_H1	359.50	53.17	125.26	1263.92	839.25
70DI2_H2	180.34	43.18	61.04	622.68	664.83
70DI3_H1	232.30	75.20	75.57	778.31	1217.53
70DI3_H2	173.23	59.33	56.49	538.83	795.51
70DI4_H1	102.81	20.04	35.87	359.09	270.97
70DI4_H2	88.05	23.25	25.91	278.77	359.10
70DI5_H1	67.05	17.69	26.44	220.81	200.42
70DI5_H2	140.16	15.68	43.35	457.02	212.88
70DI6_H1	122.99	39.66	48.56	413.44	460.59
70DI6_H2	167.37	26.86	55.56	561.98	348.11
70DI7_H1	193.44	38.61	62.40	653.25	365.14
70DI7_H2	95.97	12.36	36.55	351.86	203.55

Table 3-18: Seismic Demand Forces at Bottom of Right Column in Axis P1 in FBM4 (1/2)

	FBM4(tonf,m)				
	P(tonf)	V2(tonf)	V3(tonf)	M2(tonf.m)	M3(tonf.m)
GM Label	Axial Force	Shear force in Bridge Long. Direction	Shear force in Bridge Tran. Direction	Moment force about Bridge Long. Direction	Moment force about Bridge Tran. Direction
60CI1_H1	102.56	62.09	52.85	529.33	531.55
60CI1_H2	171.80	40.82	48.52	840.40	834.22
60CI2_H1	43.48	49.07	25.25	205.99	407.20
60CI2_H2	38.32	17.71	19.65	129.26	172.67
60CI3_H1	40.41	14.49	13.58	165.30	119.02
60CI3_H2	105.15	29.70	25.32	384.39	323.84
60CI4_H1	158.96	26.18	28.78	636.40	349.10
60CI4_H2	59.46	16.12	16.50	271.21	193.74
60CI5_H1	83.66	32.70	45.62	396.85	258.20
60CI5_H2	63.88	24.86	34.36	360.99	239.84
60CI6_H1	46.53	13.37	13.67	186.94	216.25
60CI6_H2	56.27	16.79	23.34	285.01	236.19
60CI7_H1	214.94	39.86	65.73	1162.06	810.46
60CI7_H2	196.58	29.36	44.42	853.45	398.38
60DI1_H1	161.47	32.86	46.23	792.97	693.18
60DI1_H2	54.96	27.03	21.21	237.03	326.18
60DI2_H1	178.98	22.00	34.86	729.52	405.07
60DI2_H2	82.40	18.82	20.65	398.58	254.91
60DI3_H1	42.42	18.56	27.33	208.39	175.11
60DI3_H2	34.02	16.67	14.87	156.05	151.77
60DI4_H1	33.75	9.40	9.93	148.34	133.76
60DI4_H2	93.32	15.90	19.10	389.91	342.16
60DI5_H1	444.79	51.70	102.65	2027.77	1287.06
60DI5_H2	62.50	19.23	20.53	331.25	305.72
60DI6_H1	565.00	93.74	132.68	2301.29	1634.20
60DI6_H2	256.73	46.31	60.47	1238.47	822.42
60DI7_H1	116.74	28.90	29.95	542.66	467.97
60DI7_H2	41.77	26.46	17.07	204.65	248.54
65CI1_H1	38.55	14.66	16.84	188.17	158.96
65CI1_H2	74.09	32.72	33.61	337.17	287.48
65CI2_H1	255.36	49.43	63.80	1177.18	1088.26
65CI2_H2	106.91	29.54	32.40	413.20	438.08
65CI3_H1	234.89	53.65	66.96	1127.18	1084.45
65CI3_H2	297.68	38.95	64.08	1205.97	910.51
65CI4_H1	91.23	36.57	50.08	474.06	410.12
65CI4_H2	109.71	42.27	35.16	536.95	500.96
65CI5_H1	86.74	66.21	53.03	382.28	319.44
65CI5_H2	155.57	103.37	83.73	431.99	535.61
65CI6_H1	215.65	59.95	79.24	846.16	677.63
65CI6_H2	115.26	61.92	56.56	492.50	587.11
65CI7_H1	91.14	38.23	27.30	366.78	462.90
65CI7_H2	167.49	45.39	49.54	850.60	763.78

Table 3-19: Seismic Demand Forces at Bottom of Right Column in Axis P1 in FBM4 (2/2)

	FBM4(tonf,m)				
	P(tonf)	V2(tonf)	V3(tonf)	M2(tonf.m)	M3(tonf.m)
GM Label	Axial Force	Shear force in Bridge Long. Direction	Shear force in Bridge Tran. Direction	Moment force about Bridge Long. Direction	Moment force about Bridge Tran. Direction
65DI1_H1	462.86	111.74	140.43	2112.53	1928.45
65DI1_H2	553.60	109.96	151.01	2568.19	2398.65
65DI2_H1	230.58	48.80	60.89	1010.18	1020.99
65DI2_H2	274.80	45.03	66.09	1131.84	858.89
65DI3_H1	110.34	29.55	39.84	638.26	480.75
65DI3_H2	23.88	21.60	15.02	155.60	225.61
65DI4_H1	683.91	87.04	152.41	2917.87	2231.27
65DI4_H2	475.01	46.41	111.30	2109.78	1294.42
65DI5_H1	173.17	38.67	40.94	718.99	686.15
65DI5_H2	113.82	34.43	29.38	509.59	600.98
65DI6_H1	103.32	41.82	45.40	525.83	533.69
65DI6_H2	169.04	29.91	43.40	745.48	837.48
65DI7_H1	80.00	39.66	28.60	251.77	352.63
65DI7_H2	83.50	45.77	29.96	297.27	340.72
70CI1_H1	142.88	58.69	57.40	788.02	624.99
70CI1_H2	234.66	73.02	63.64	1117.14	1028.89
70CI2_H1	277.61	65.35	70.81	1257.33	1083.06
70CI2_H2	227.16	46.85	65.93	1183.53	1014.86
70CI3_H1	537.03	86.59	132.73	2508.05	1972.90
70CI3_H2	553.06	92.81	135.29	2559.53	2437.51
70CI4_H1	183.13	43.37	51.30	912.82	842.62
70CI4_H2	186.89	120.42	122.71	860.29	908.27
70CI5_H1	160.40	43.91	48.20	824.97	949.11
70CI5_H2	173.77	37.14	46.73	830.10	846.15
70CI6_H1	297.38	51.56	69.04	1227.45	1216.34
70CI6_H2	189.78	41.38	54.62	870.28	836.91
70CI7_H1	137.05	47.03	58.08	731.79	670.20
70CI7_H2	175.21	37.79	49.31	857.75	831.61
70DI1_H1	314.36	60.48	76.30	1361.31	1043.84
70DI1_H2	310.16	61.08	90.04	1387.07	1212.39
70DI2_H1	249.79	48.22	77.57	1128.77	1014.77
70DI2_H2	293.56	65.42	82.41	1405.92	1611.99
70DI3_H1	497.50	65.77	113.70	2185.11	1463.70
70DI3_H2	214.96	60.55	60.89	1086.89	886.66
70DI4_H1	153.13	30.99	43.11	720.75	437.37
70DI4_H2	153.53	23.71	43.66	738.84	417.00
70DI5_H1	70.04	33.01	30.18	342.68	345.23
70DI5_H2	92.98	26.98	35.89	438.62	370.97
70DI6_H1	212.15	50.02	57.77	886.99	890.93
70DI6_H2	146.98	35.13	36.16	558.11	442.53
70DI7_H1	176.42	73.80	39.06	657.34	630.41
70DI7_H2	76.12	39.37	32.62	331.56	368.55

]

CHAPTER 4

CORRELATION BETWEEN INTENSITY MEASURES AND SEISMIC FORCE PARAMETERS

Vibrating motion on ground and vibration of structures are usually observed during earthquakes. In order to solve problems related to the dynamic response of soils and structures, dynamic events are needed to be identified. Vibratory motion can be divided into two main classes: periodic motion and non-periodic motion. Periodic movements are movements that are repeated at certain intervals over time. The simplest form of periodic motion is simple harmonic motion in which displacement changes sinusoidally over time. Non-periodic movements that are not repeated at fixed intervals consist of impulsive loads. Dynamic loads that can affect the soils can be grouped under four groups; harmonic movements, periodic movements, random vibrations, transient vibrations. Natural events such as earthquakes, waves, and wind create random vibrations on the ground.

The acceleration values, which contain important engineering information, are used in the development of earthquake resistant structures and in the development of the reduction relations with the distances of the earthquake. Ground movements caused by earthquakes can be quite complex. It is possible to define earthquake motion with three components of linear motion at a given point. The movement recorded from an accelerogram has two horizontal components; parallel and perpendicular to fault.

Amplitude parameters - acceleration, velocity, and displacement appear to be prominent among the many characteristics shown for defining motion in analyzes to be performed on soil and/or soil-structure problems.

In this chapter, seismic demand parameters obtained by implementing selected ground motions shall be correlated with intensity measures mentioned in Chapter 2.3.

Magnitude or acceleration criteria may not be enough to predict the effect of ground motion. In this context, ground motions are compared with ground motion intensity measures with the nonlinear time history analysis mentioned in Chapter 3. The use of the parameters mainly depends on their application to present recorded life problems.

The workability of the parameters of strong movement depends mainly on their use. In earthquake-resistant design, few parameters are available and are immediately associated with the structural analysis techniques employed in present practice. To evaluate the seismic risk, any parameter can theoretically be used by means of empirical loss functions that relate structural deterioration rates to a certain level of ground-motion intensity (Buratti, 2012). This will only rely on the extent to which it measures the damaging capacity of the movement. The parameters are of useful importance in this case. It appears that exceptionally few parameters, in case any, can effectively characterize the nature of solid movement and numerous, by themselves, pass on nothing around the destructive potential of the shaking. (Pejovic & Jankovic, 2015)

Seismic demand parameters on four bridges with two types layout of bearings and various column heights will be compared. In order for the results of this comparison to be consistent, it is necessary to understand the impact of the selected earthquakes on the structure. From the aforementioned, starting from the magnitude of an earthquake, the ground class of the earthquake movement, peak acceleration can lead to unpredicted estimates and incorrect comparisons. Therefore, the ground motion intensity measures mentioned in the theory are compared with resulting seismic demand parameters. Comparison steps are explained in detail in subchapters 4.1 and 4.2.

4.1. Grouping Ground Motion Intensity Measures

All the ground motion intensity measures are found and listed by following the theory mentioned in Chapter 0. Ground motion intensity measures can be grouped as amplitude parameters, frequency content parameters, duration parameters. The grouping of some of the intensity measures by Kramer, 1996 is shown in Table 4-1 .

Table 4-1: Ground Motion Characteristics That Are Strongly Reflected in Various Ground Motion Intensity Measures

Ground Motion Parameter	Ground Motion Characteristic		
	Amplitude	Frequency Content	Duration
Peak acceleration, PHA and PHV	x		
Peak velocity, PHV	x		
Sustained maximum acceleration, SMA	x		
Effective design acceleration, EDA	x		
Predominant period, T_p		x	
Bandwidth		x	
Central frequency, Q		x	
Shape factor, 8		x	
Power spectrum intensity, G_0	x	x	x
Ground frequency, w_g		x	
Ground damping, $t_{,g}$		x	
vmax/amax		x	
Duration, T_d			x
rms acceleration, a_{rms}	x	x	
Characteristic intensity, I_c	x	x	x
Arias intensity, I_a	x	x	x
Cumulative absolute velocity, CAV	x	x	x
Response spectrum intensity, SI©	x	x	
Velocity spectrum intensity, VSI	x	x	
Acceleration spectrum intensity, ASI	x	x	
Effective peak accleration, EPA	x	x	
Effective peak velocity, EPV	x	x	

In this study, the intensity measures are grouped by means of acceleration, velocity, displacement measures. The grouping of parameters can be seen in Table 4-2.

Table 4-2: Groups of Intensity Measures

Acceleration	**Velocity**
Max. Acceleration (g)	Max. Velocity (cm/sec)
Acceleration RMS: (g)	Housner Intensity (cm)
Arias Intensity: (m/sec)	Max Incremental Velocity (cm/sec)
Characteristic Intensity (Ic)	Sustained Maximum Velocity (cm/sec)
Sa (T1)	Velocity RMS: (cm/sec)
Sa (T2)	Velocity Spectrum Intensity (cm)
A95 parameter	Specific Energy Density (cm2/sec)
Effective Design Acceleration (g)	**Other**
Sustained Maximum Acceleration (g)	Mean Period (sec)
Acceleration Spectrum Intensity (g*sec)	Predominant Period (sec)
Cumulative Absolute Velocity (cm/sec)	Vmax / Amax: (sec)
Displacement	
Displacement RMS: (cm)	
Max. Displacement (cm)	

Acceleration based ground motion intensity measures for each ground motion can be seen in Table E- 1 to Table E- 5.

Velocity based ground motion intensity measures for each ground motion can be seen in Table E- 6 and Table E- 7.

Displacement-based ground motion intensity measures and other ground motion intensity measures can be found in Table E- 8 and Table E- 9.

4.2. Comparison of Intensity Measures with Seismic Demand Parameters

Each of the five seismic demand parameters is compared with twenty-three different intensity measures for each model. As in the previous studies similar to this study, log-log graphs are used to simulate the similarities and differences between ground motion intensity measures and seismic demand parameters.

As an example of strong correlation, FBM1 and seismic demand parameters at the bottom of right column in axis P1 in FBM1 vs Sa(T1) values for each ground motion graph can be seen in Figure 4-1.

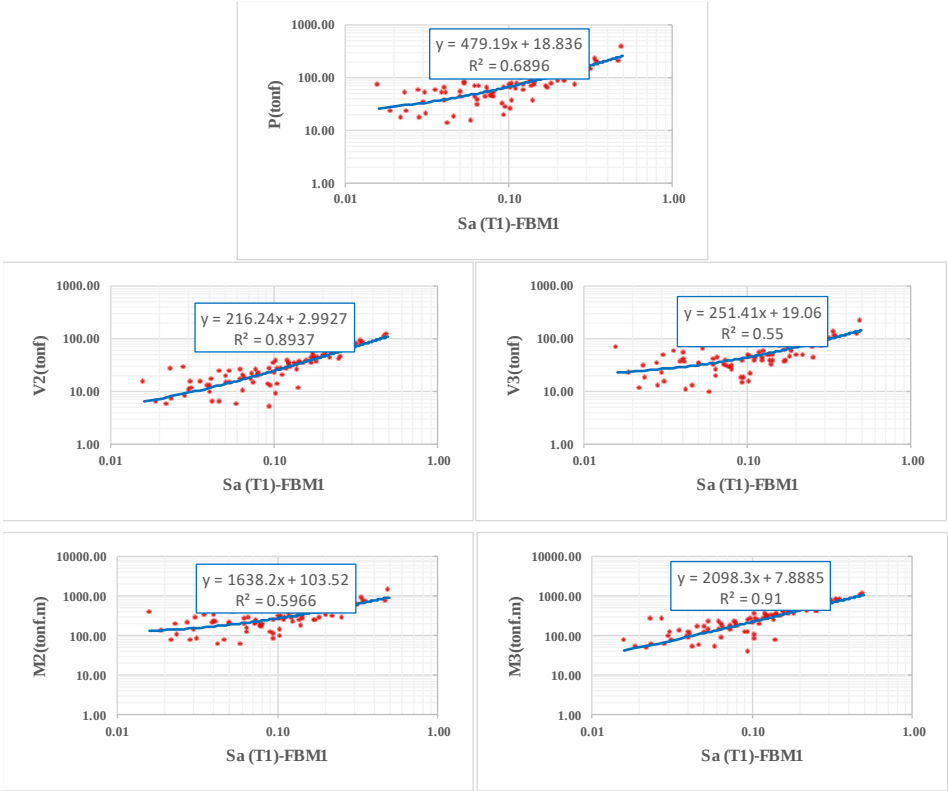


Figure 4-1:Seismic demand parameters at the bottom of right column in axis P1 in FBM1 vs Sa(T1)

As an example of weak correlation, FBM1 and seismic demand parameters at the bottom of right column in axis P1 in FBM1 vs PGA values for each ground motion graph can be seen in Figure 4-2 .

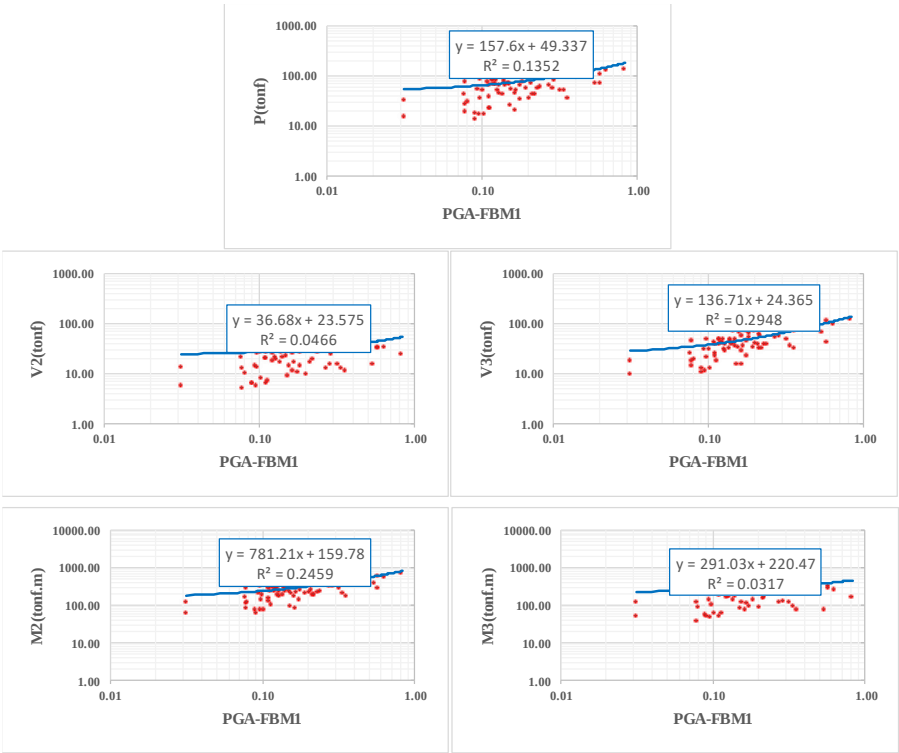


Figure 4-2: Seismic demand parameters at the bottom of right column in axis P1 in FBM1 vs PGA

All comparisons between each of the five demand parameters and twenty-three ground motion intensity measures can be found at Figure A- 1 to Figure A- 460 .

The equations of trend lines can be used to interpret the compatibility on two series. For strong correlations where R^2 values are greater than 80%, the equations can even be used for predicting seismic demand parameters by just looking at intensity measures. However, for weak correlations where R^2 values are less than 40%, the equations should not be used since all input values may result in different values. For moderate correlations where R^2 values are between 40% and 80%, the data in two series and equations must be interpreted and used very carefully.

4.3. Results and Discussion

The correlations between seismic demand parameters and intensity measures on different models are found by implementing two regression analyses mentioned in Chapter 0, Pearson's correlation coefficient and R-squared method. R^2 values are above the trendlines on the graphs of comparisons in Figure A- 1 to Figure A- 460.

Pearson's correlation coefficients and R^2 values are given in Table C- 1 to Table C- 8. In addition to Pearson's linear correlation coefficient, in order to evaluate the relative adequacy of each IM parameter, the coefficients of determination R^2 were computed for each curve fit. The R2 value is an indicator that takes values between 0 and 1.0 and reveals how closely the values predicted through a trendline correspond to the recorded data. Illustration of data in Table C- 1 to Table C- 8 is shown in Figure 4-3.

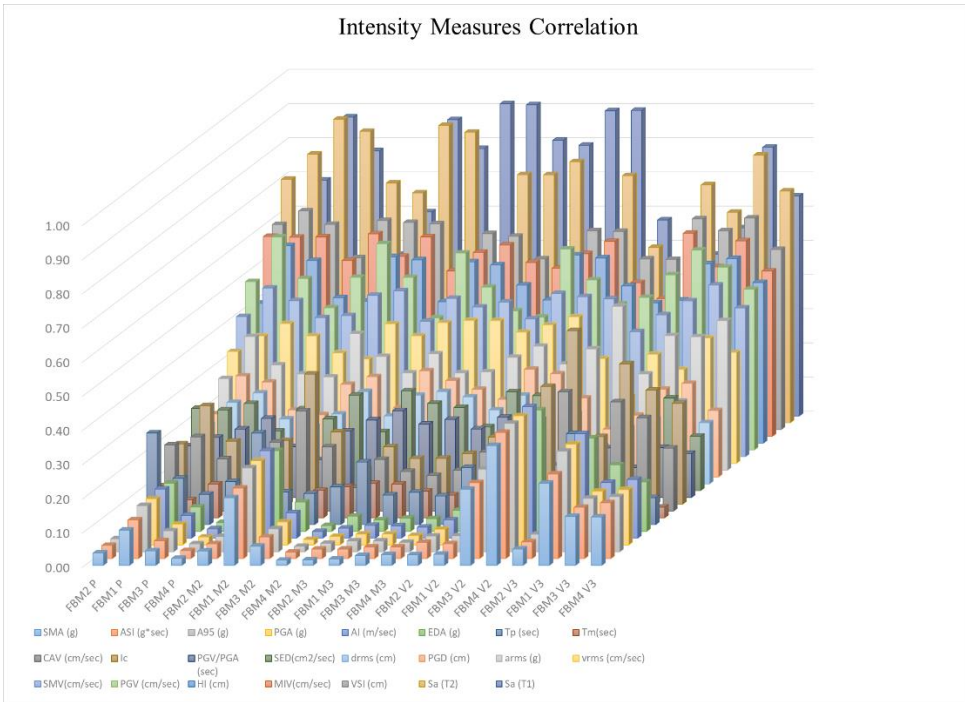


Figure 4-3: R^2 values between all ground motion intensity measures and all seismic demand parameters at the bottom of right column in axis P1 in each model

As an example, R^2 values between ground motion intensity measures and moment demand parameters about bridge transverse direction at the bottom of right

column in axis P1 in each model are shown in Figure 4-4. All figures illustrating correlations including Pearson's method between intensity measures and other seismic demand parameters can be found in Appendix B.

Considering correlation results found by using linear methods R^2 and Pearson's correlation coefficient, acceleration, velocity, displacement based and other parameters can be interpreted separately.

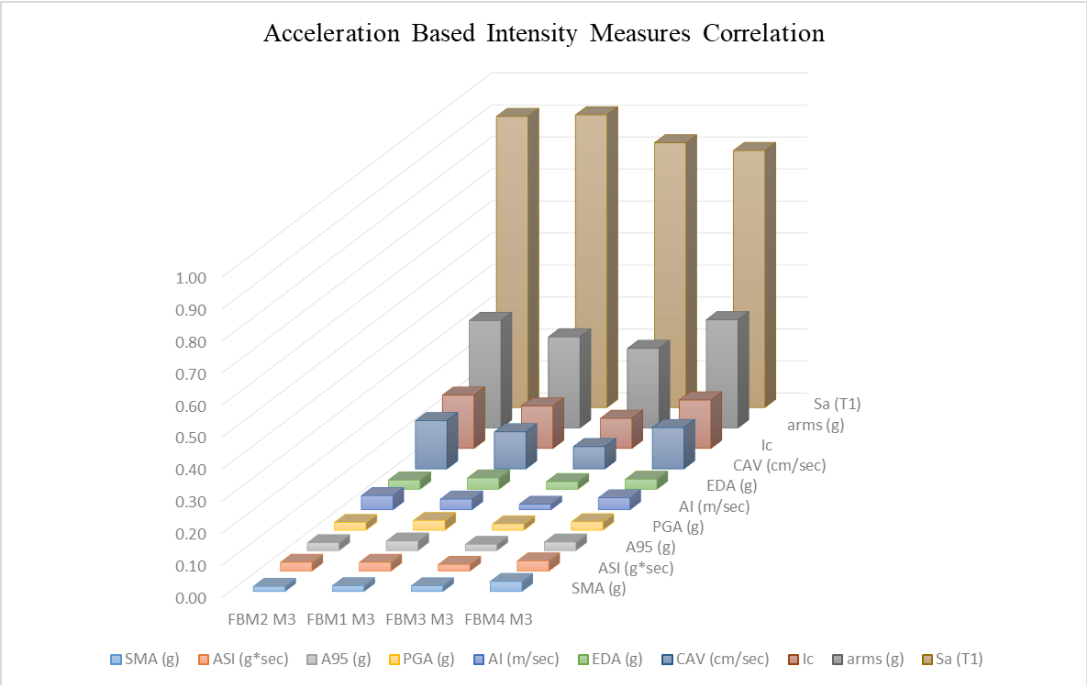


Figure 4-4: R^2 values between acceleration based ground motion intensity measures and moment demand parameters about bridge transverse direction at the bottom of right column in axis P1 in each model

For acceleration parameters, the largest R^2 value is determined for Sa(T1). This indicates that the behavior of the bridges selected is dominated by the response in the first mode in longitudinal direction as can be observed from Figure 4-4 and confirmed by looking first mode participation ratios in Table 3-4 to Table 3-7. Considering first mode periods can be ordered in flyover bridge models as FBM2(0.84s) < FBM1(1.24 s) < FBM3(1.46 s) < FBM4 (1.78 s), better correlations can be resulted in lower first mode periods which are affected from mass participation also. If all the models had

same mass participation ratios, the distribution can be concluded more clearly since acceleration parameters give better correlations in lower first mode periods. Chopra, 1995 mentioned that a very short period system is rigid thus result in very little deformation and its peak acceleration should be similar to ground motion's peak acceleration which is not a valid case for the bridges in this study.

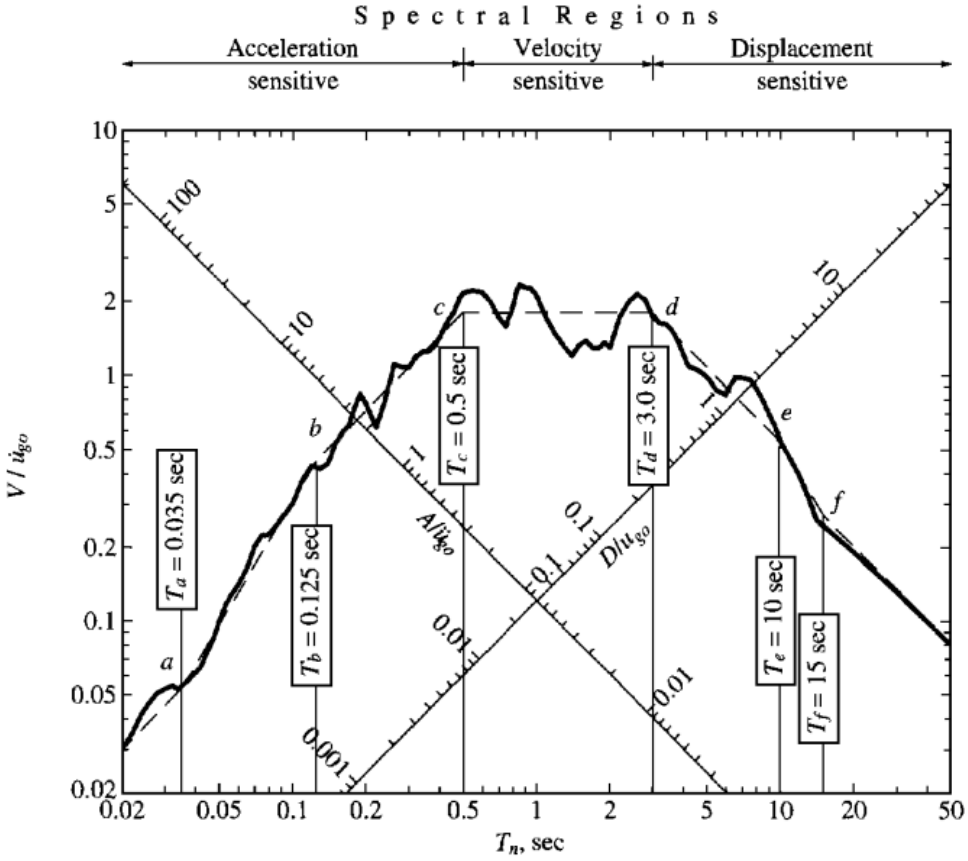
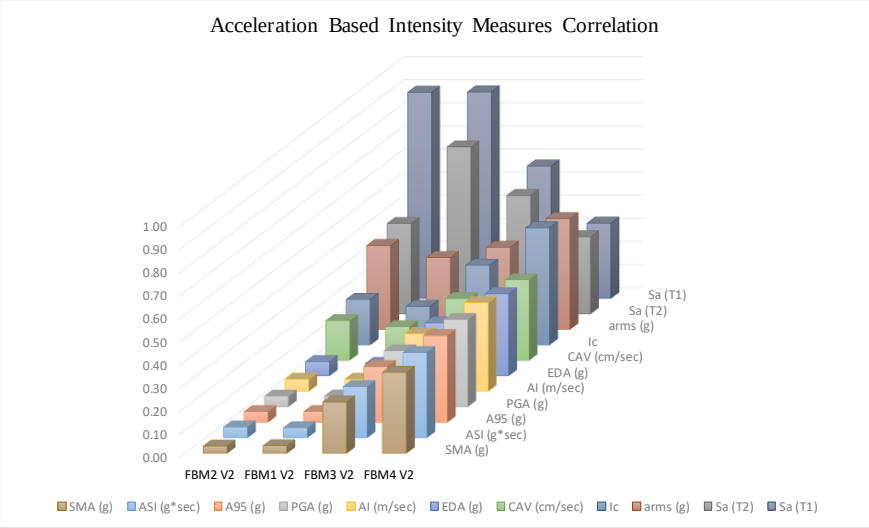


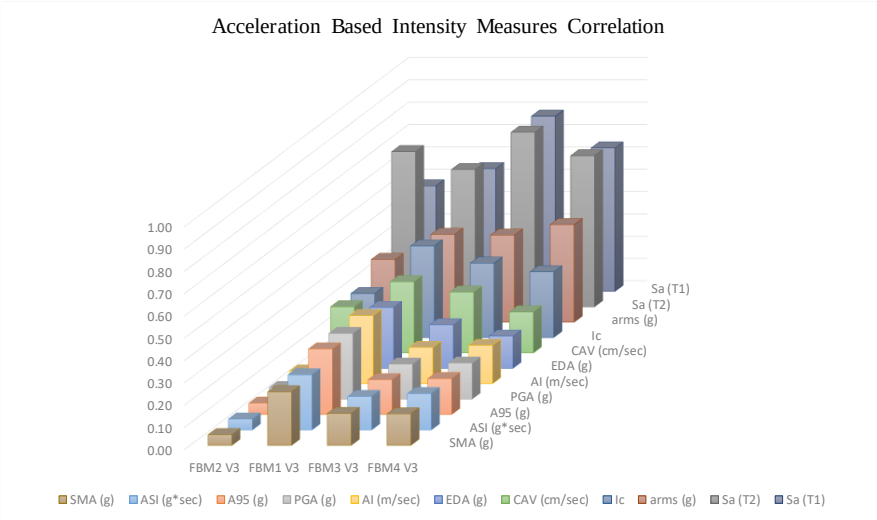
Figure 4-5: Spectral Regions Distributions (Chopra, 1995)

Similar distribution of correlation can be observed in Figure B- 7, Figure B- 10 and Figure B- 25. However, for correlations illustrated in Figure B- 1, Figure B- 4, Figure B- 13, Figure B- 16, Figure B- 19, and Figure B- 22, the same distribution is not achieved since first mode participation governs in bridge longitudinal direction. Even though the distribution is not achieved, Sa(T1) parameters is still the most correlated parameters among all seismic demand parameters.

In addition, for seismic demand parameters in transverse direction, mass participation can be achieved in second modes where periods are relatively lower compared to first mode periods. Second mode periods in all four bridges can be found in Table 3-4 to Table 3-7. As it is stated in Figure 4-5, lower periods can be considered as acceleration sensitive zone meaning acceleration parameters are better correlated with seismic demand parameters. To compare this, R^2 values between acceleration-based ground motion intensity measures and shear demand parameters in bridge longitudinal (V2) and transverse (V3) direction at the bottom of right column in axis P1 in each model are illustrated in Figure 4-6. Considerably higher correlations are observed in acceleration based parameters in Figure 4-6 (b) than in Figure 4-6 (a) since the dominant period in transverse direction is lower than in longitudinal direction. It is also observed that, with Sa (T2) intensity measure, higher correlations can be achieved in Figure 4-6 (b) compared to correlations in Figure 4-6 (a) but since the mass participations are getting lower, the same correlations of Sa(T1) in first mode is not achieved with Sa(T2) in second modes.



(a)



(b)

Figure 4-6: R^2 values between acceleration-based ground motion intensity measures and shear demand parameters in bridge longitudinal (V2) (a) and transverse (V3) (b) direction at the bottom of right column in axis P1 in each model

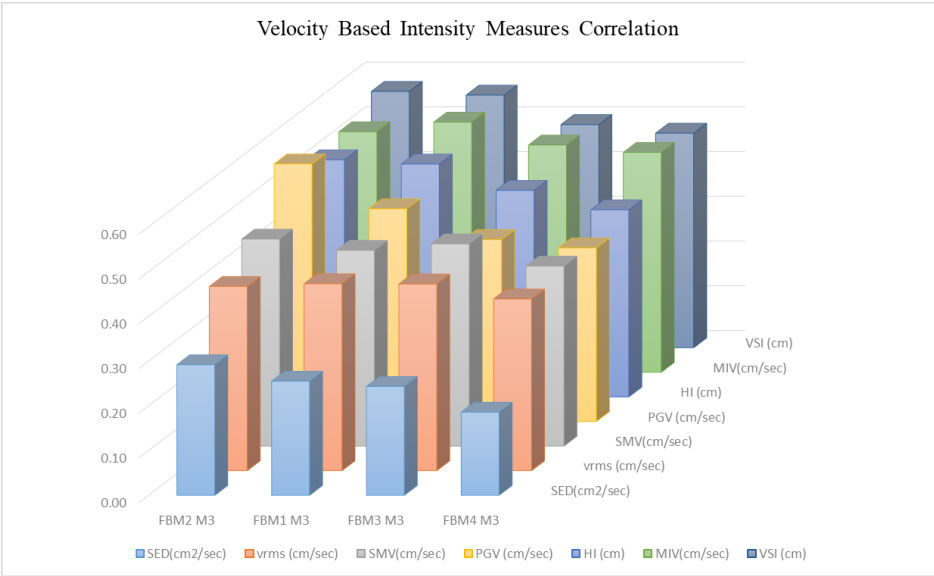


Figure 4-7: R^2 values between velocity based ground motion intensity measures *and moment demand parameters about bridge transverse direction at the bottom of right column in axis P1 in each model*

Compared to acceleration parameters, velocity-based parameters have better correlations with all seismic demand parameters. This the indication of that the rigidities of the bridges selected have great importance on the correlation of seismic destructivity as it can be observed in Figure 4-7. As in most highway bridges, all four bridges in this study have first mode periods of 0.5 s to 3.0 s. According to Chopra, 1995, this range of period can be idealized as velocity sensitive region spectral region as it can be seen from Figure 4-5 by mentioning the period values Ta, Tb, Tc, Td, Te, and Tf are not unique in the sense that they vary from one ground motion to the next. He mentioned that this range is called velocity-sensitive region since structural response is better related to velocity-based ground motion intensity measures than to other ground motion intensity measures. Furthermore, correlations shown in Figure B- 2, Figure B- 5, Figure B- 8, Figure B- 11, Figure B- 14, Figure B- 17, Figure B- 23, and Figure B- 26 indicate that all seismic demand parameters are reasonable to predict the velocity based intensity measures of ground motion. By investigating velocity based parameters in all seismic demand parameters, intensity measures VSI (cm), MIV (cm/sec), PGV (cm/sec), and HI (cm) have better correlation values

compared to SMV (cm/sec), v_{rms} (cm/sec) and SED (cm^2/sec). The best velocity based ground motion intensity measure for the bridges in this study with periods between 0.84 and 1.78 s is observed to be VSI (cm), followed by MIV (cm/sec), PGV (cm/sec), and HI (cm) respectively.

Compatibly with this study, Yakut & Yılmaz, 2008 stated in their article that ground motion intensity measure that gives the best correlation with seismic demand parameters on structures in their study with natural periods ranging between 0.2 s and 0.5 s was PGA (g). In addition to that, as the natural periods of structures in their study started to increase to a range between 0.5 s and 1.1 s, the best correlated ground motion intensity measures were velocity based parameters such as VSI (cm) and HI(cm).

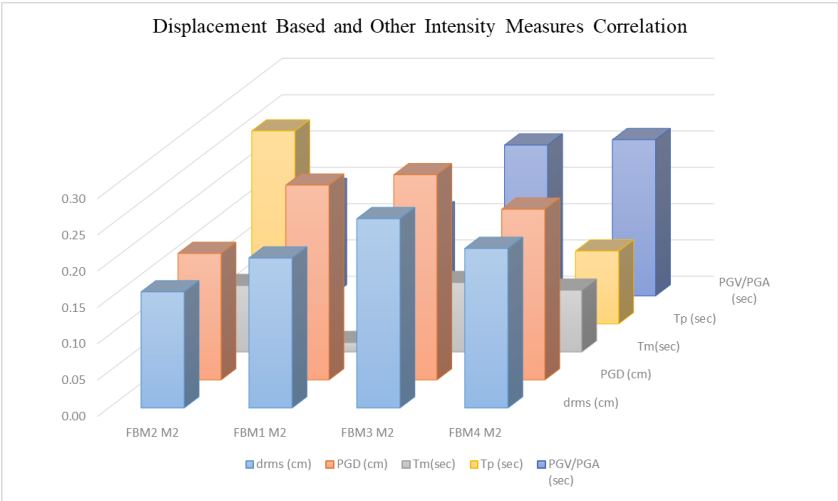


Figure 4-8: R^2 values between displacement based and other ground motion intensity measures and moment demand parameters about bridge transverse direction at the bottom of right column in axis P1 in each model

In Figure 4-8, displacement based parameters show poor correlations compared to other parameters. This is because the bridges in this study do not have long periods ranged in periods longer than 3.0 s. In other words, these bridges are not included in displacement sensitive period zone mentioned in Figure 4-5. Very-long-period systems are very flexible resulting in the mass remains stationary while the

ground below moves. This is not the case for the bridges in this study because the systems are relatively more rigid for this case. In addition, other parameters such as period parameters Tm (sec), Tp (sec) and PGV/PGA (sec) ratio is also studied and concluded they do not show good correlations. Together with this, in none of Figure B- 3, Figure B- 6, Figure B- 9, Figure B- 12, Figure B- 15, Figure B- 18, Figure B- 21, Figure B- 27, and Figure B- 30 correlations are not good enough to interpret the ground motions' severity for the bridges in this study.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1. Summary

In this thesis, effects of different earthquakes on different structures were analyzed. To do this, six sets of recorded ground motions were selected in three different magnitudes, 6.0, 6.5 and 7.0 according to Richter scale and soil classes C and D according to NEHRP. In each set, seven recorded ground motion data are selected incompatible with these sets resulting in a total of forty-two recorded ground motions using PEER database. The effects of unscaled earthquake records on nonlinear time history analysis models of on four different flyover intersection highway bridge models with natural periods varying between 0.84 s and 1.78 s investigated. All bridges have mass participation around 90% in their natural periods separately. Seismic demand parameters on the bottom of right columns in P1 axis in each bridge are determined and compared with twenty-three ground motion intensity measures of the earthquake records which then grouped as acceleration, velocity and displacement based and other intensity measures. This comparison is then connected with statistical analyses of Pearson's correlation coefficient (r) and R^2 values resulting in correlation values.

5.2. Conclusion

Results of analysis lead that, contrary to the general assumption on selecting acceleration parameters while determining recorded earthquake data to be used in the analysis of seismic assessment of bridges, rigidities of structures are needed to be checked also.

Among twenty-three ground motion intensity measures, S_a (T1) is the one that has the strongest correlation between ground motion intensity measures and seismic demand parameters. However, it should be noted that exact natural periods and their pseudo acceleration spectrum values are needed for S_a (T1) value to be effective.

Except for S_a (T1), examining acceleration based ground motion intensity measures by themselves concluded that as the bridges' rigidities increase, they undergo very little deformation and the mass contributed in seismic actions moves rigidly with the ground so the structure's peak acceleration approaches ground motion's peak acceleration (Chopra, 1995). This is the reason, as the natural periods decrease, correlation values between acceleration based ground motion intensity measures and seismic demand parameters started to increase in all of four bridges in this study. However, four bridges are not rigid enough to show good correlation with acceleration based parameters as their natural periods range between 0.84 s and 1.78 s.

For highway bridges, the natural periods are ranging generally between 0.5 s and 3.0 s, which is called medium period range. Velocity based ground motion intensity measures yielded healthier results by means of correlation in predicting severity of ground motion on structures. VSI (cm), followed by MIV (cm/sec), PGV (cm/sec), and HI (cm) are the best correlated velocity based intensity measures with four bridges in this study respectively. Without knowing structures' natural period or ground motions' spectrum information, unlike acceleration based intensity measures, velocity based intensity measures showed better correlation. For current ground

motion record databases, Sa(T1) and PGV may be preferred as a predictive intensity measures to find compatible data.

Another difference between velocity based and acceleration based intensity measures is that acceleration based intensity measures are affected by mass participation in dominant period of structures to a great extent. In this case, for acceleration based parameters, the direction of participated mass in dominant period changes severity of seismic demand parameters in dominant direction. For example, all bridges in their natural period with contribution of 90% mass in longitudinal direction result in that only correlation with seismic demand parameters in longitudinal direction such as V2 (tonf) and M3 (tonf.m) can be interpreted. When evaluating second modes, contribution of 90% mass in transverse direction results in that only correlation with seismic demand parameters in transverse direction such as V3 (tonf) and M2 (tonf.m) can be interpreted. However, for velocity based intensity measures, since the periods of bridges' both first modes and second modes are in velocity sensitive range, they result in good correlation in every direction of seismic demand parameters.

By using the same logic behind the correlation between rigidities and acceleration intensity measures, the poor correlation between displacement based ground motion intensity measures and seismic demand parameters can be explained. In this case, contrary to in acceleration based intensity measures, they undergo very large deformation and the mass contributed in seismic actions moves freely compared with the ground so the structure's peak acceleration becomes independent to ground motion's peak acceleration. In this case, the displacement based intensity measures show good correlation. However, since the bridges in this study are relatively rigid enough to move with ground, displacement based intensity measures show poor correlations with all seismic demand parameters.

Furthermore, period based ground motion intensity measures and PGV/PGA ratio grouped in another category also shows poor correlation. Period based ground

motion intensity measures give information only about dominant period where the maximum spectral acceleration occurs in an acceleration response spectrum calculated at 5% damping or mean period which is the Fourier Amplitude Spectrum, averaging periods. However, important conclusions can be resulted in evaluating correlation of intensity measures with seismic demand parameters are acceleration, velocity or displacement values.

In addition, natural periods of bridges as well as load distribution between bridge elements are changing significantly with change in supporting conditions of elastomeric bearings. Different periods shall result in different seismic demand parameters on bridges. Changing the number or layout of elastomeric bearings can significantly affect the optimized and economical designs for bridges.

5.3. Recommendations

Considering the findings in this study, it will be important to consider the following issues.

- Recorded hazard study should be implemented with constructed bridges designed with response spectrum analysis defined in specifications. With the help of this study, difference between using recorded ground motions and design spectrums can be understood.
- By using ground motion intensity measures, effects of actual ground motions in near faults effects should be investigated also with vertical component of earthquakes.
- Long span bridges with tall piers should be studied to see the displacement based intensity measures' effect on those kinds of bridges
- In order to fully evaluate usability of acceleration based intensity measures, much more rigid bridges compared to the bridges in this study should be analyzed.

In the days where nonlinear time history analyses are getting popular in solution of certain applications of highway bridges, the findings of this study may lead designers or researchers to choose matching ground motions. With the increasing data of recorded ground motions, there would be a need in filtering ground motions for specific types of structures. It is hoped that findings in this study may be a tool for predicting and grouping intensity measures and consequently foreseeing severity of ground motion on a structure.

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APPENDICES

A. Comparison of Seismic Demand Parameters and Ground Motion Intensity Measures

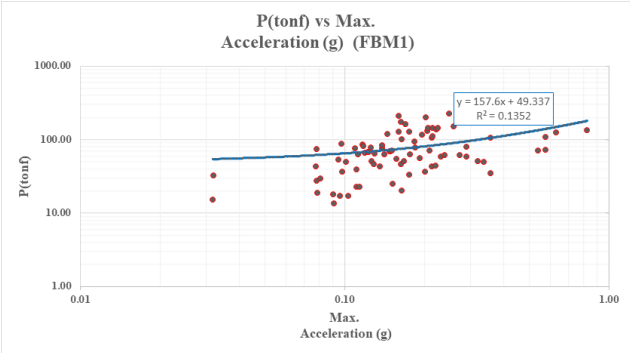


Figure A- 1:P(tonf) in FBM1 vs PGA(g)

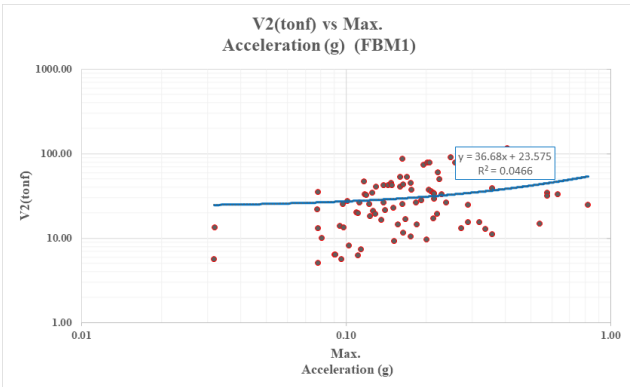


Figure A- 2:V2(tonf) in FBM1 vs PGA(g)

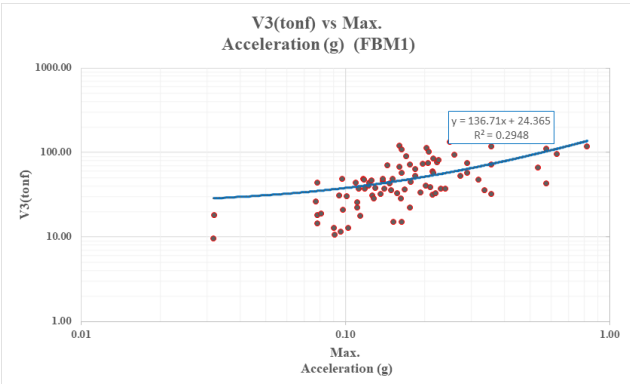


Figure A- 3:V3(tonf) in FBM1 vs PGA(g)

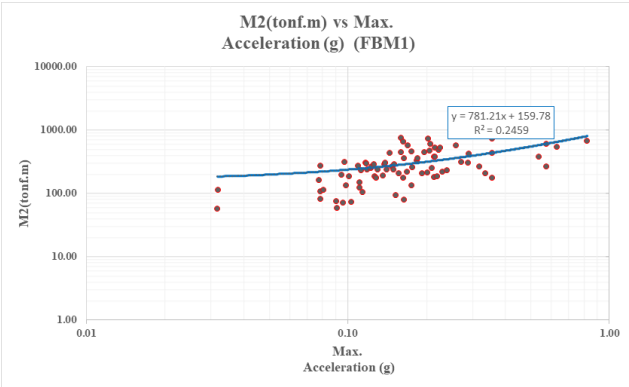
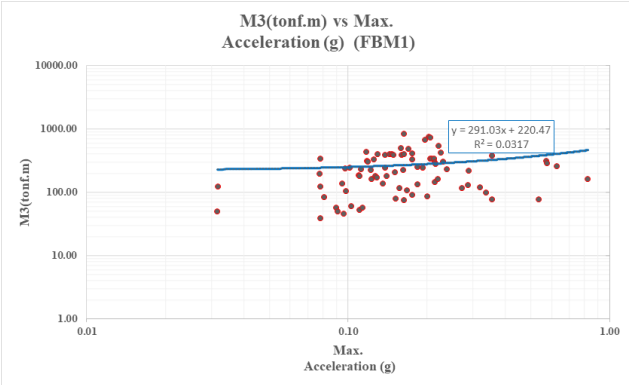


Figure A- 4:M2(tonf.m) in FBM1 vs PGA(g)



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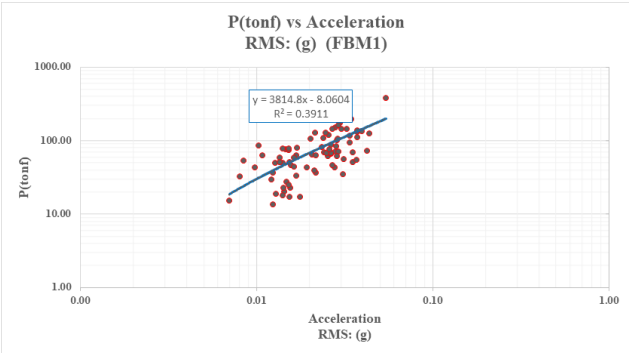


Figure A- 6:P(tonf) in FBM1 vs arms(g)

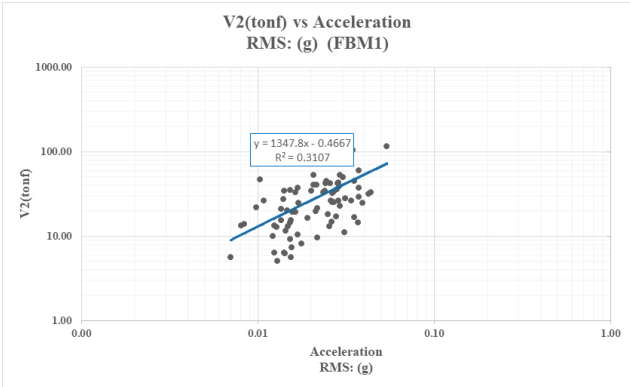
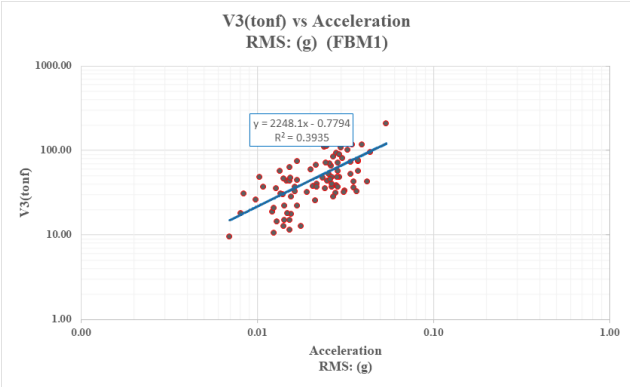


Figure A- 7:V2(tonf) in FBM1 vs arms(g)



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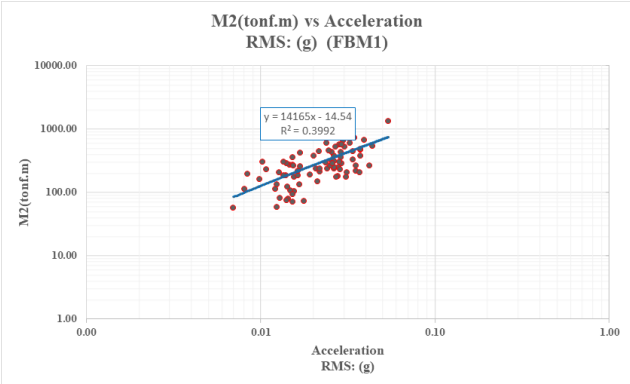


Figure A- 9:M2(tonf.m) in FBM1 vs arms(g)

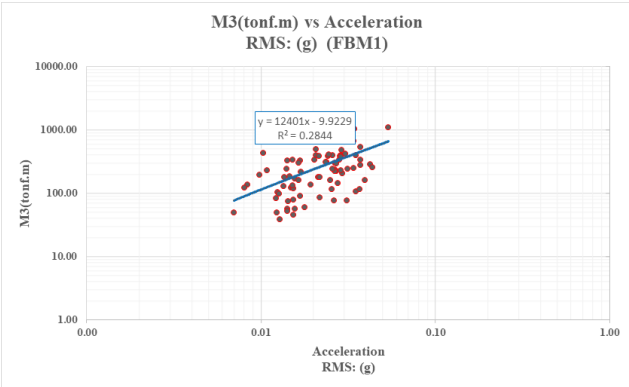


Figure A- 10:M3(tonf.m) in FBM1 vs arms(g)

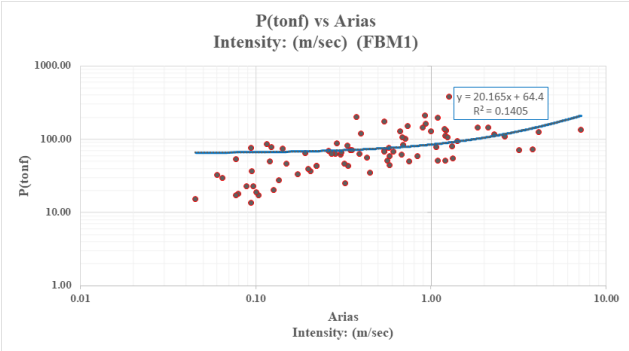


Figure A- 11:P(tonf) in FBM1 vs AI(m/sec)

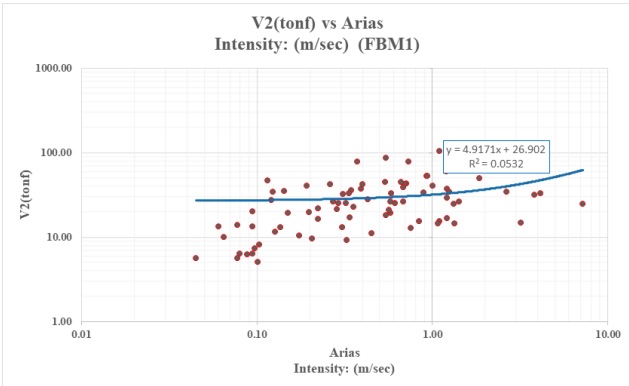
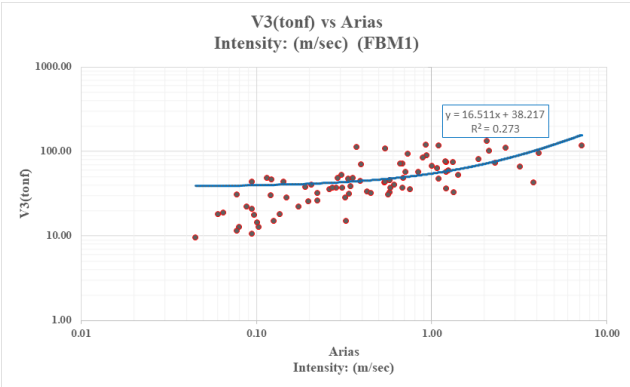


Figure A- 12:V2(tonf) in FBM1 vs AI(m/sec)



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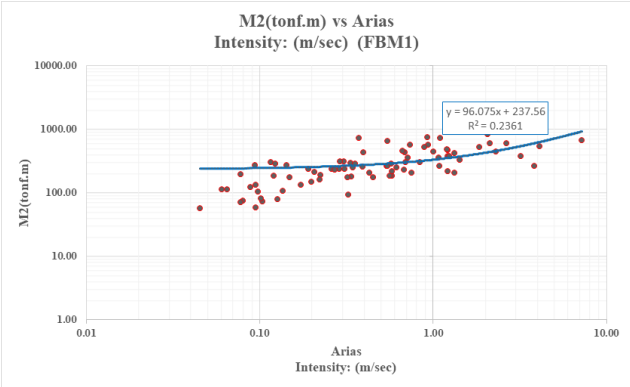


Figure A- 14:M2(tonf.m) in FBM1 vs AI(m/sec)

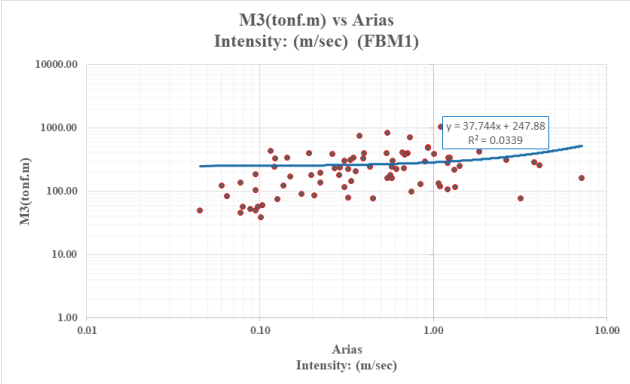


Figure A- 15:M3(tonf.m) in FBM1 vs AI(m/sec)

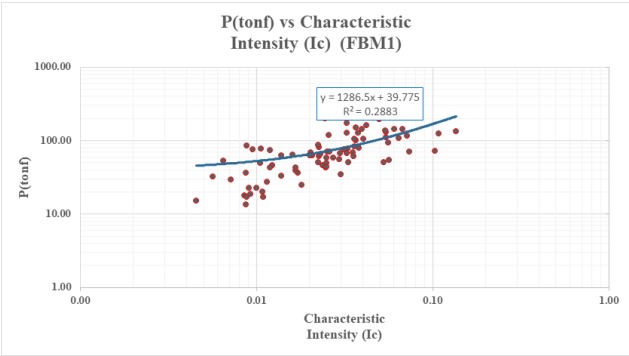


Figure A- 16:P(tonf) in FBM1 vs Ic

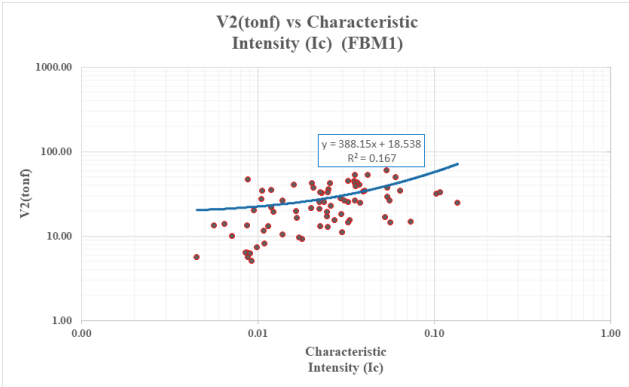


Figure A- 17:V2(tonf) in FBM1 vs Ic

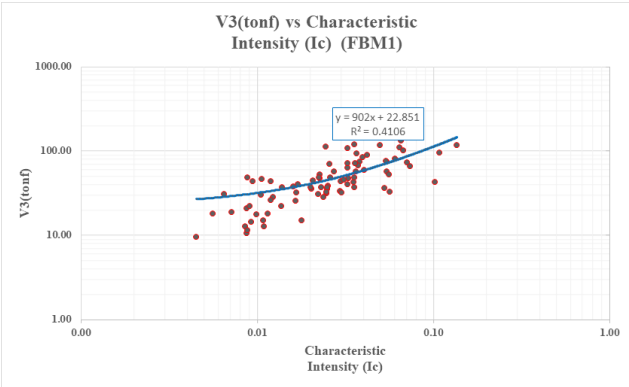
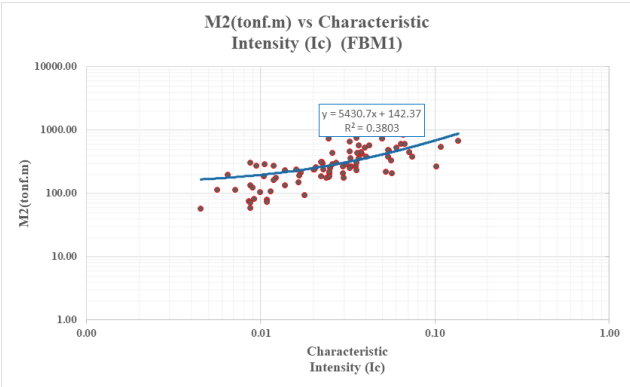


Figure A- 18:V3(tonf) in FBM1 vs Ic



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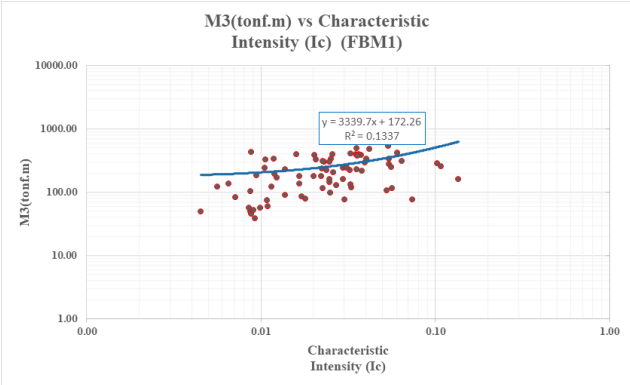


Figure A- 20:M3(tonf.m) in FBM1 vs Ic

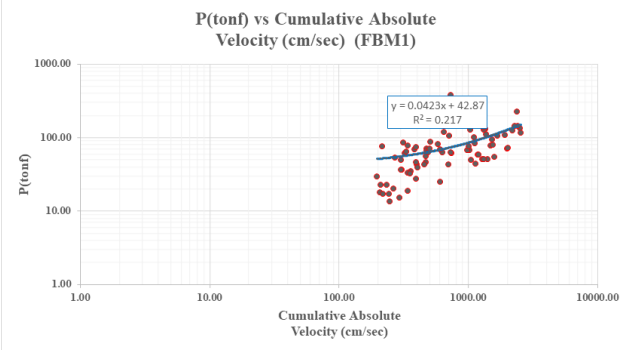


Figure A- 21:P(tonf) in FBM1 vs CAV (cm/sec)

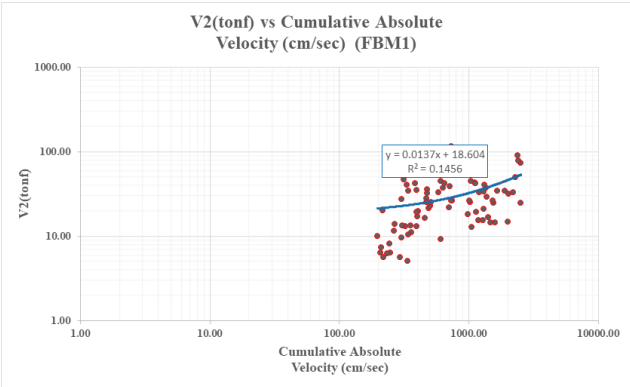


Figure A- 22:V2(tonf) in FBM1 vs CAV (cm/sec)

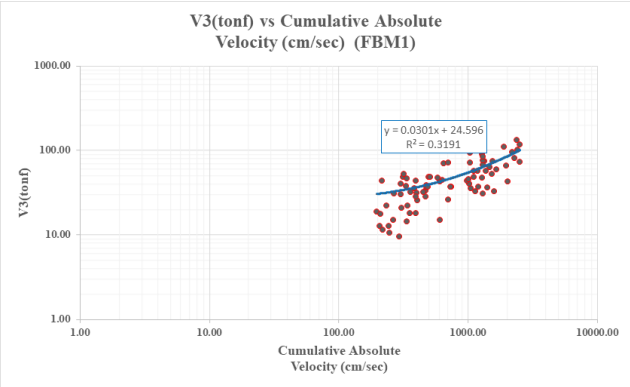


Figure A- 23:V3(tonf) in FBM1 vs CAV (cm/sec)

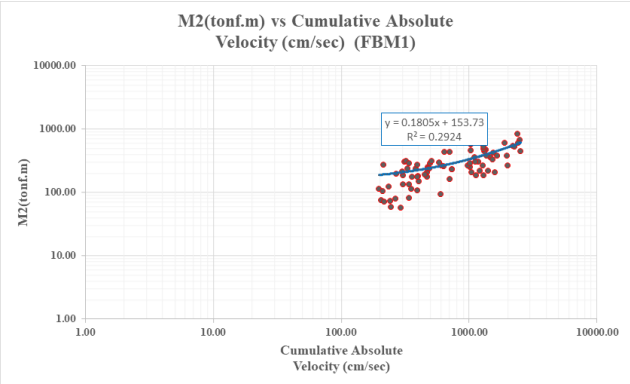


Figure A- 24:M2(tonf.m) in FBM1 vs CAV (cm/sec)

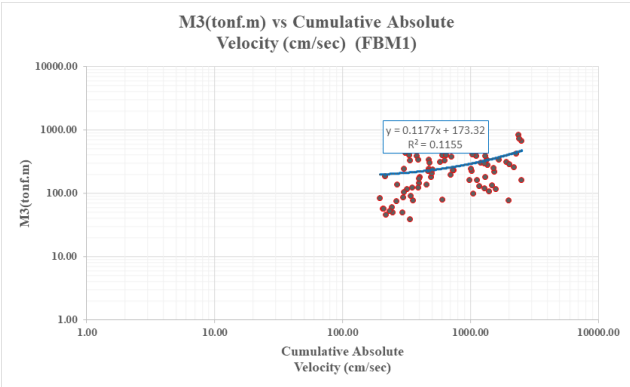


Figure A- 25:M3(tonf.m) in FBM1 vs CAV (cm/sec)

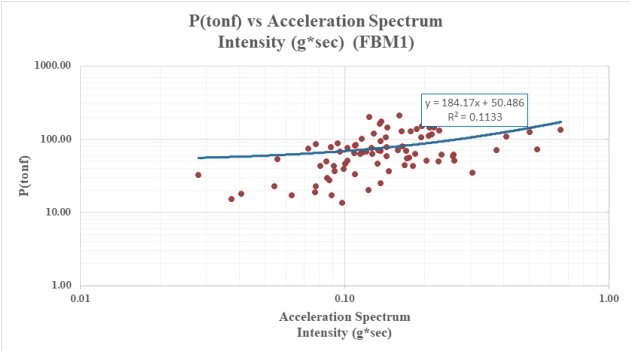


*Figure A- 26:P(tonf) in FBM1 vs ASI (g*sec)*

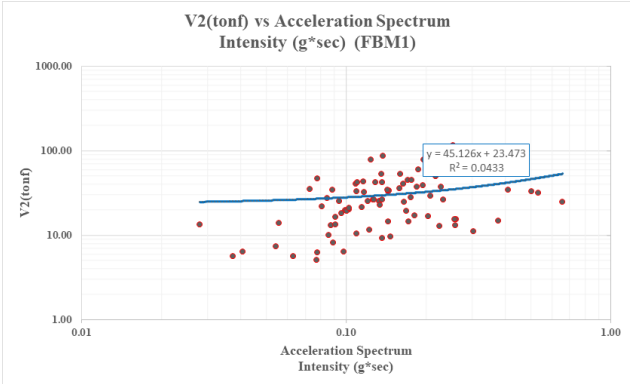


*Figure A- 27:V2(tonf) in FBM1 vs ASI (g*sec)*

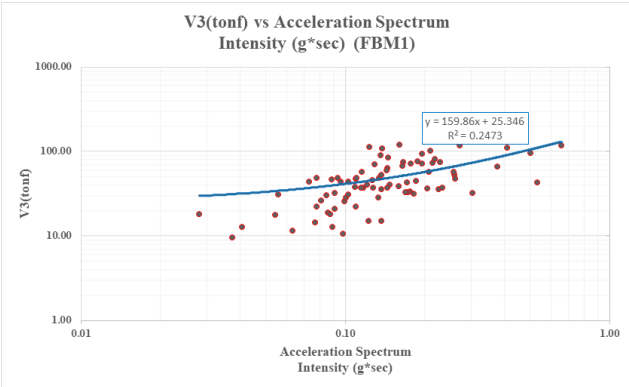


*Figure A- 28:V3(tonf) in FBM1 vs ASI (g*sec)*

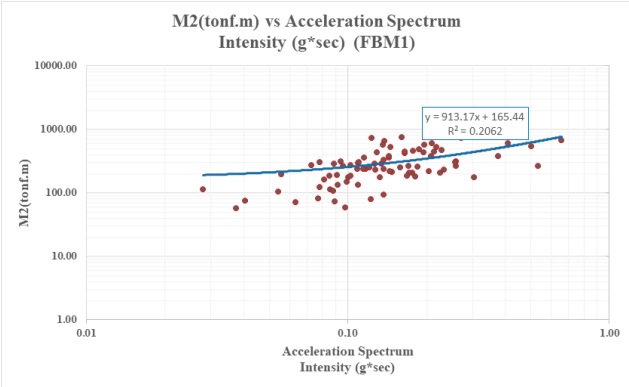


*Figure A- 29:M2(tonf.m) in FBM1 vs ASI (g*sec)*

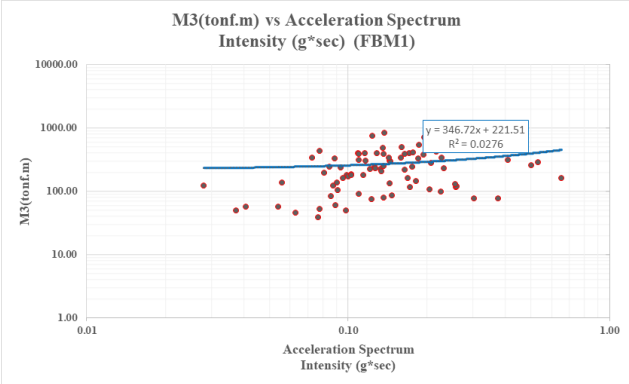


*Figure A- 30:M3(tonf.m) in FBM1 vs ASI (g*sec)*

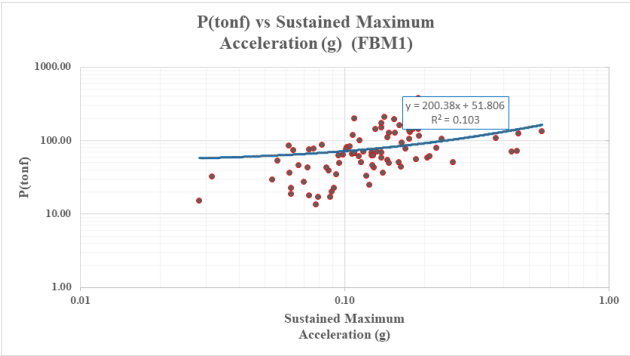


Figure A- 31:P(tonf) in FBM1 vs SMA (g)

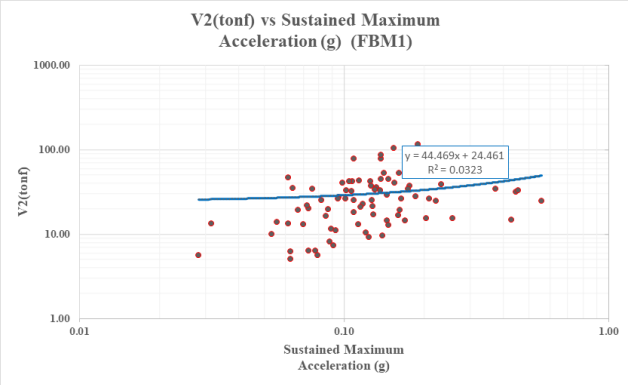


Figure A- 32:V2(tonf) in FBM1 vs SMA (g)

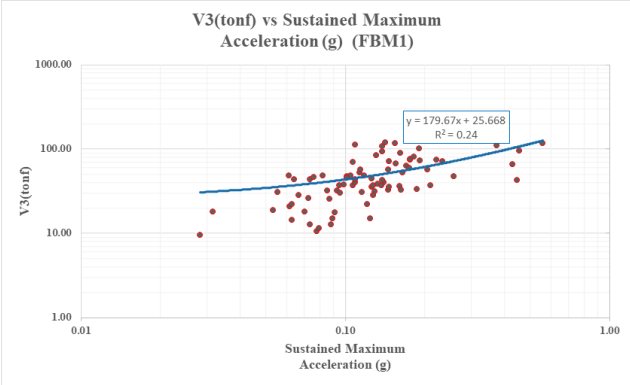


Figure A- 33:V3(tonf) in FBM1 vs SMA (g)

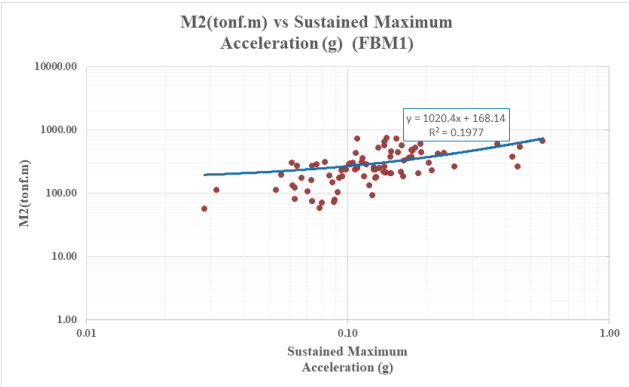


Figure A- 34:M2(tonf.m) in FBM1 vs SMA (g)

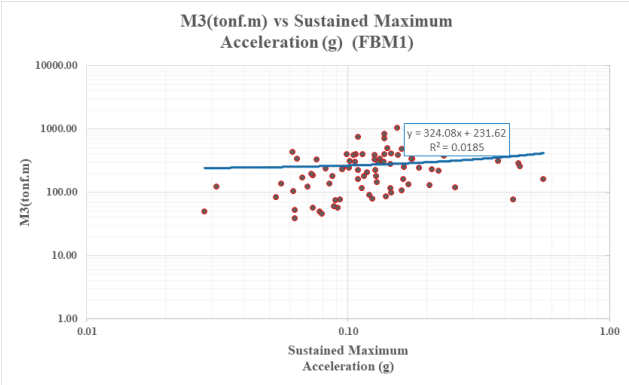


Figure A- 35:M3(tonf.m) in FBM1 vs SMA (g)

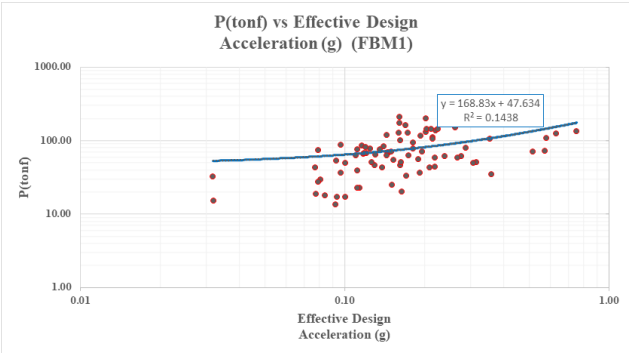


Figure A- 36:P(tonf) in FBM1 vs EDA (g)

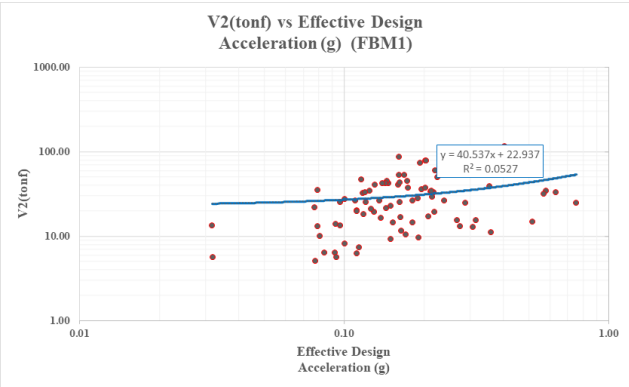


Figure A- 37:V2(tonf) in FBM1 vs EDA (g)

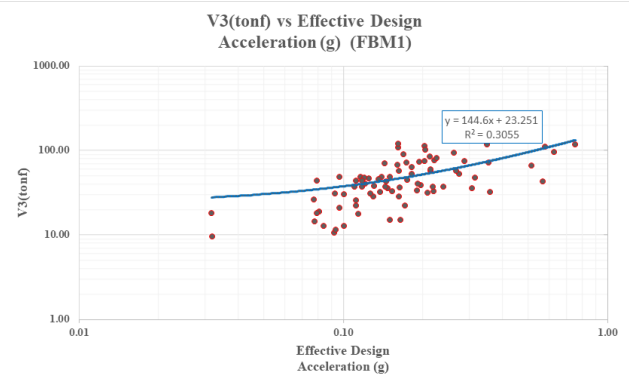


Figure A- 38:V3(tonf) in FBM1 vs EDA (g)

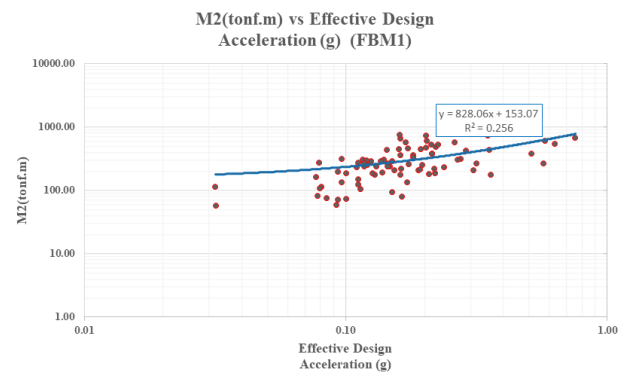


Figure A- 39:M2(tonf.m) in FBM1 vs EDA (g)

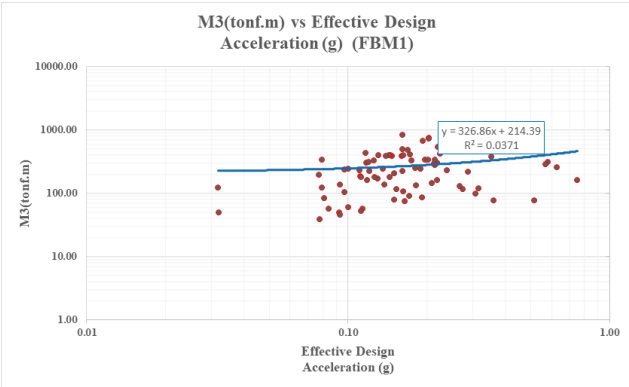


Figure A- 40:M3(tonf.m) in FBM1 vs EDA (g)

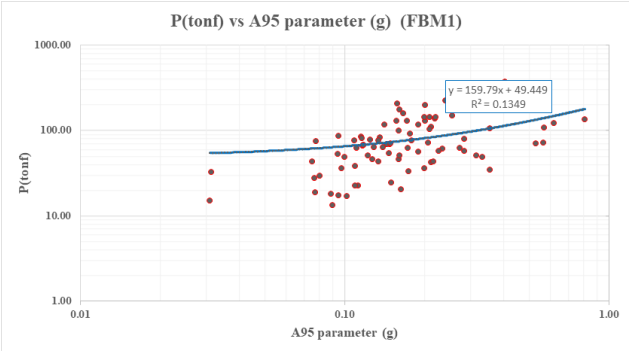


Figure A- 41:P(tonf) in FBM1 vs a95 (g)

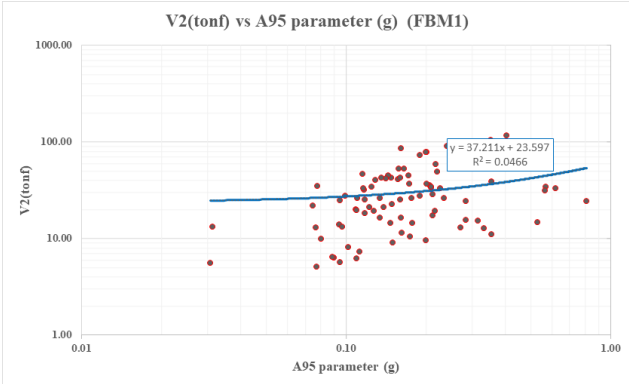


Figure A- 42:V2(tonf) in FBM1 vs a95 (g)

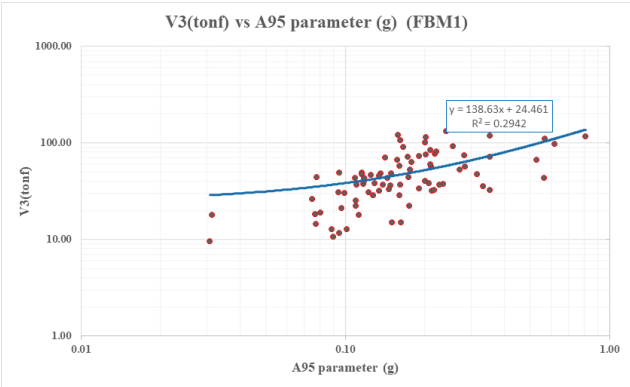


Figure A- 43:V3(tonf) in FBM1 vs a95 (g)

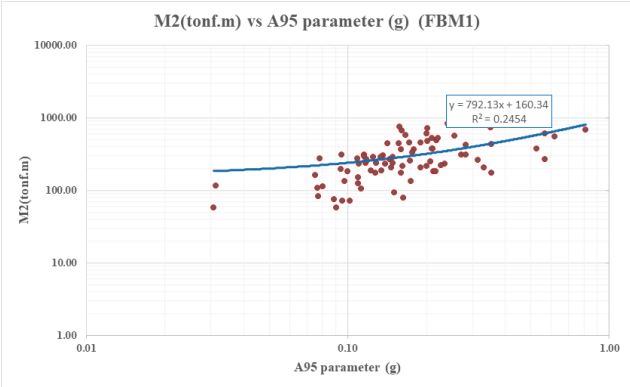


Figure A- 44:M2(tonf.m) in FBM1 vs a95 (g)

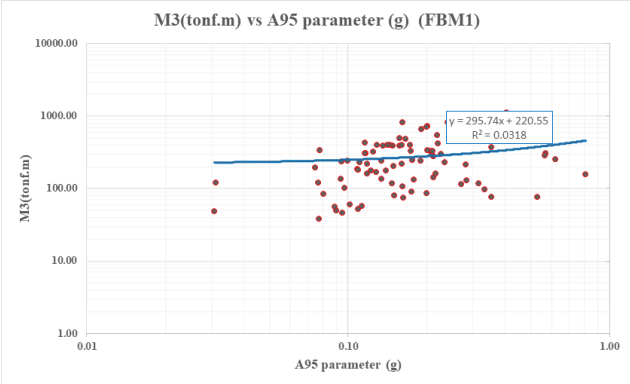


Figure A- 45:M3(tonf.m) in FBM1 vs a95 (g)

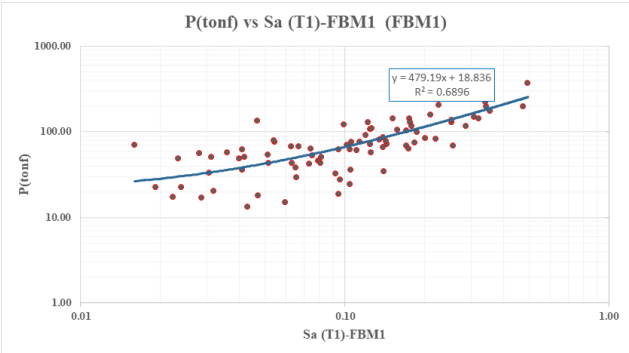


Figure A- 46:P(tonf) in FBM1 vs Sa (T1) (g)

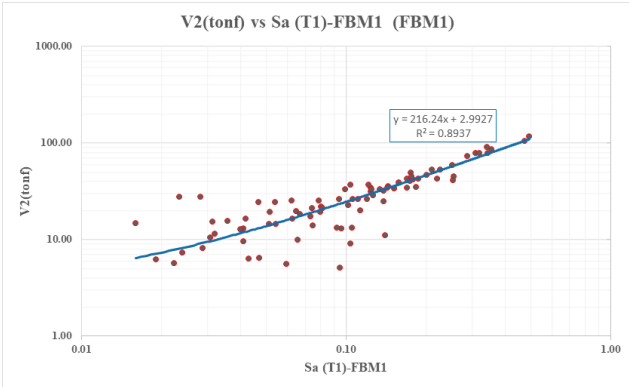


Figure A- 47:V2(tonf) in FBM1 vs Sa (T1) (g)

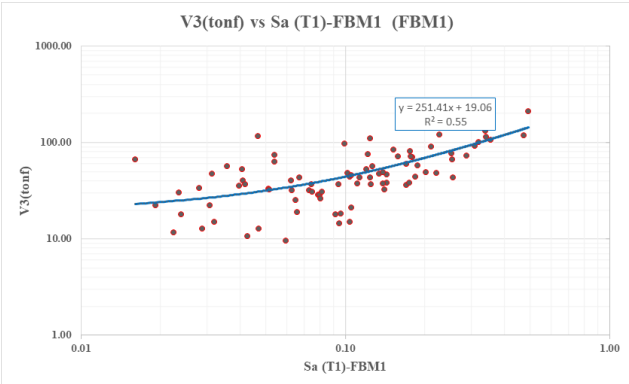


Figure A- 48:V3(tonf) in FBM1 vs Sa (T1) (g)

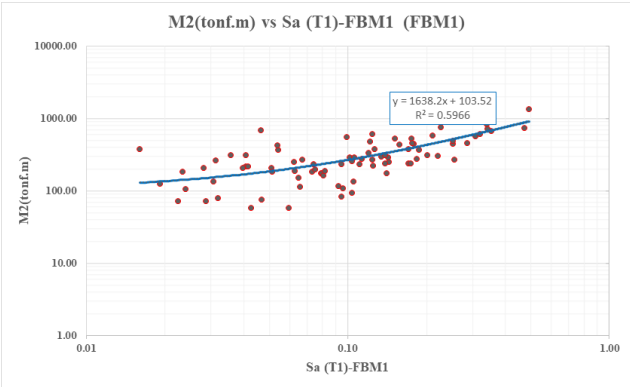


Figure A- 49:M2(tonf.m) in FBM1 vs Sa (T1) (g)

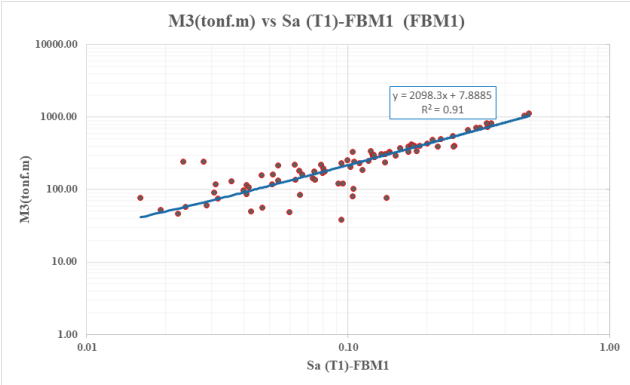


Figure A- 50:M3(tonf.m) in FBM1 vs Sa (T1) (g)

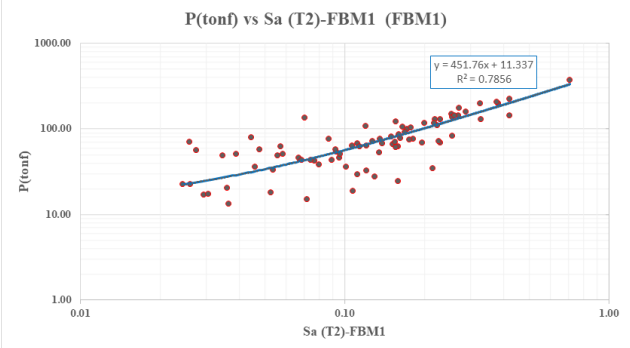


Figure A- 51:P(tonf) in FBM1 vs Sa (T2) (g)

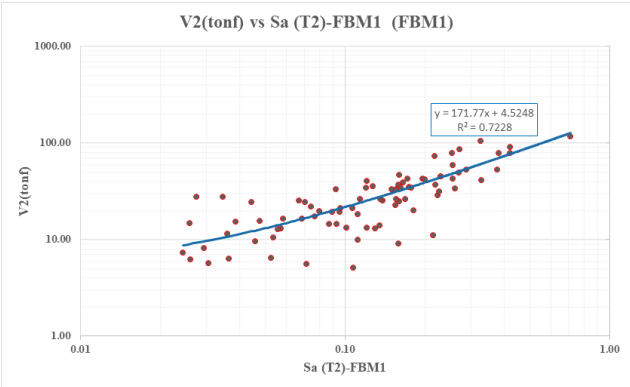


Figure A- 52:V2(tonf) in FBM1 vs Sa (T2) (g)

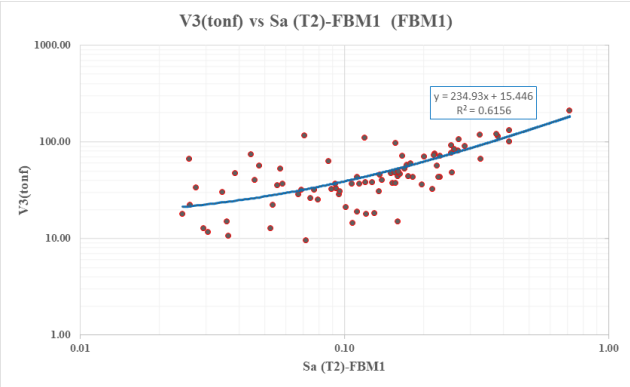


Figure A- 53:V3(tonf) in FBM1 vs Sa (T2) (g)

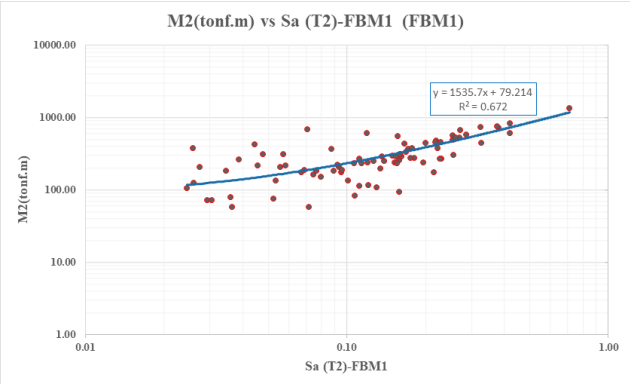


Figure A- 54:M2(tonf.m) in FBM1 vs Sa (T2) (g)

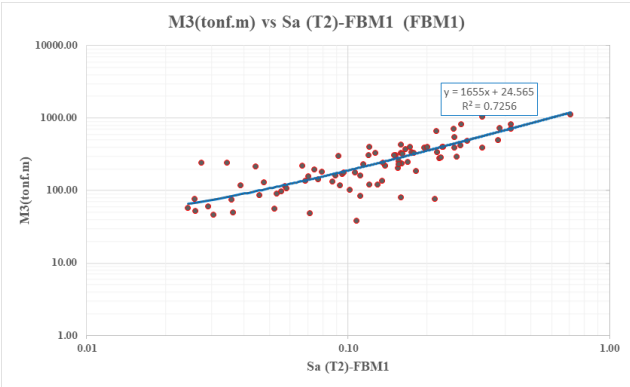


Figure A- 55:M3(tonf.m) in FBM1 vs Sa (T2) (g)

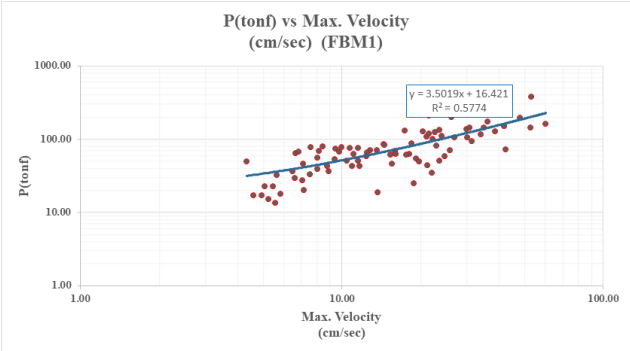


Figure A- 56:P(tonf) in FBM1 vs PGV (cm/sec)

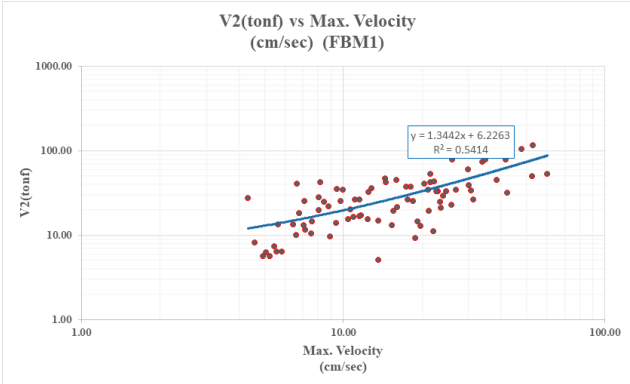


Figure A- 57:V2(tonf) in FBM1 vs PGV (cm/sec)

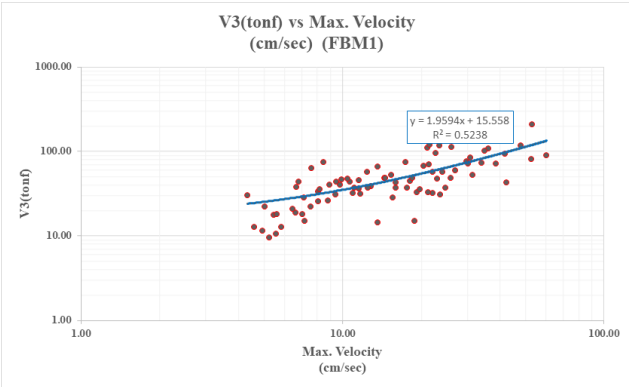


Figure A- 58:V3(tonf) in FBM1 vs PGV (cm/sec)

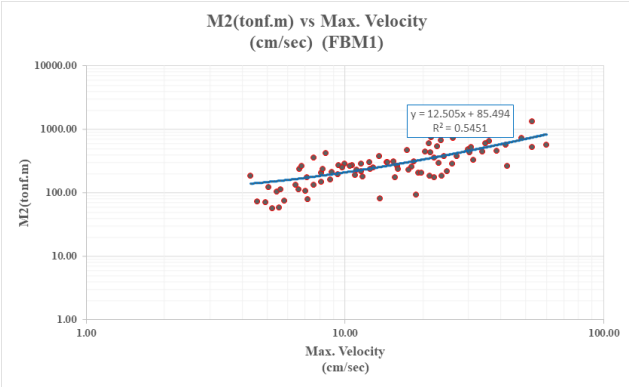


Figure A- 59:M2(tonf.m) in FBM1 vs PGV (cm/sec)

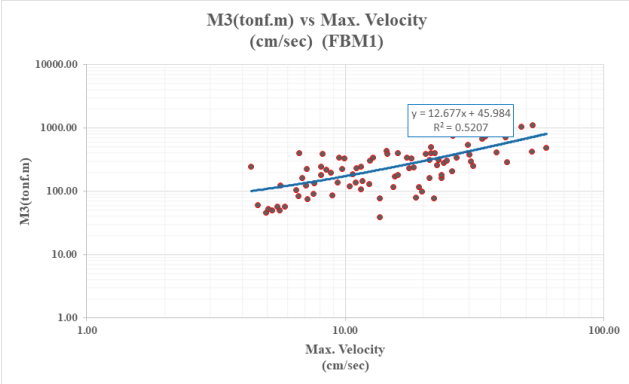


Figure A- 60:M3(tonf.m) in FBM1 vs PGV (cm/sec)

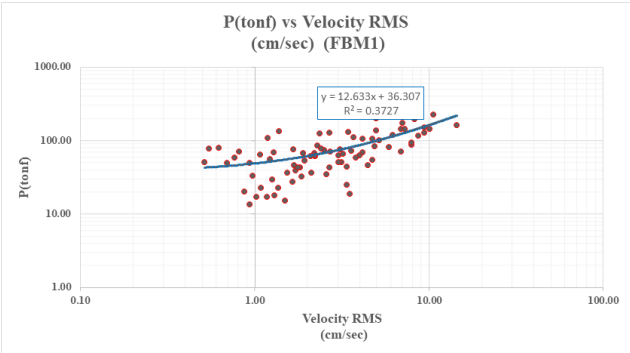


Figure A- 61:P(tonf) in FBM1 vs vrms (cm/sec)

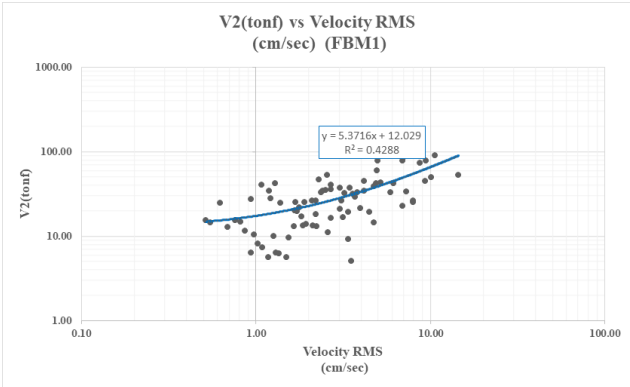


Figure A- 62:V2(tonf) in FBM1 vs vrms (cm/sec)

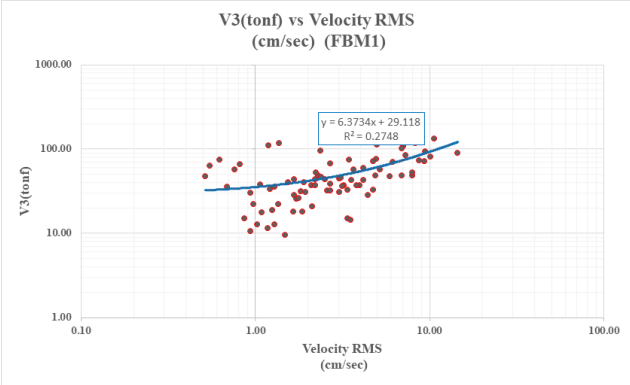


Figure A- 63:V3(tonf) in FBM1 vs vrms (cm/sec)

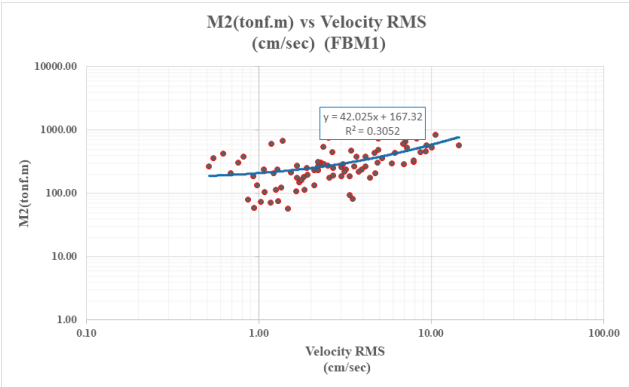


Figure A- 64:M2(tonf.m) in FBM1 vs vrms (cm/sec)

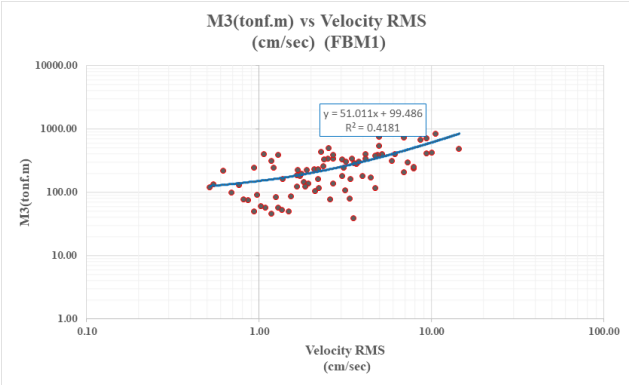


Figure A- 65:M3(tonf.m) in FBM1 vs vrms (cm/sec)

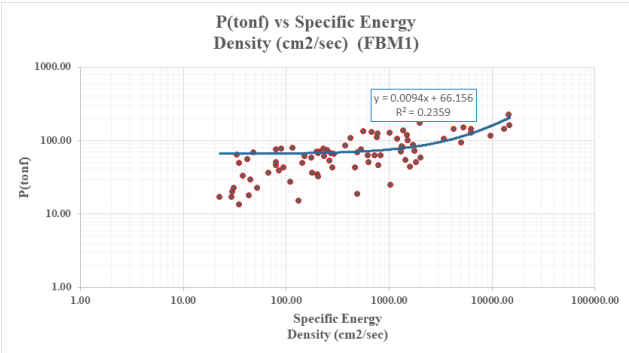


Figure A- 66:P(tonf) in FBM1 vs SED (cm²/sec)

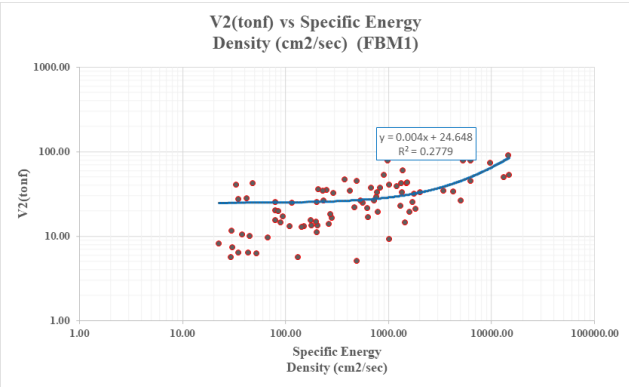


Figure A- 67:V2(tonf) in FBM1 vs SED (cm²/sec)

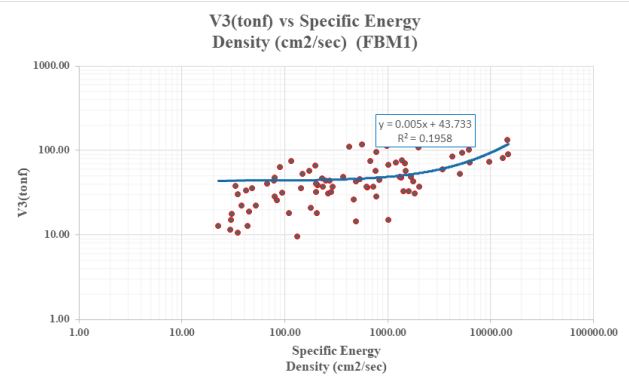


Figure A- 68:V3(tonf) in FBM1 vs SED (cm²/sec)

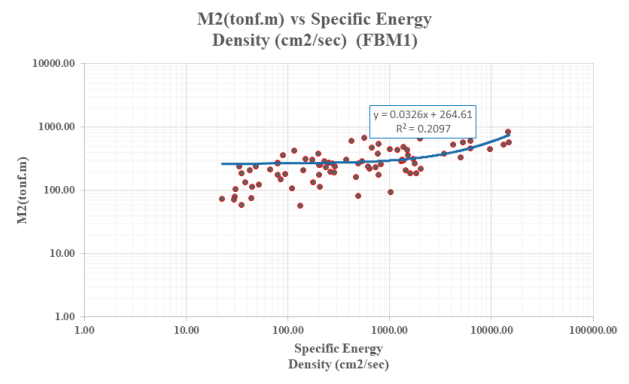


Figure A- 69:M2(tonf.m) in FBM1 vs SED (cm²/sec)

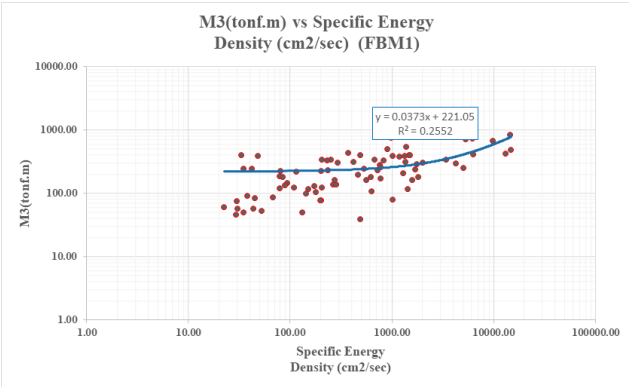


Figure A- 70:M3(tonf.m) in FBM1 vs SED (cm²/sec)

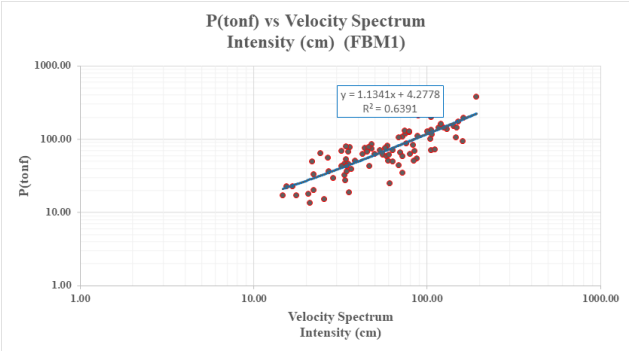


Figure A- 71:P(tonf) in FBM1 vs VSI (cm)

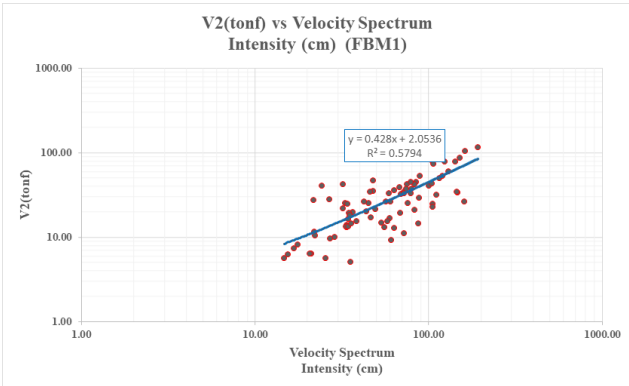


Figure A- 72:V2(tonf) in FBM1 vs VSI (cm)

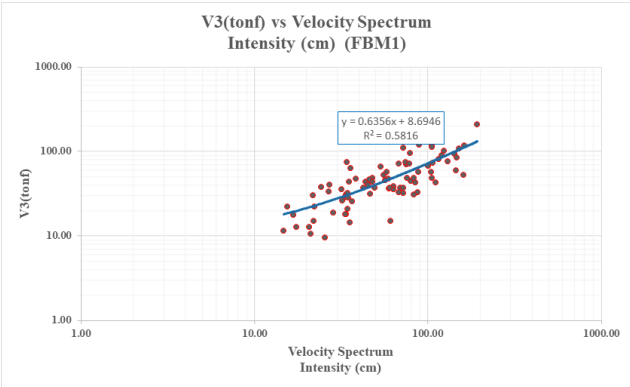


Figure A- 73:V3(tonf) in FBM1 vs VSI (cm)

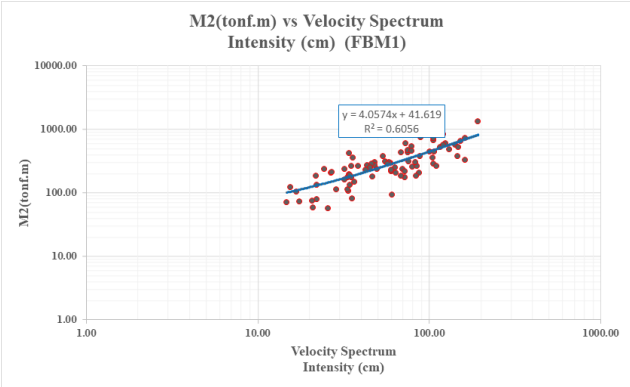


Figure A- 74:M2(tonf.m) in FBM1 vs VSI (cm)

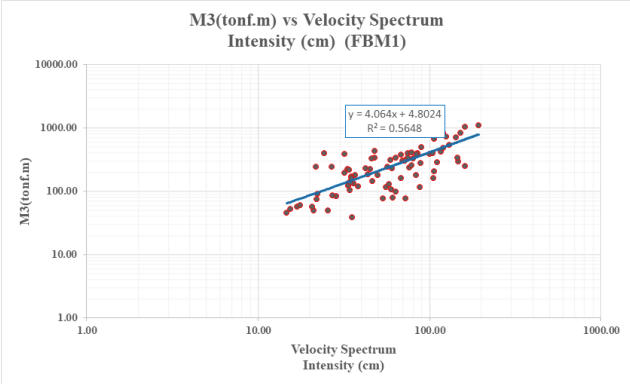


Figure A- 75:M3(tonf.m) in FBM1 vs VSI (cm)

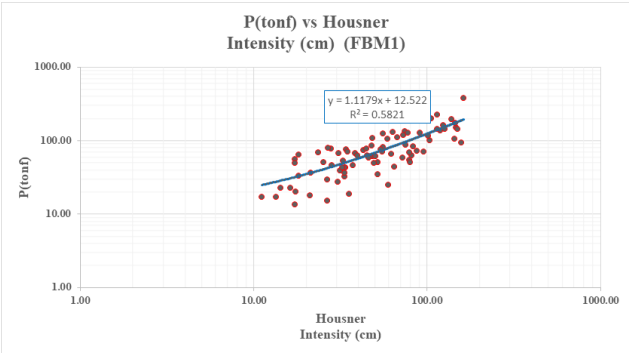


Figure A- 76:P(tonf) in FBM1 vs HI (cm)

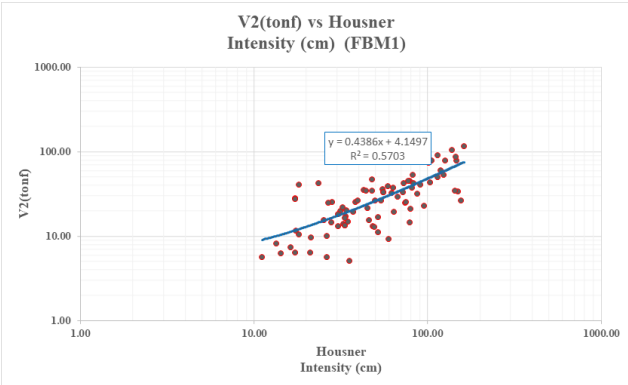


Figure A- 77:V2(tonf) in FBM1 vs HI (cm)

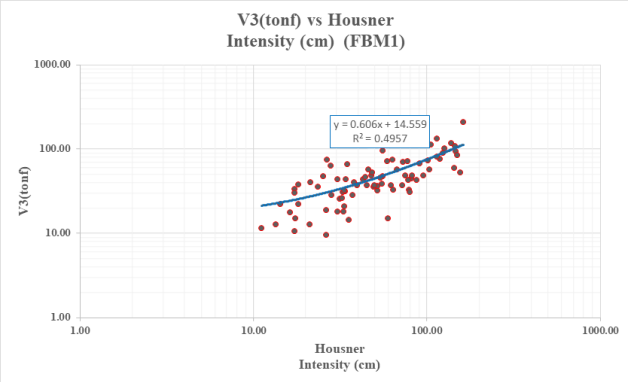


Figure A- 78:V3(tonf) in FBM1 vs HI (cm)

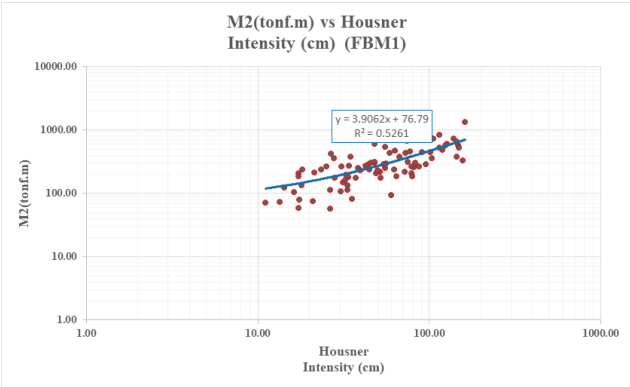


Figure A- 79:M2(tonf.m) in FBM1 vs HI (cm)

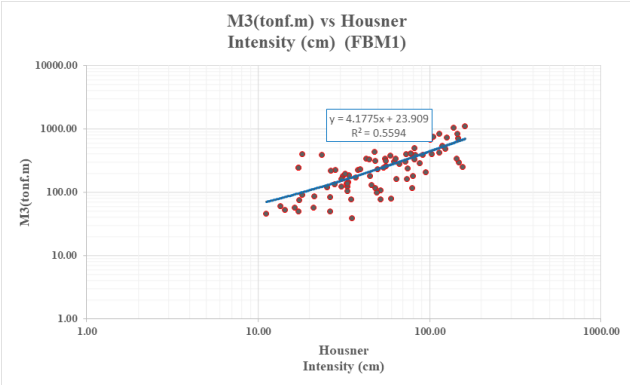


Figure A- 80:M3(tonf.m) in FBM1 vs HI (cm)

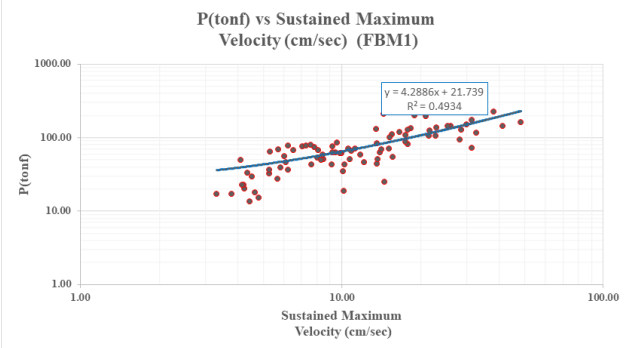


Figure A- 81:P(tonf) in FBM1 vs SMV (cm/sec)

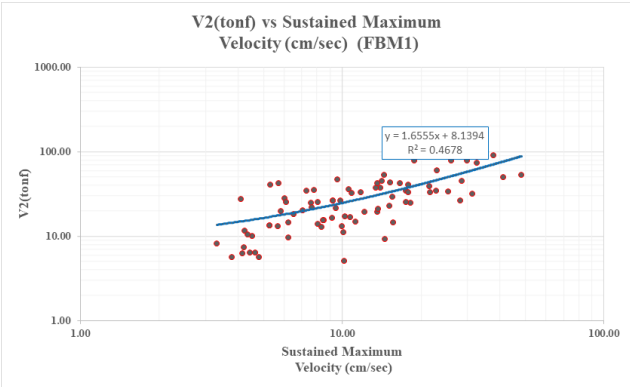


Figure A- 82:V2(tonf) in FBM1 vs SMV (cm/sec)

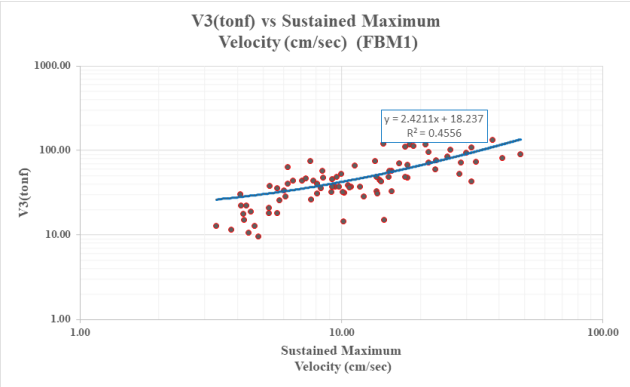


Figure A- 83:V3(tonf) in FBM1 vs SMV (cm/sec)

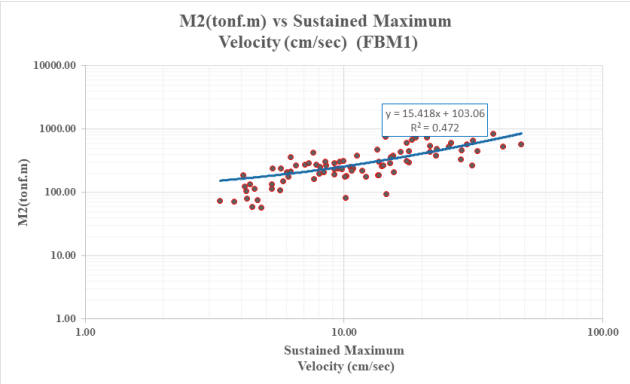


Figure A- 84:M2(tonf.m) in FBM1 vs SMV (cm/sec)

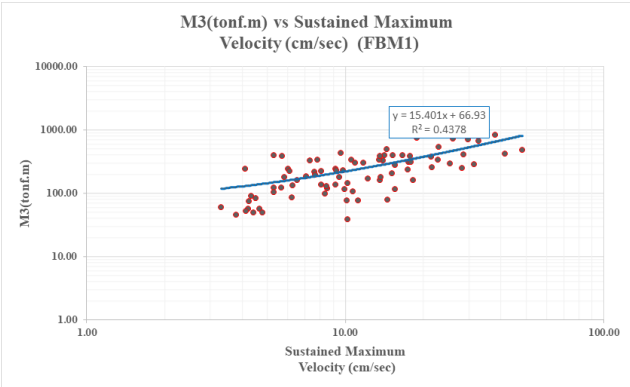


Figure A- 85:M3(tonf.m) in FBM1 vs SMV (cm/sec)

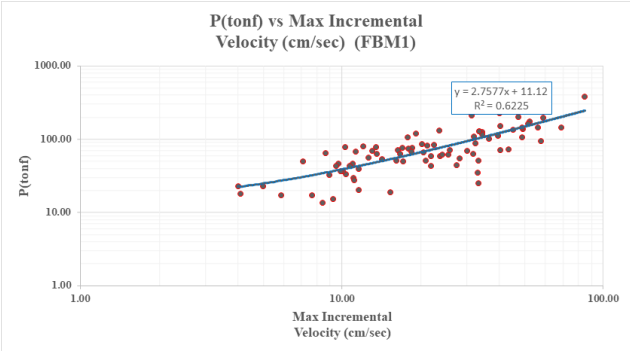


Figure A- 86:P(tonf) in FBM1 vs MIV (cm/sec)

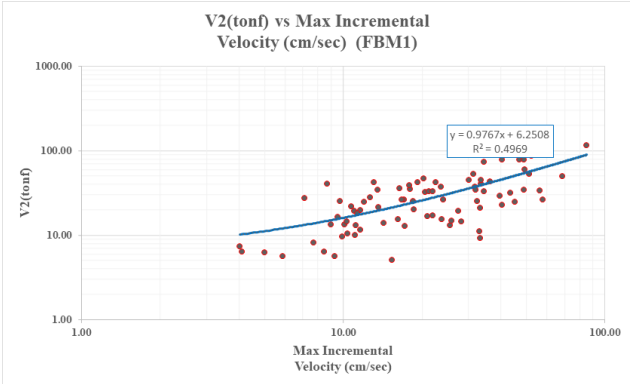


Figure A- 87:V2(tonf) in FBM1 vs MIV (cm/sec)

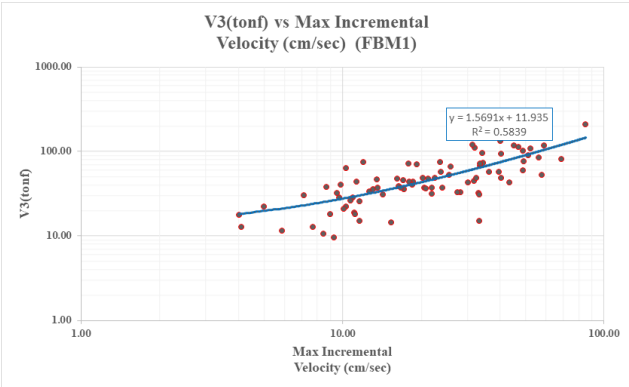


Figure A- 88:V3(tonf) in FBM1 vs MIV (cm/sec)

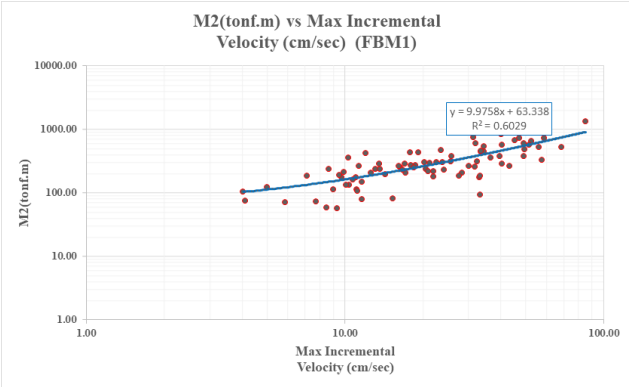


Figure A- 89:M2(tonf.m) in FBM1 vs MIV (cm/sec)

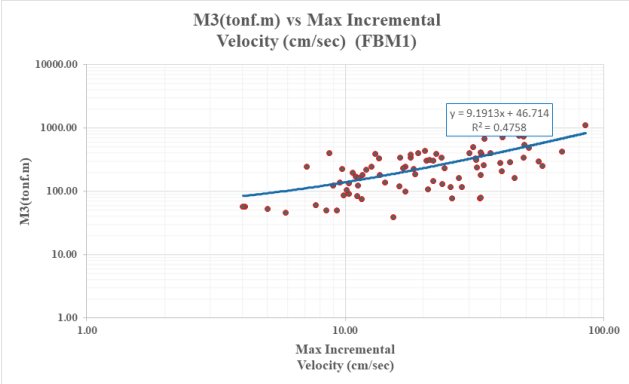


Figure A- 90:M3(tonf.m) in FBM1 vs MIV (cm/sec)

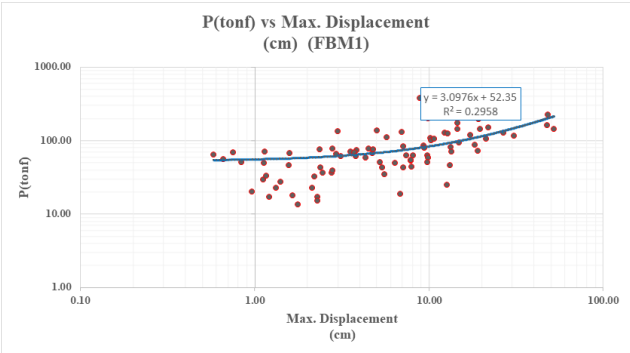


Figure A- 91:P(tonf) in FBM1 vs PGD (cm)

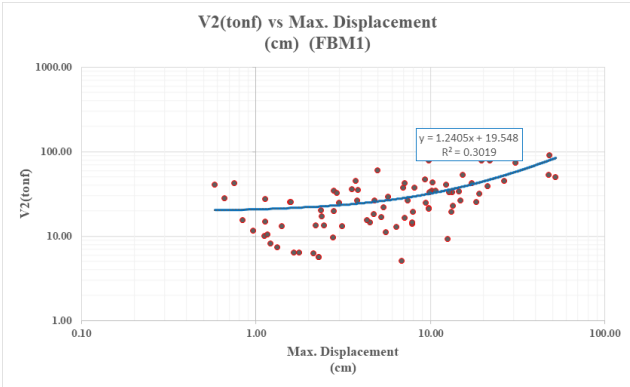


Figure A- 92:V2(tonf) in FBM1 vs PGD (cm)

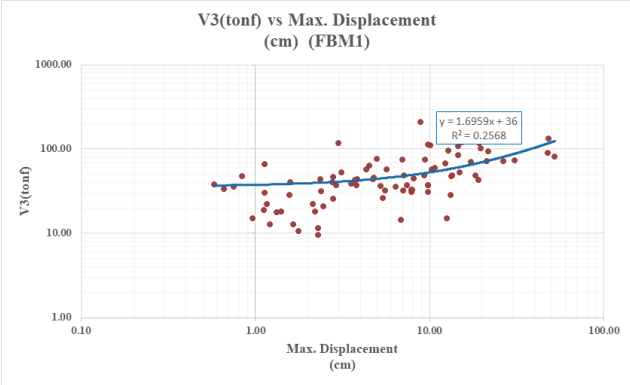


Figure A- 93:V3(tonf) in FBM1 vs PGD (cm)

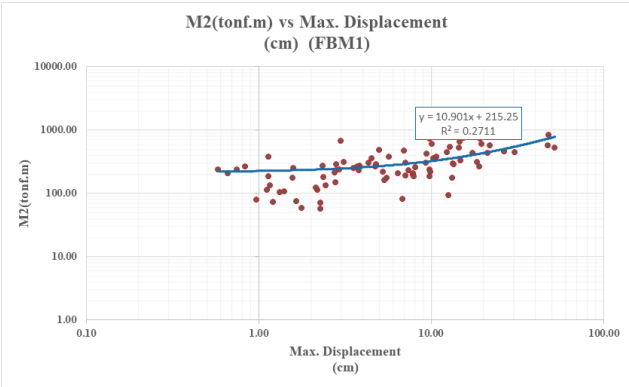


Figure A- 94:M2(tonf.m) in FBM1 vs PGD (cm)

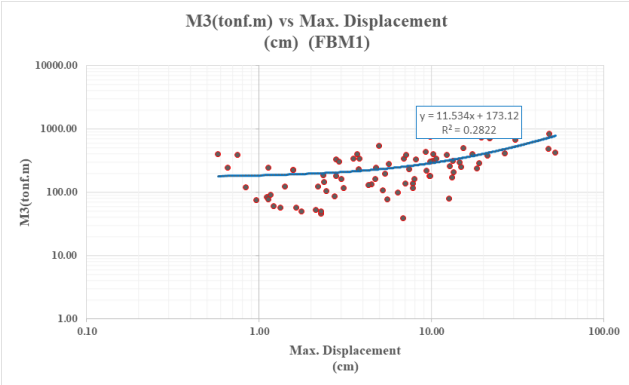


Figure A- 95:M3(tonf.m) in FBM1 vs PGD (cm)

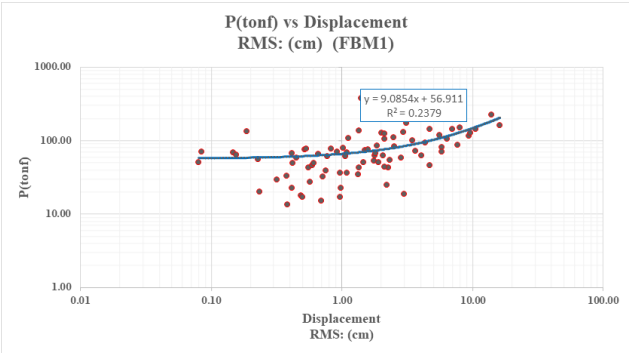


Figure A- 96:P(tonf) in FBM1 vs drms (cm)

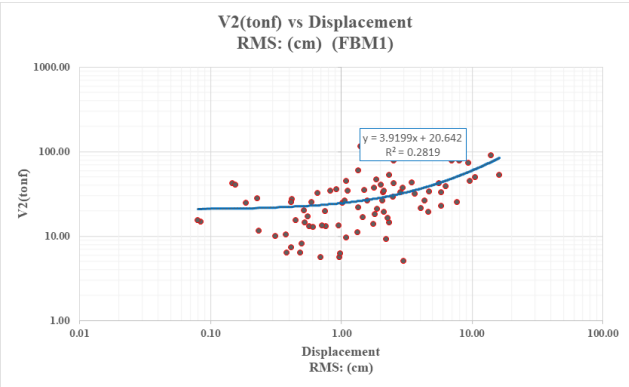


Figure A- 97:V2(tonf) in FBM1 vs drms (cm)

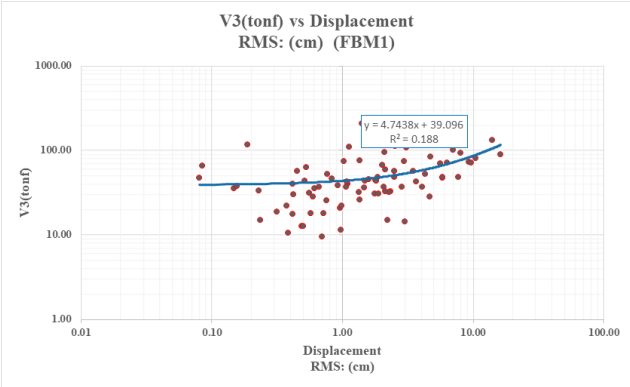


Figure A- 98:V3(tonf) in FBM1 vs drms (cm)

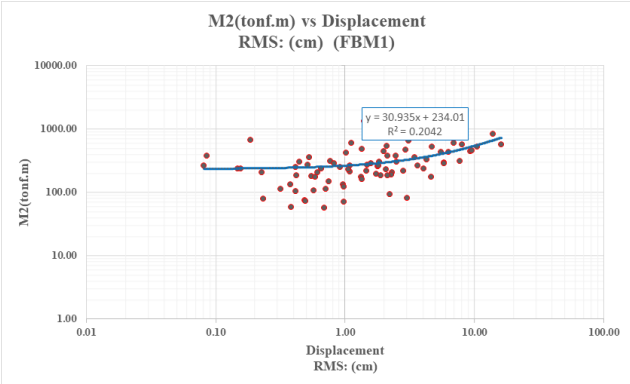


Figure A- 99:M2(tonf.m) in FBM1 vs drms (cm)

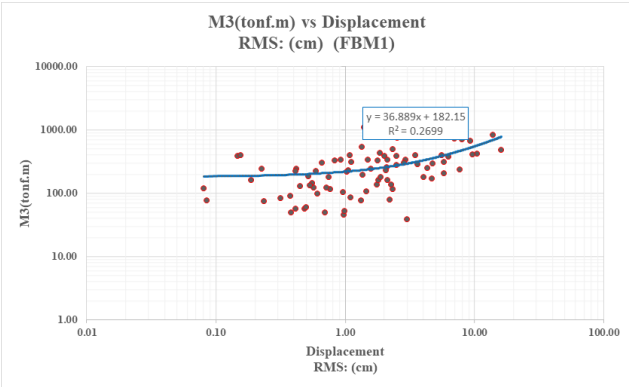


Figure A- 100:M3(tonf.m) in FBM1 vs drms (cm)

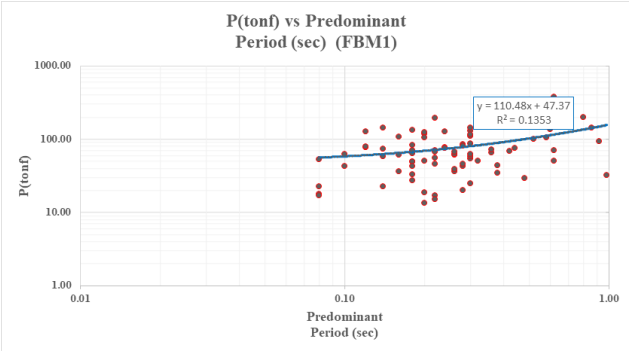


Figure A- 101:P(tonf) in FBM1 vs PP (sec)

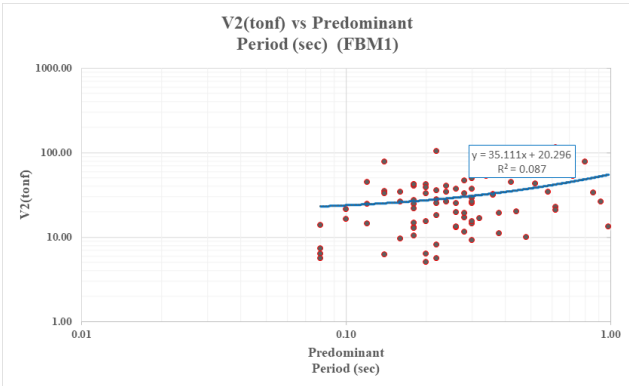


Figure A- 102:V2(tonf) in FBM1 vs PP (sec)

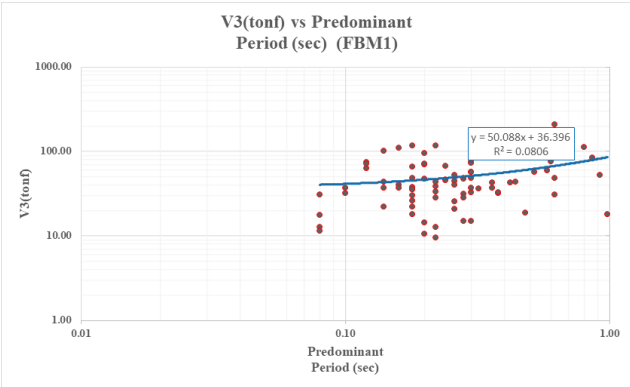


Figure A- 103:V3(tonf) in FBM1 vs PP (sec)

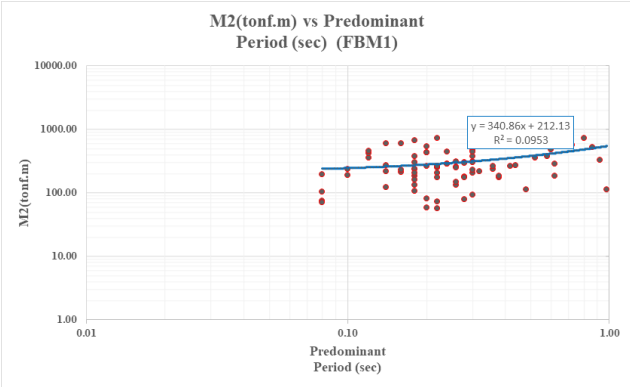


Figure A- 104:M2(tonf.m) in FBM1 vs PP (sec)

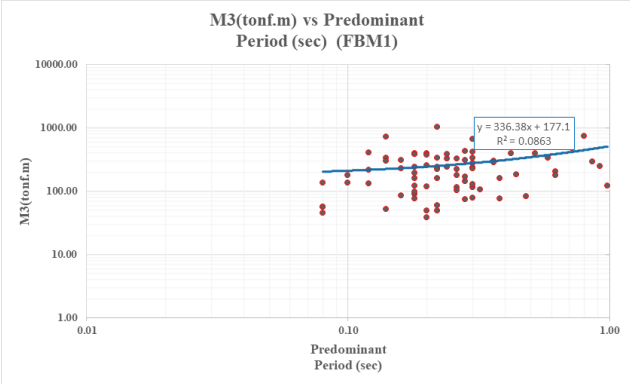


Figure A- 105:M3(tonf.m) in FBM1 vs PP (sec)

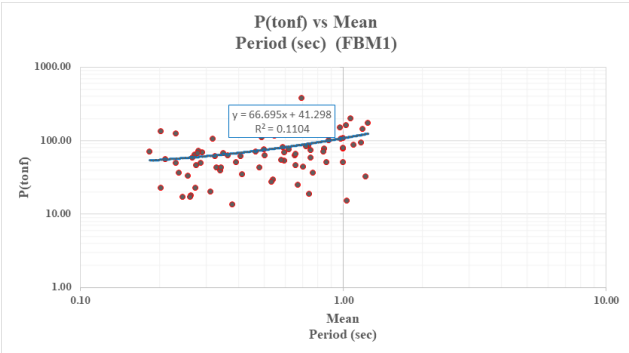


Figure A- 106:P(tonf) in FBM1 vs MP (sec)

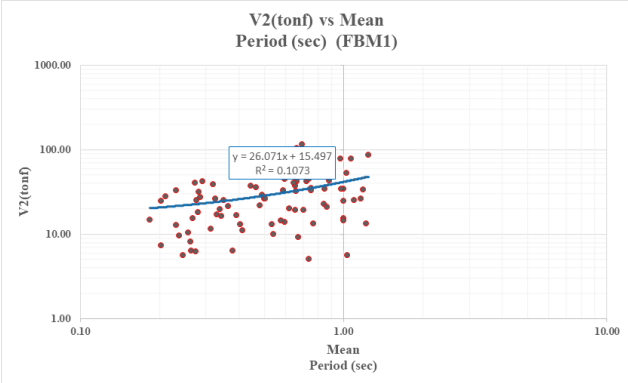


Figure A- 107:V2(tonf) in FBM1 vs MP (sec)

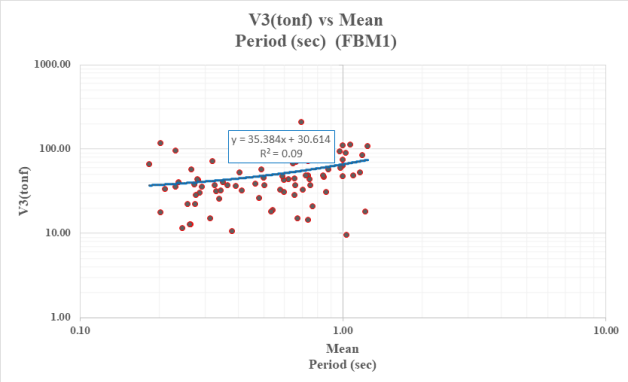


Figure A- 108:V3(tonf) in FBM1 vs MP (sec)

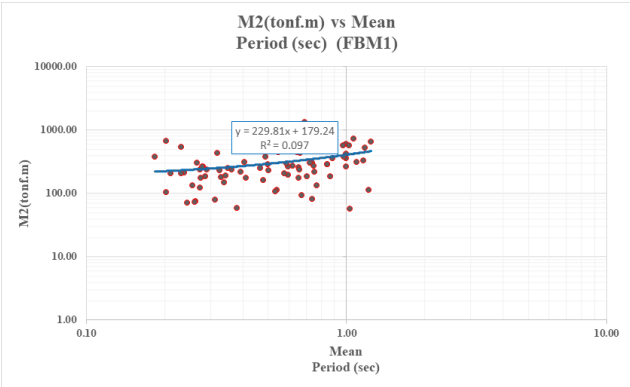


Figure A- 109:M2(tonf.m) in FBM1 vs MP (sec)

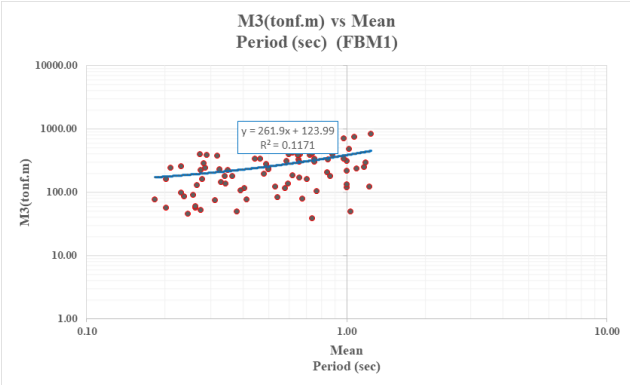


Figure A- 110:M3(tonf.m) in FBM1 vs MP (sec)

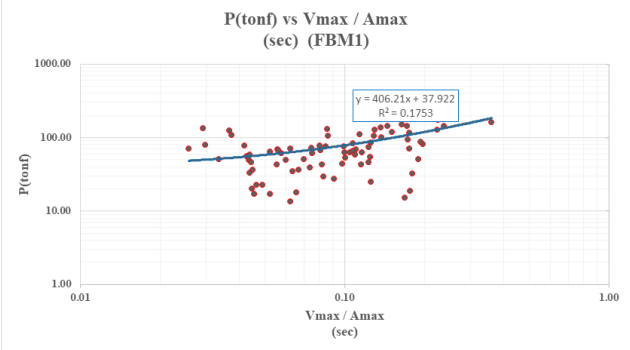


Figure A- 111:P(tonf) in FBM1 vs PGV/PGA(sec)

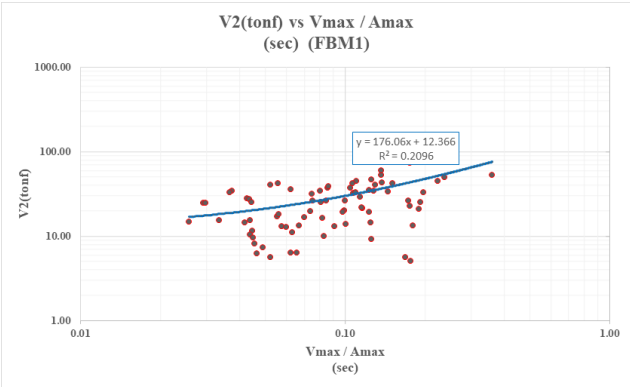


Figure A- 112:V2(tonf) in FBM1 vs PGV/PGA(sec)

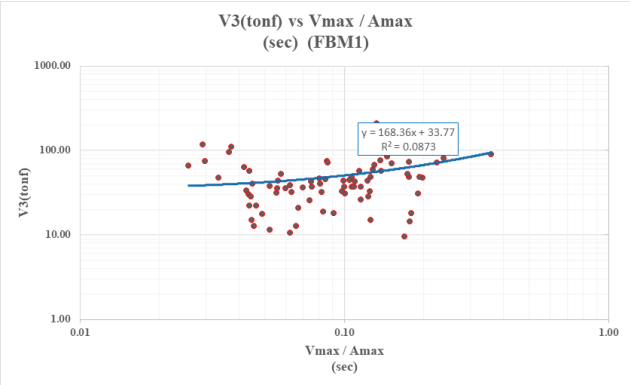


Figure A- 113:V3(tonf) in FBM1 vs PGV/PGA(sec)

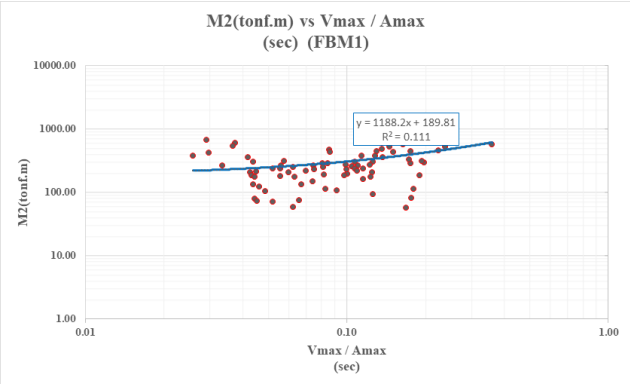


Figure A- 114:M2(tonf.m) in FBM1 vs PGV/PGA(sec)

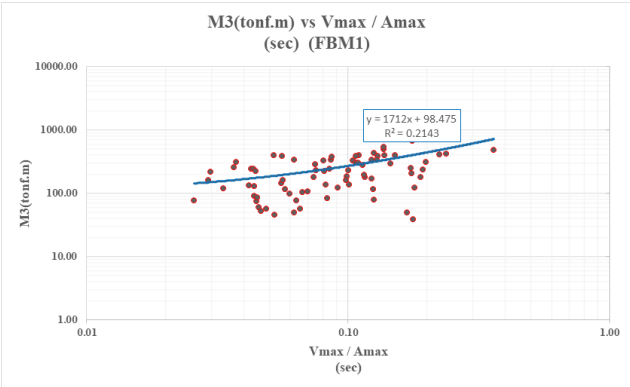


Figure A- 115:M3(tonf.m) in FBM1 vs PGV/PGA(sec)

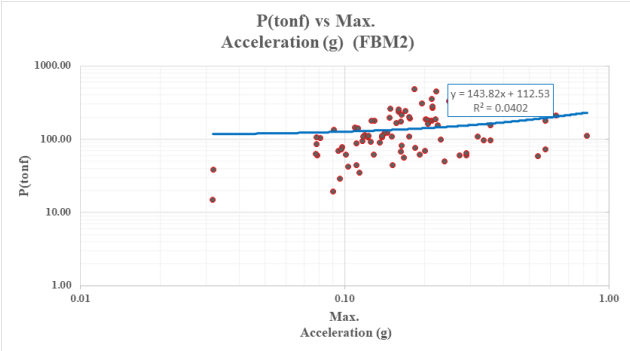


Figure A- 116:P(tonf) in FBM2 vs PGA(g)

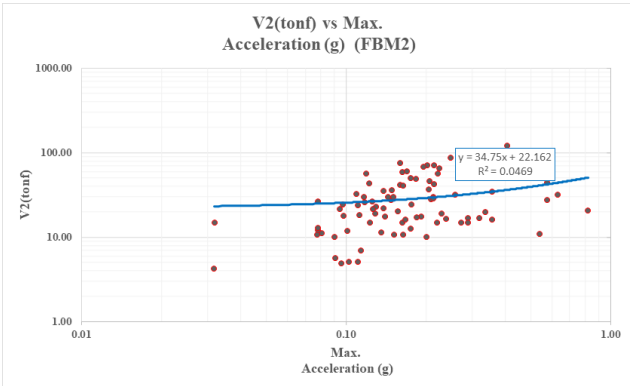


Figure A- 117:V2(tonf) in FBM2 vs PGA(g)

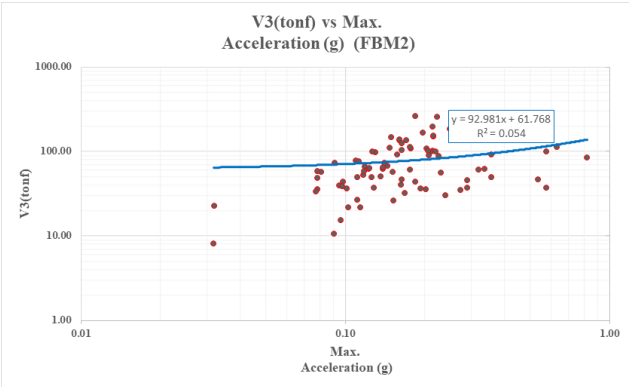


Figure A- 118:V3(tonf) in FBM2 vs PGA(g)

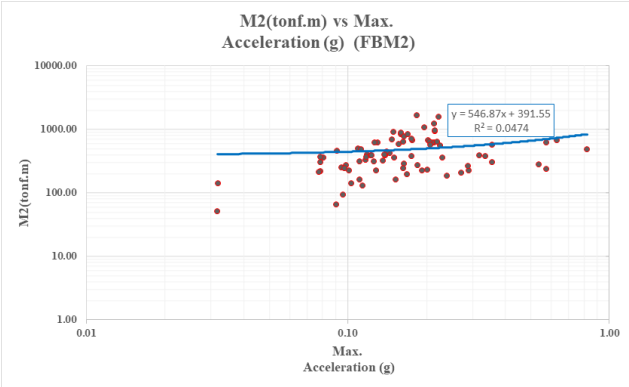


Figure A- 119:M2(tonf.m) in FBM2 vs PGA(g)

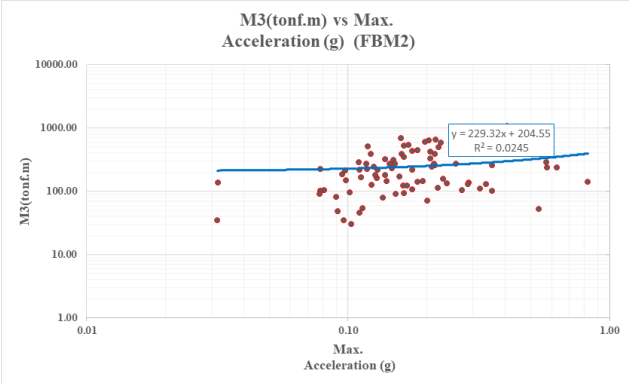


Figure A- 120:M3(tonf.m) in FBM2 vs PGA(g)

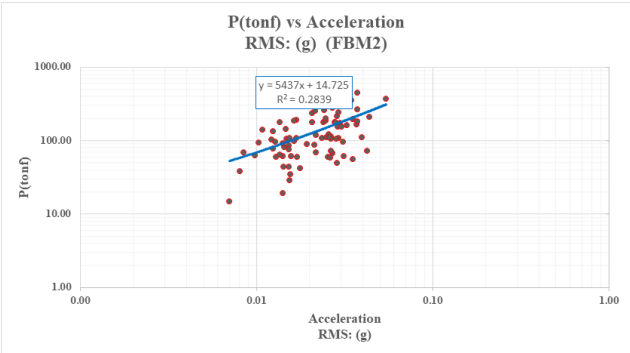


Figure A- 121:P(tonf) in FBM2 vs arms(g)

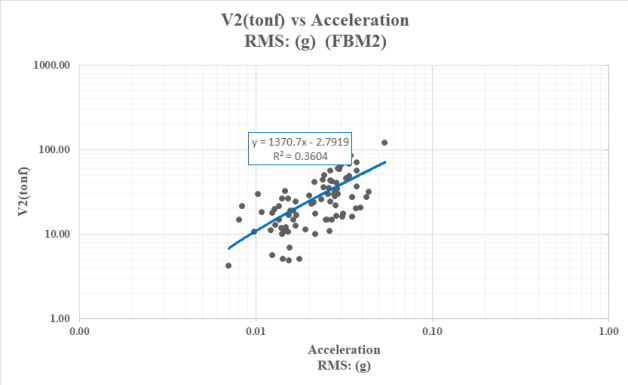


Figure A- 122:V2(tonf) in FBM2 vs arms(g)

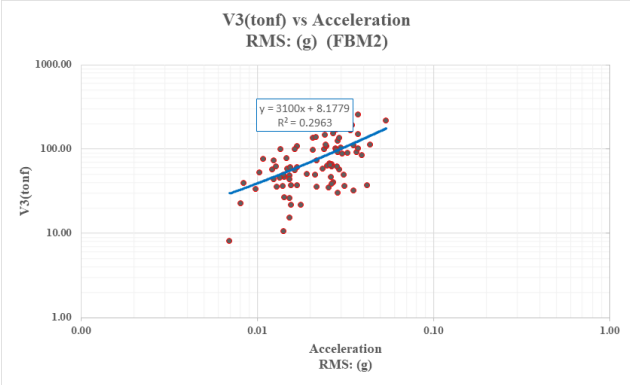


Figure A- 123:V3(tonf) in FBM2 vs arms(g)

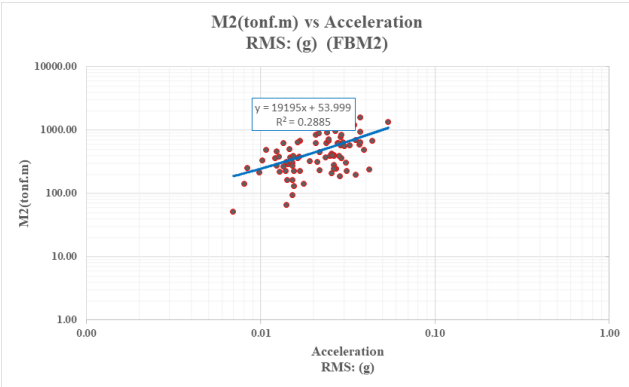


Figure A- 124:M2(tonf.m) in FBM2 vs arms(g)

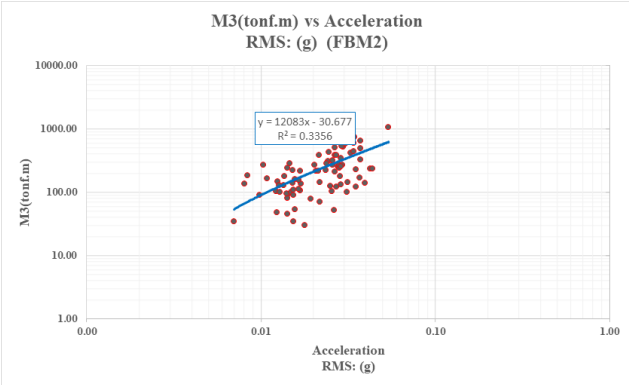


Figure A- 125:M3(tonf.m) in FBM2 vs arms(g)

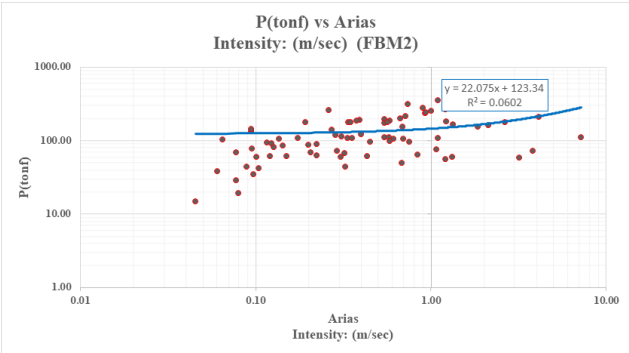


Figure A- 126:P(tonf) in FBM2 vs AI(m/sec)

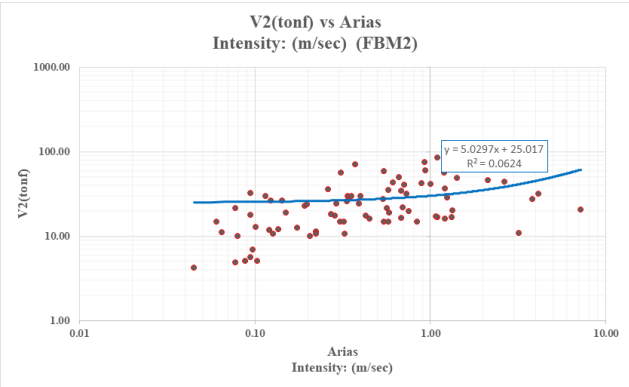


Figure A- 127:V2(tonf) in FBM2 vs AI(m/sec)

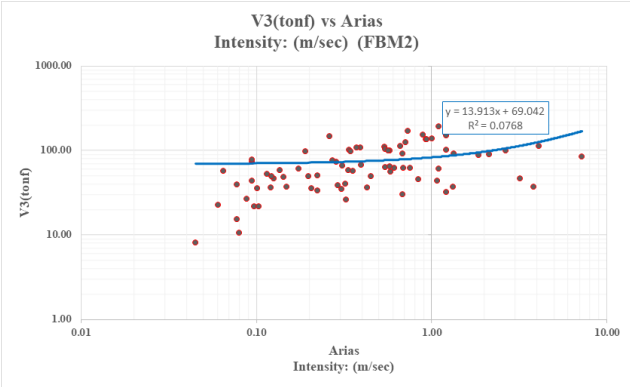


Figure A- 128:V3(tonf) in FBM2 vs AI(m/sec)

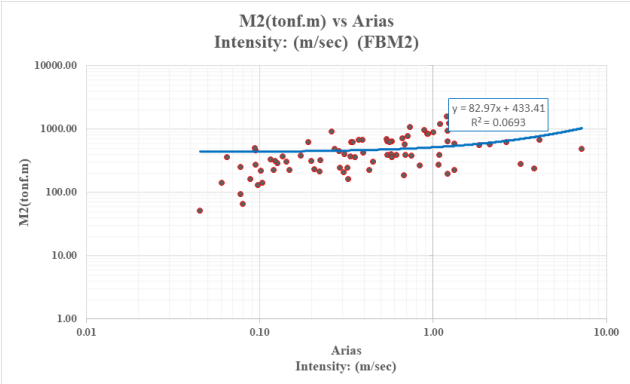


Figure A- 129:M2(tonf.m) in FBM2 vs AI(m/sec)

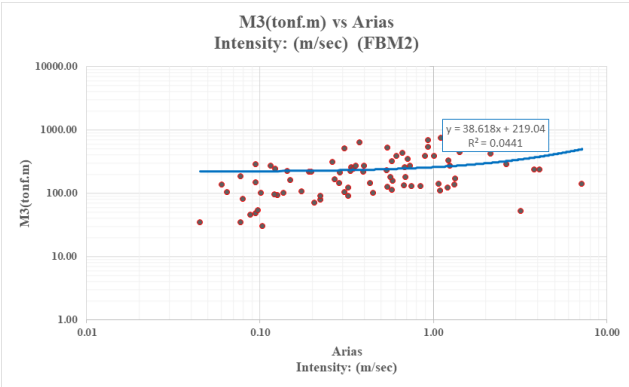


Figure A- 130:M3(tonf.m) in FBM2 vs AI(m/sec)

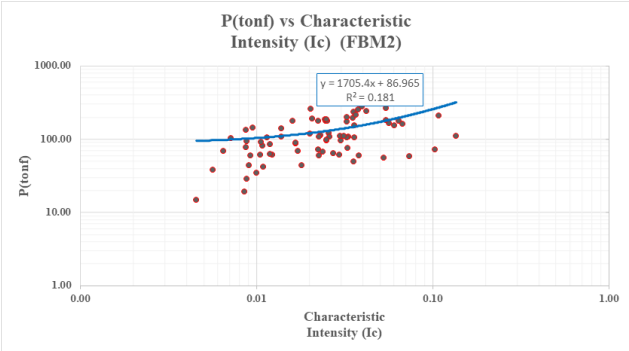


Figure A- 131:P(tonf) in FBM2 vs Ic

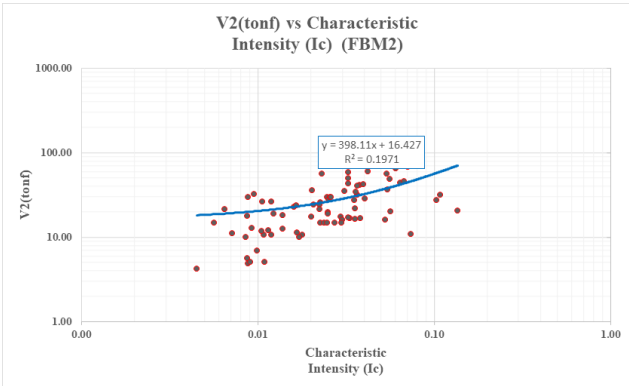


Figure A- 132:V2(tonf) in FBM2 vs Ic

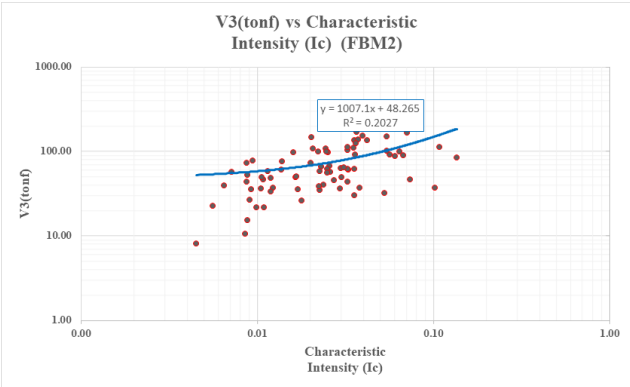


Figure A- 133:V3(tonf) in FBM2 vs Ic

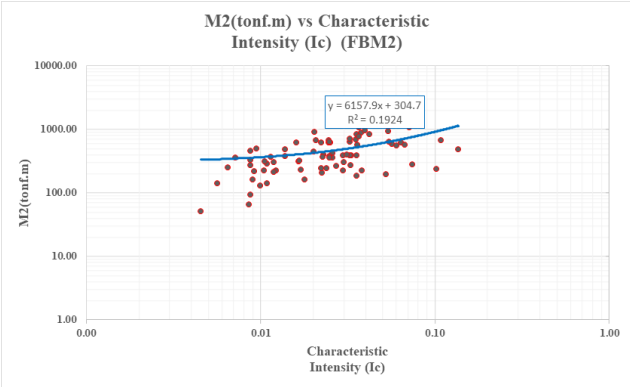


Figure A- 134:M2(tonf.m) in FBM2 vs Ic

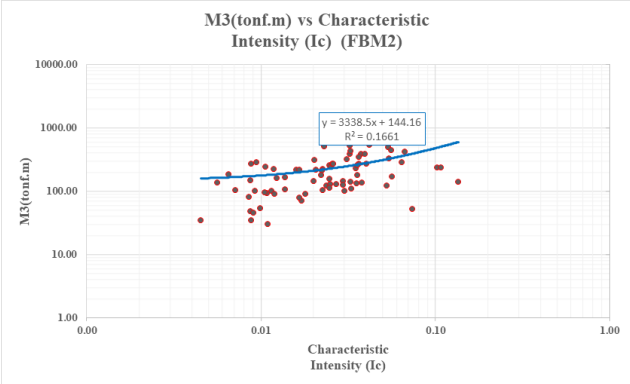


Figure A- 135:M3(tonf.m) in FBM2 vs Ic

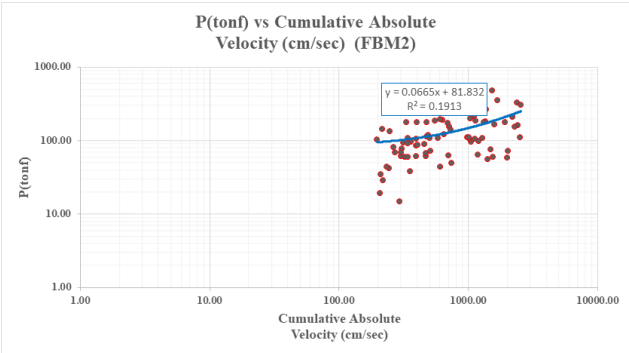


Figure A- 136:P(tonf) in FBM2 vs CAV (cm/sec)

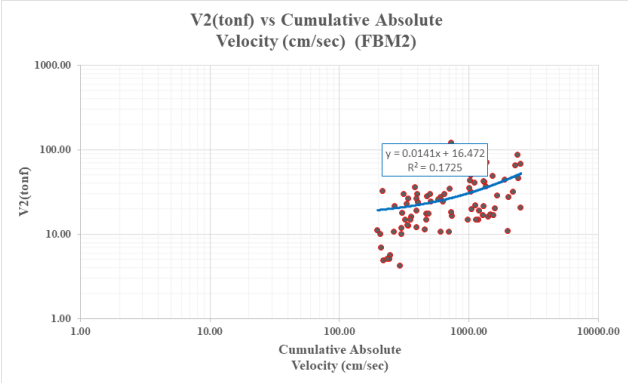


Figure A- 137:V2(tonf) in FBM2 vs CAV (cm/sec)

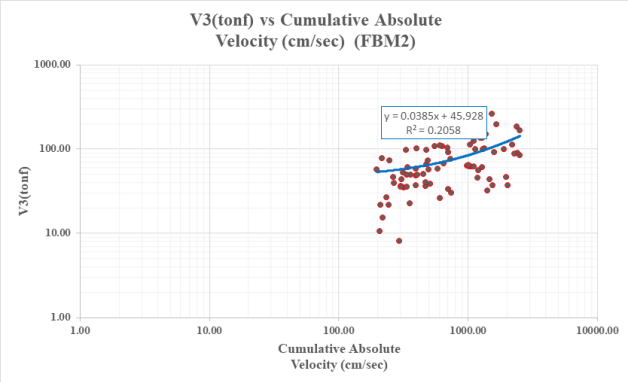


Figure A- 138:V3(tonf) in FBM2 vs CAV (cm/sec)

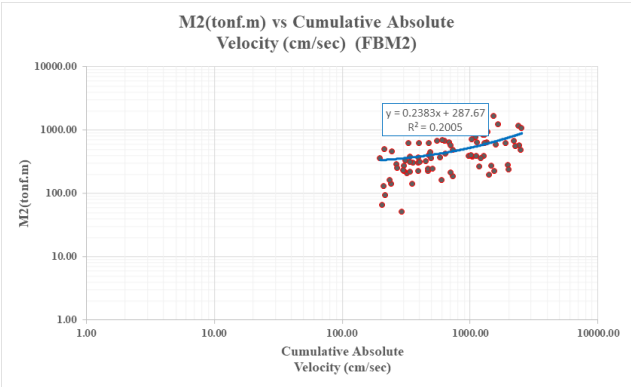


Figure A- 139:M2(tonf.m) in FBM2 vs CAV (cm/sec)

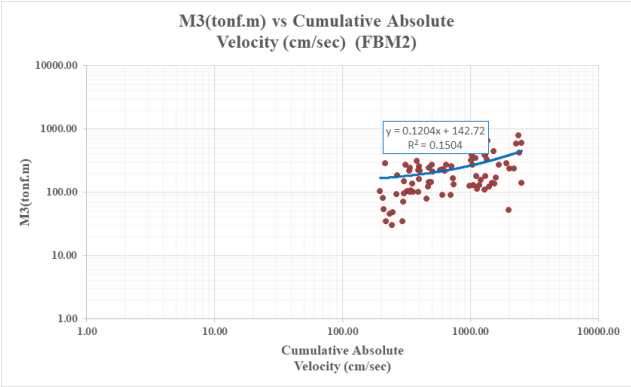


Figure A- 140:M3(tonf.m) in FBM2 vs CAV (cm/sec)

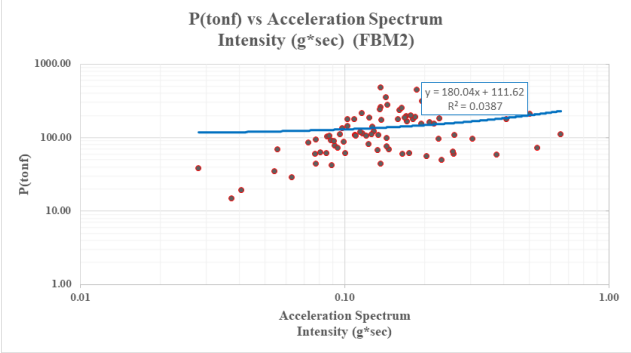


*Figure A- 141:P(tonf) in FBM2 vs ASI (g*sec)*

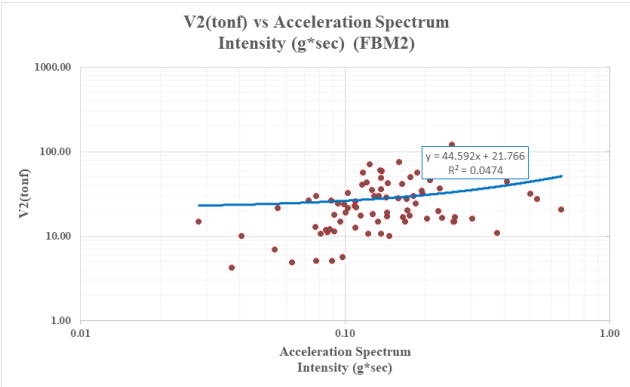


*Figure A- 142:V2(tonf) in FBM2 vs ASI (g*sec)*

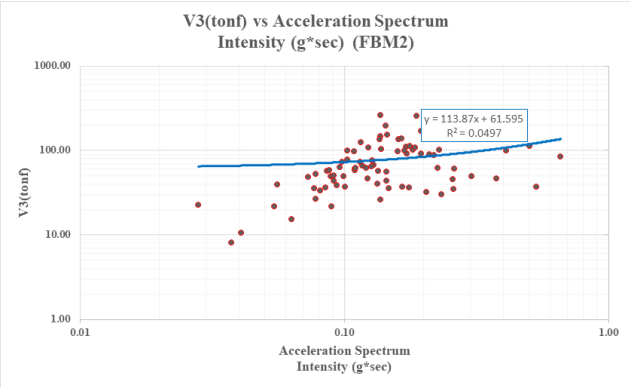


*Figure A- 143:V3(tonf) in FBM2 vs ASI (g*sec)*

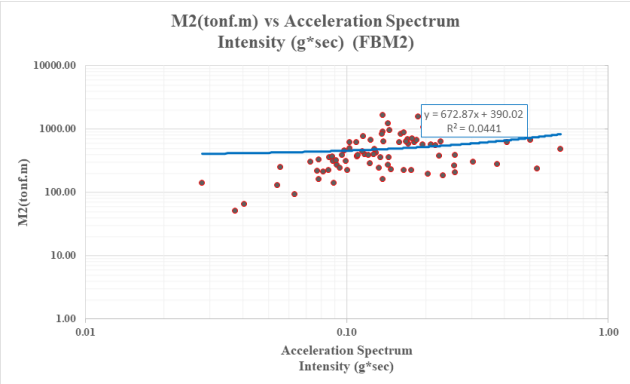


*Figure A- 144:M2(tonf.m) in FBM2 vs ASI (g*sec)*

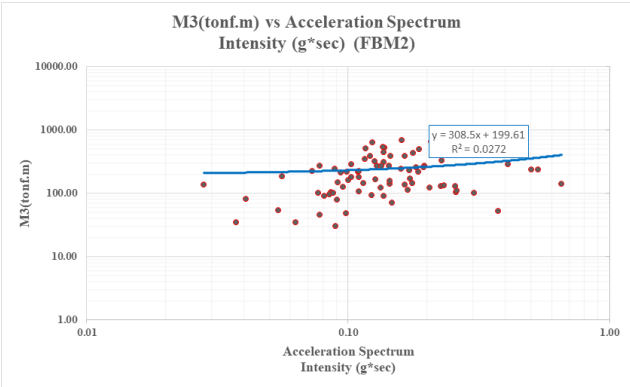


*Figure A- 145:M3(tonf.m) in FBM2 vs ASI (g*sec)*

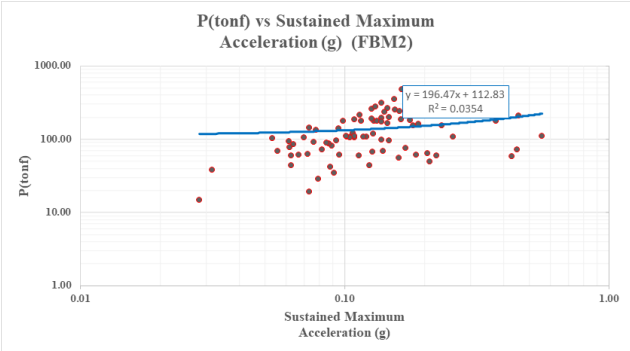


Figure A- 146:P(tonf) in FBM2 vs SMA (g)

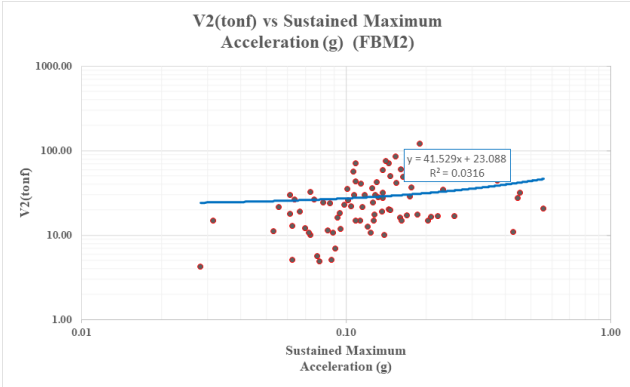


Figure A- 147:V2(tonf) in FBM2 vs SMA (g)

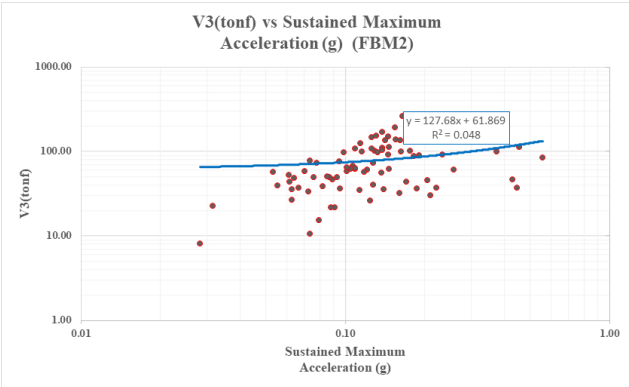


Figure A- 148:V3(tonf) in FBM2 vs SMA (g)

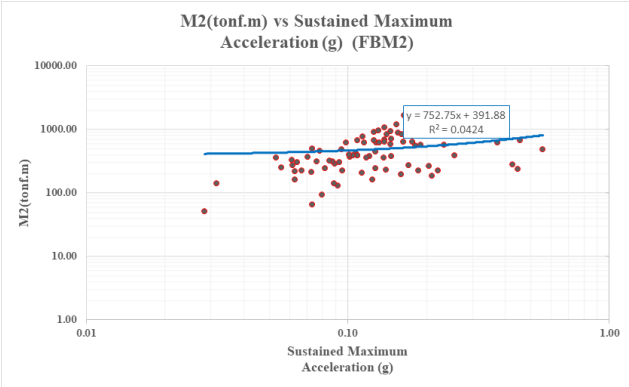


Figure A- 149:M2(tonf.m) in FBM2 vs SMA (g)

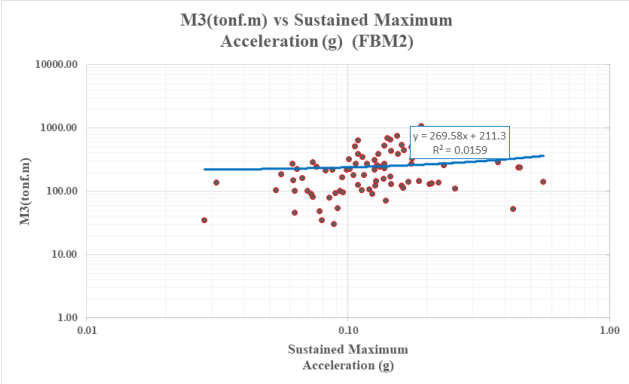


Figure A- 150:M3(tonf.m) in FBM2 vs SMA (g)

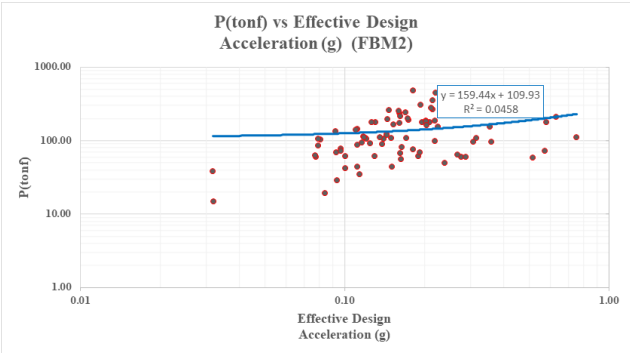


Figure A- 151:P(tonf) in FBM2 vs EDA (g)

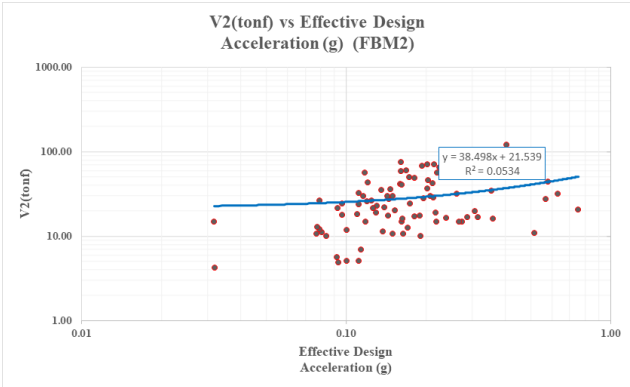


Figure A- 152:V2(tonf) in FBM2 vs EDA (g)

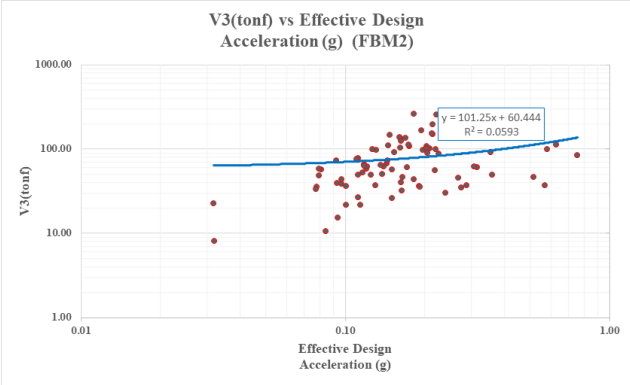


Figure A- 153:V3(tonf) in FBM2 vs EDA (g)

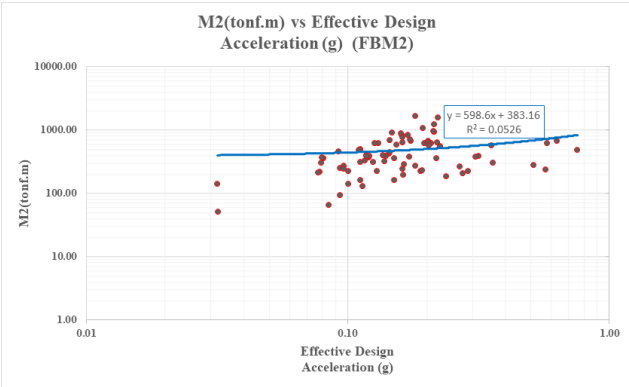


Figure A- 154:M2(tonf.m) in FBM2 vs EDA (g)

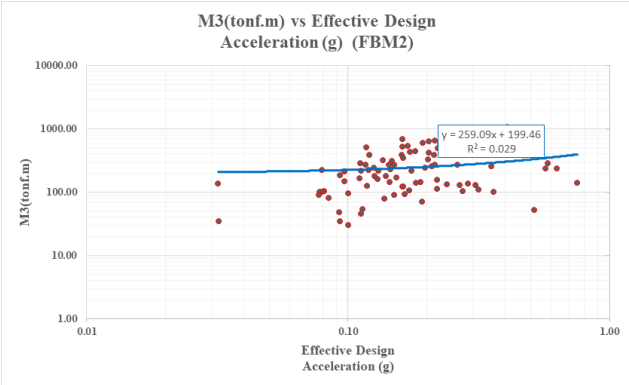


Figure A- 155:M3(tonf.m) in FBM2 vs EDA (g)

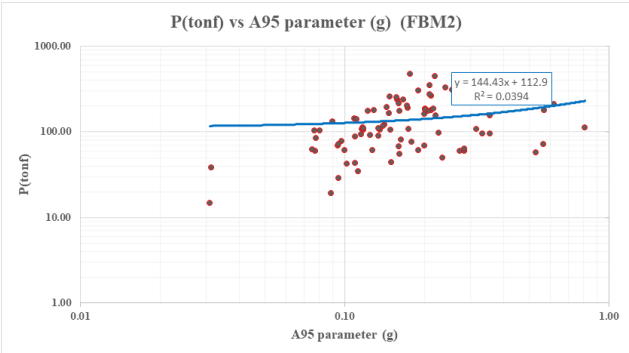


Figure A- 156:P(tonf) in FBM2 vs a95 (g)

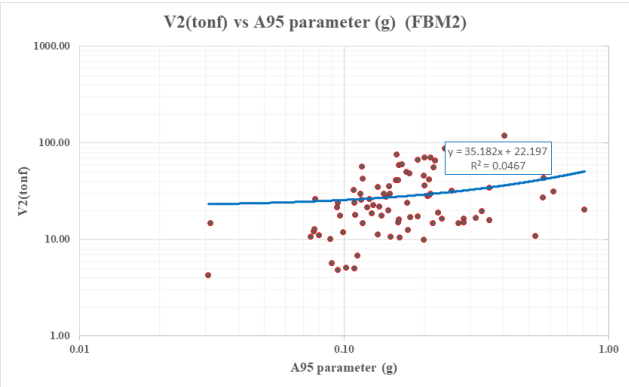


Figure A- 157:V2(tonf) in FBM2 vs a95 (g)

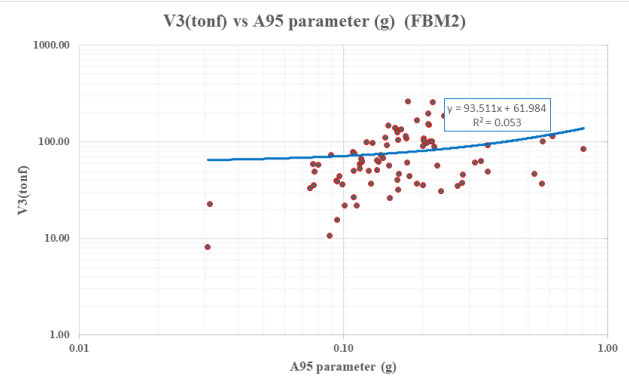


Figure A- 158:V3(tonf) in FBM2 vs a95 (g)

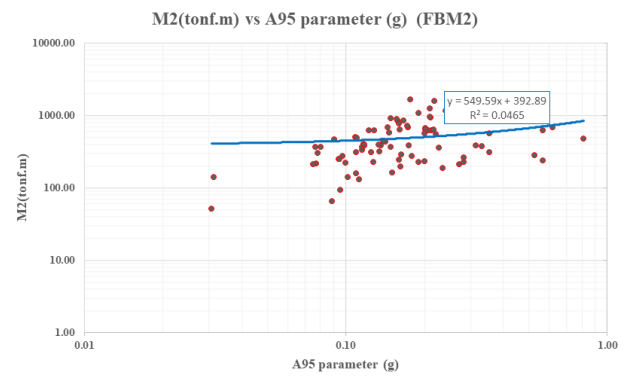


Figure A- 159:M2(tonf.m) in FBM2 vs a95 (g)

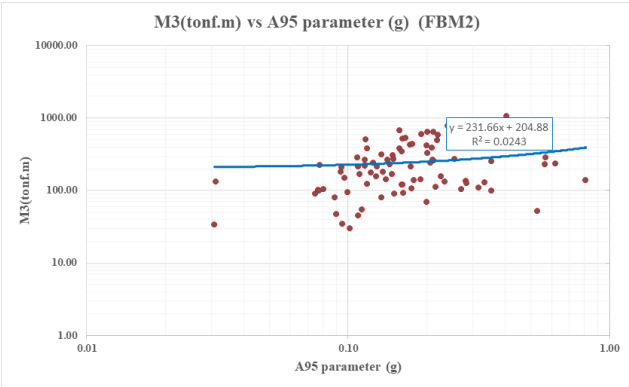


Figure A- 160:M3(tonf.m) in FBM2 vs a95 (g)

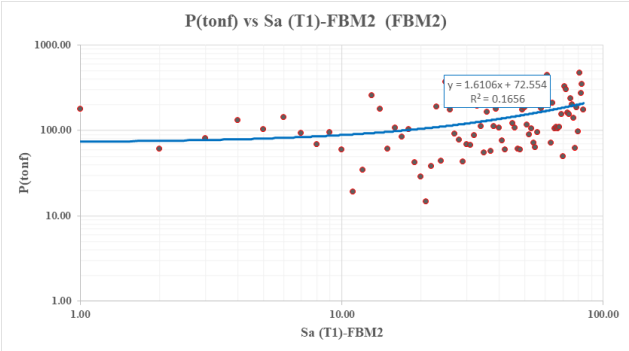


Figure A- 161:P(tonf) in FBM2 vs Sa (T1) (g)

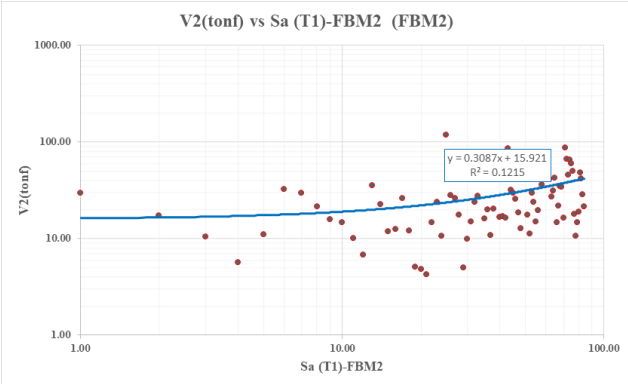


Figure A- 162:V2(tonf) in FBM2 vs Sa (T1) (g)

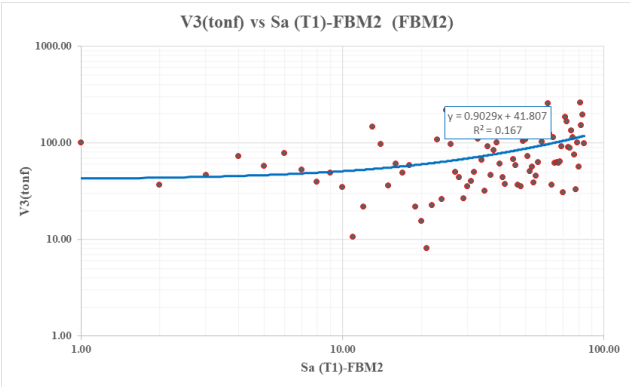


Figure A- 163:V3(tonf) in FBM2 vs Sa (T1) (g)

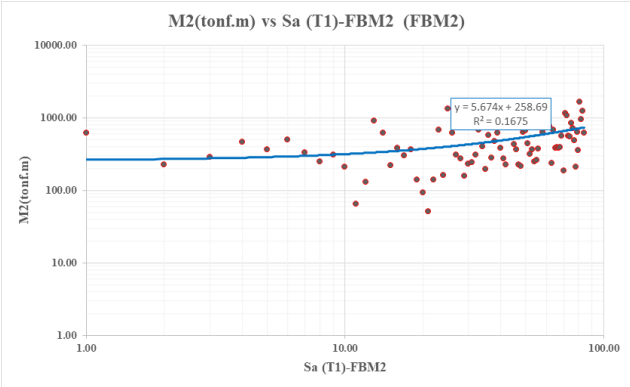


Figure A- 164:M2(tonf.m) in FBM2 vs Sa (T1) (g)

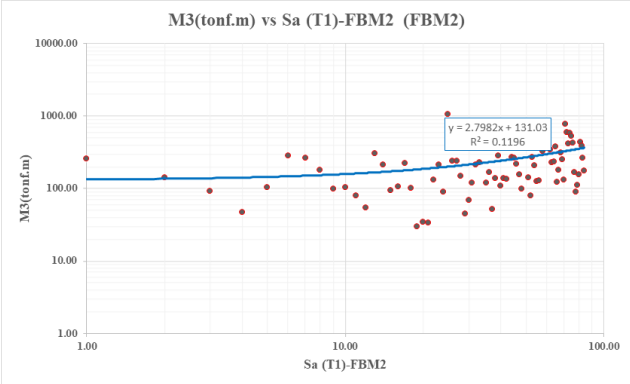


Figure A- 165:M3(tonf.m) in FBM2 vs Sa (T1) (g)

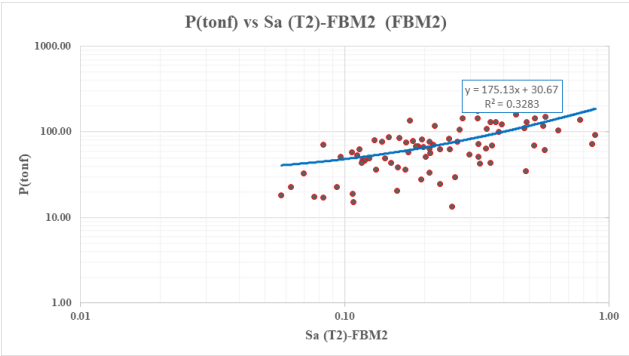


Figure A- 166:P(tonf) in FBM2 vs Sa (T2) (g)

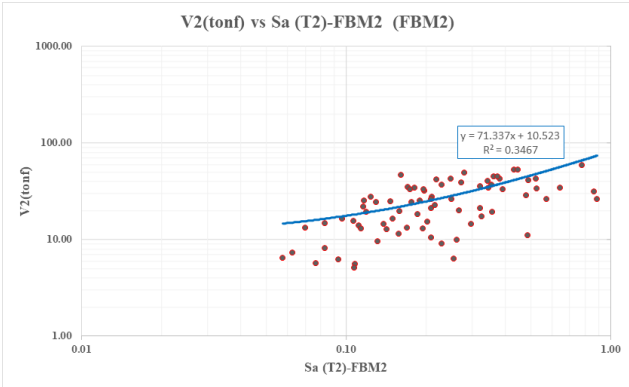


Figure A- 167:V2(tonf) in FBM2 vs Sa (T2) (g)

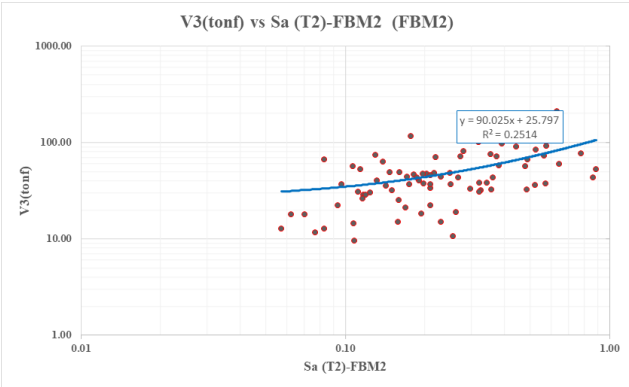


Figure A- 168:V3(tonf) in FBM2 vs Sa (T2) (g)

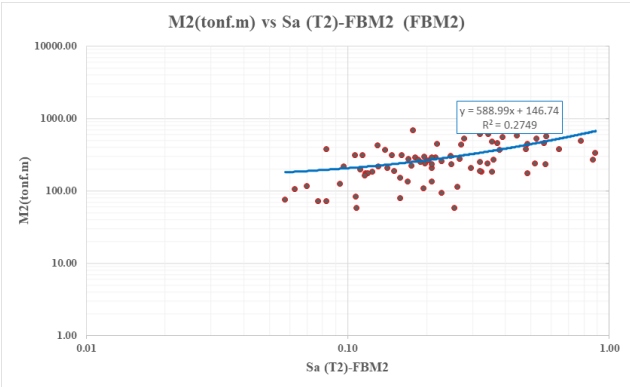


Figure A- 169:M2(tonf.m) in FBM2 vs Sa (T2) (g)

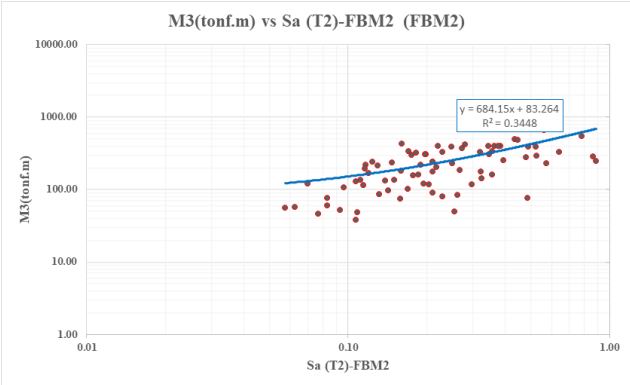


Figure A- 170:M3(tonf.m) in FBM2 vs Sa (T2) (g)

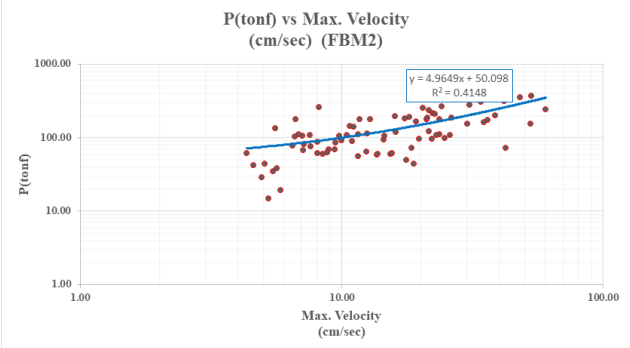


Figure A- 171:P(tonf) in FBM2 vs PGV (cm/sec)

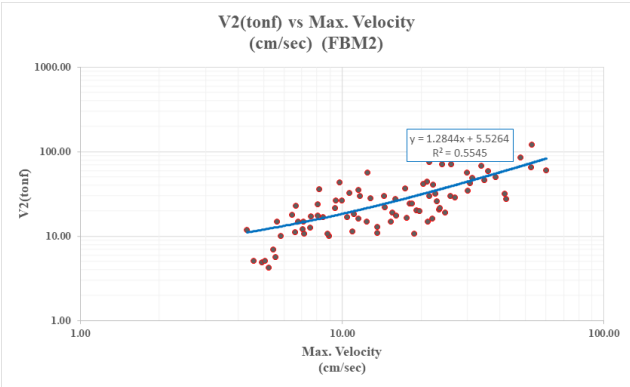


Figure A- 172:V2(tonf) in FBM2 vs PGV (cm/sec)

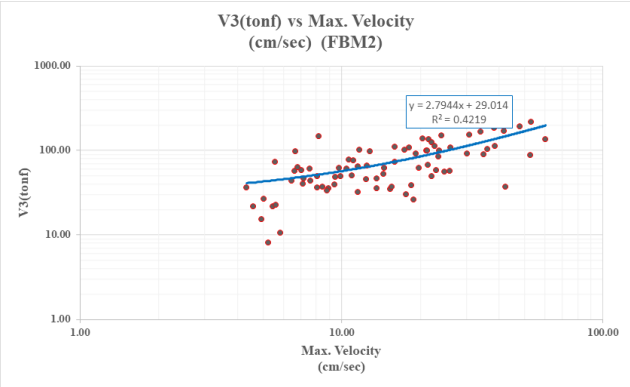


Figure A- 173:V3(tonf) in FBM2 vs PGV (cm/sec)

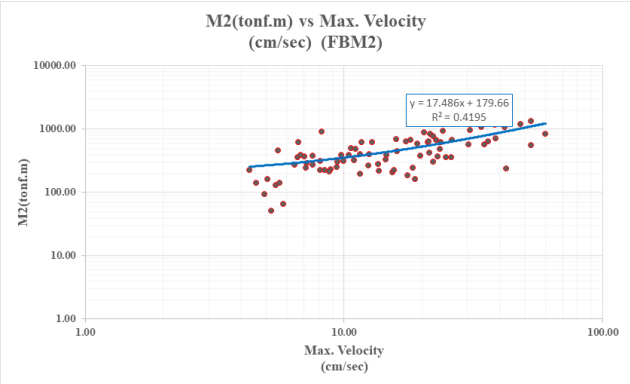


Figure A- 174:M2(tonf.m) in FBM2 vs PGV (cm/sec)

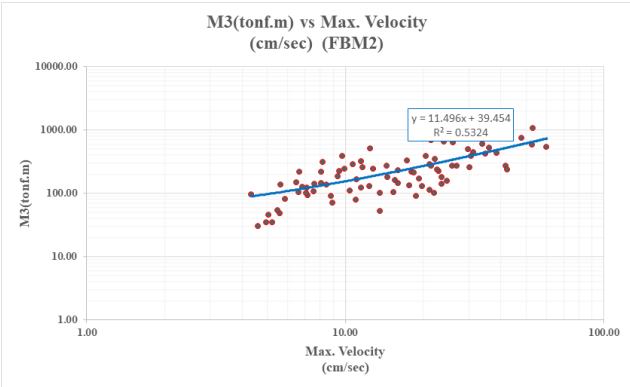


Figure A- 175:M3(tonf.m) in FBM2 vs PGV (cm/sec)

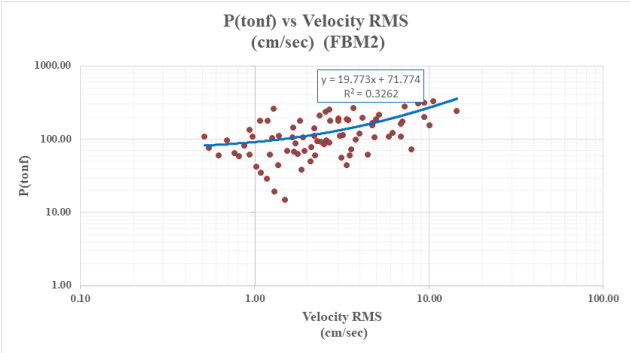


Figure A- 176:P(tonf) in FBM2 vs vrms (cm/sec)

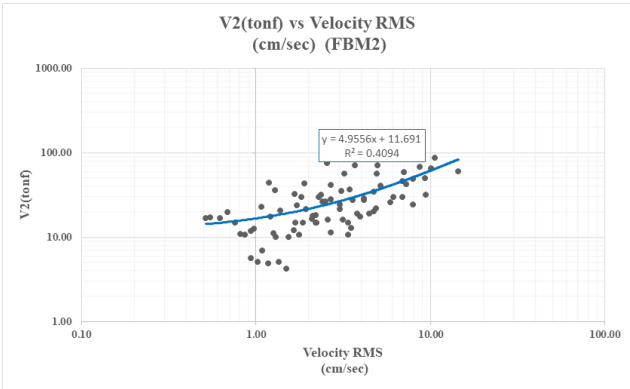


Figure A- 177:V2(tonf) in FBM2 vs vrms (cm/sec)

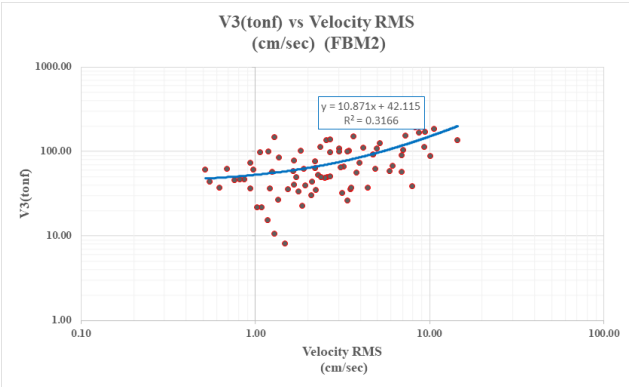


Figure A- 178:V3(tonf) in FBM2 vs vrms (cm/sec)

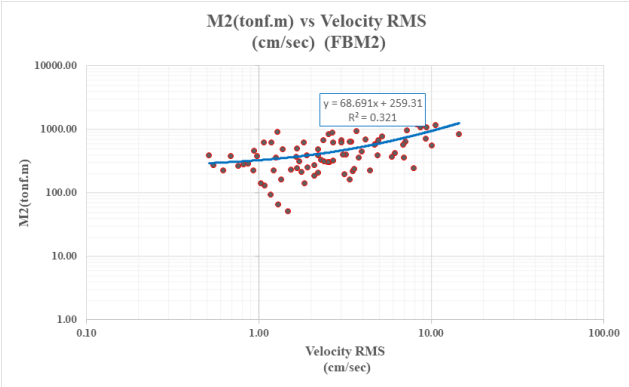


Figure A- 179:M2(tonf.m) in FBM2 vs vrms (cm/sec)

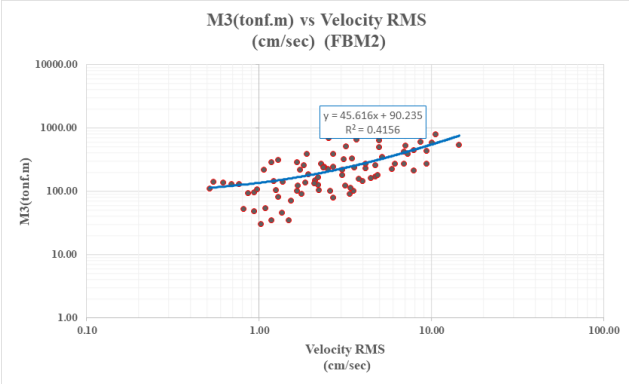


Figure A- 180:M3(tonf.m) in FBM2 vs vrms (cm/sec)

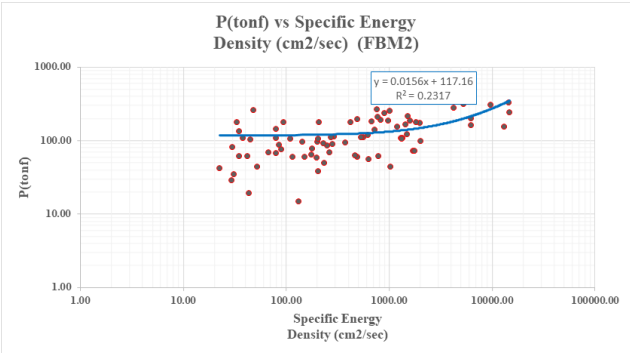


Figure A- 181:P(tonf) in FBM2 vs SED (cm²/sec)

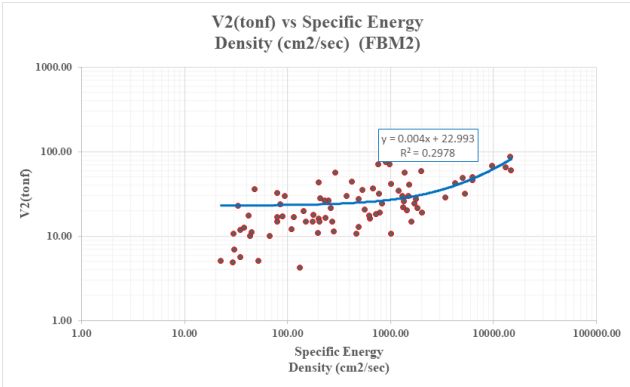


Figure A- 182:V2(tonf) in FBM2 vs SED (cm²/sec)

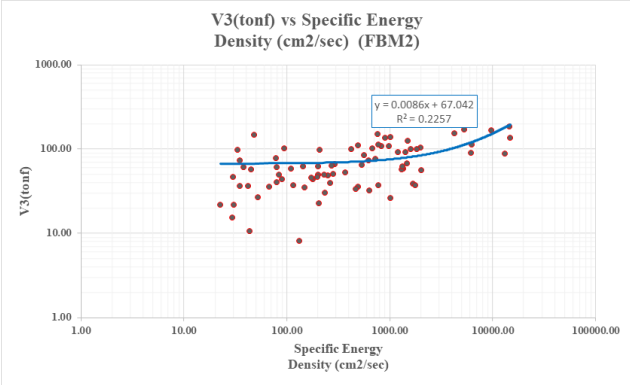


Figure A- 183:V3(tonf) in FBM2 vs SED (cm²/sec)

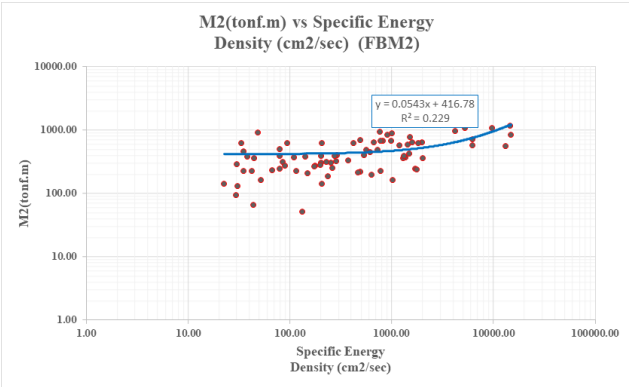


Figure A- 184:M2(tonf.m) in FBM2 vs SED (cm²/sec)

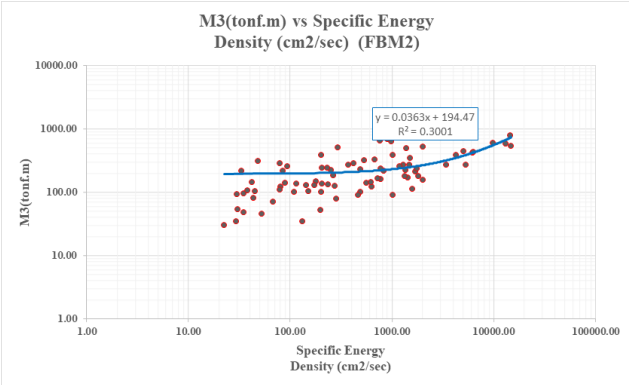


Figure A- 185:M3(tonf.m) in FBM2 vs SED (cm²/sec)

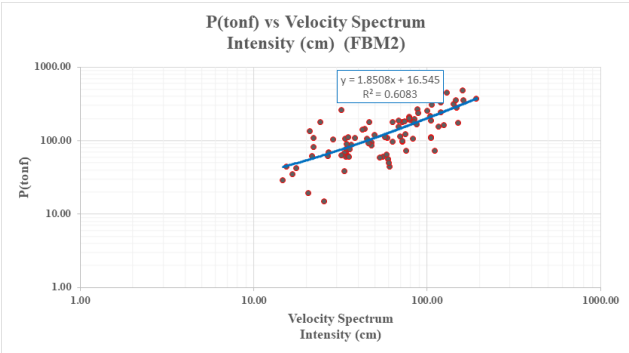


Figure A- 186:P(tonf) in FBM2 vs VSI (cm)

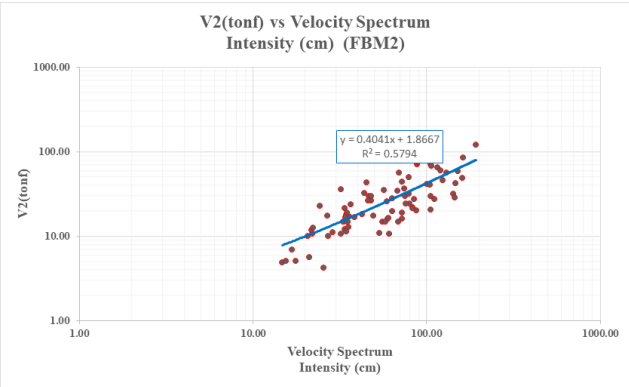


Figure A- 187:V2(tonf) in FBM2 vs VSI (cm)

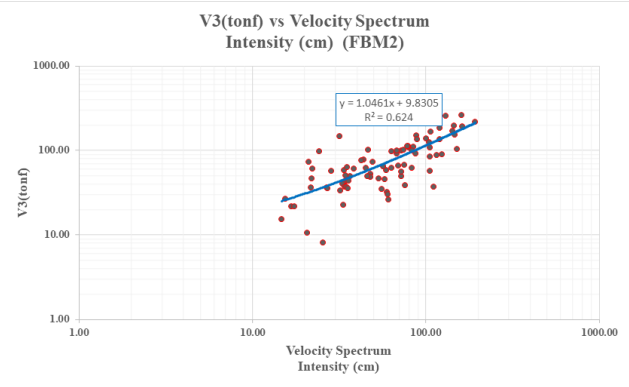


Figure A- 188:V3(tonf) in FBM2 vs VSI (cm)

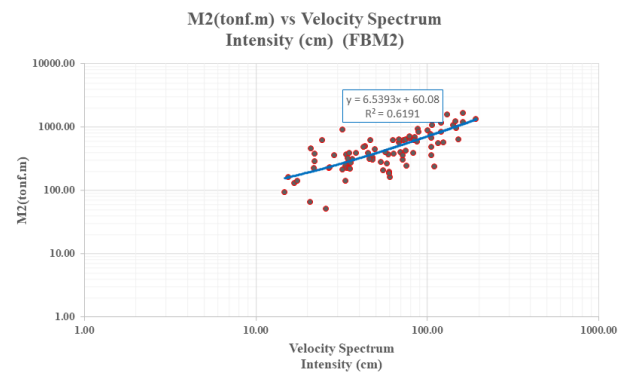


Figure A- 189:M2(tonf.m) in FBM2 vs VSI (cm)

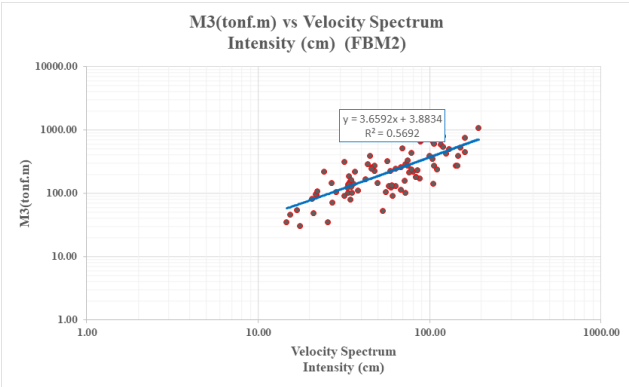


Figure A- 190:M3(tonf.m) in FBM2 vs VSI (cm)

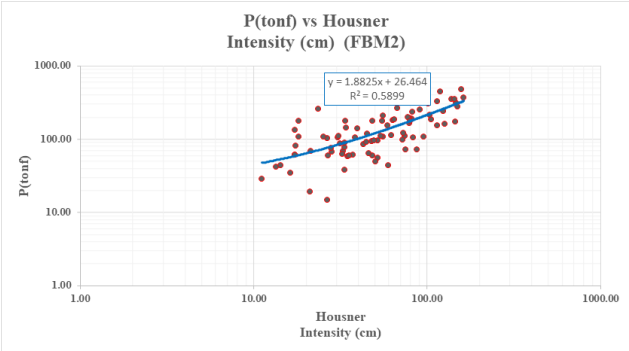


Figure A- 191:P(tonf) in FBM2 vs HI (cm)

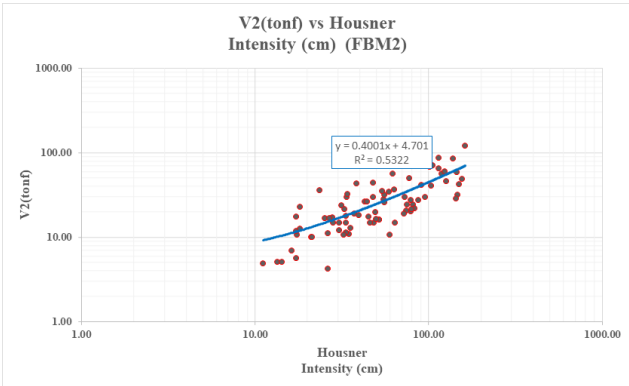


Figure A- 192:V2(tonf) in FBM2 vs HI (cm)

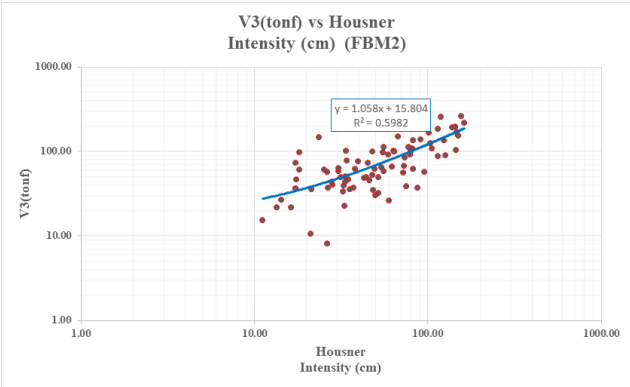


Figure A- 193:V3(tonf) in FBM2 vs HI (cm)

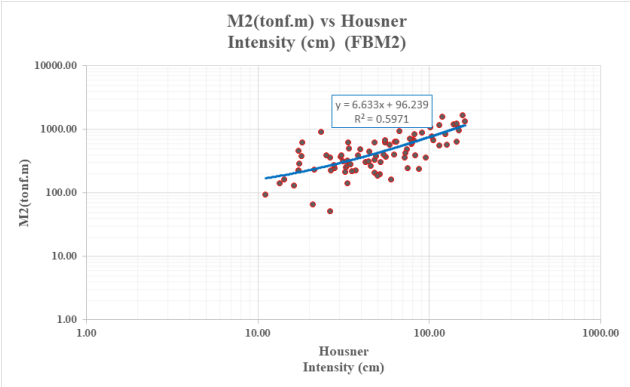


Figure A- 194:M2(tonf.m) in FBM2 vs HI (cm)

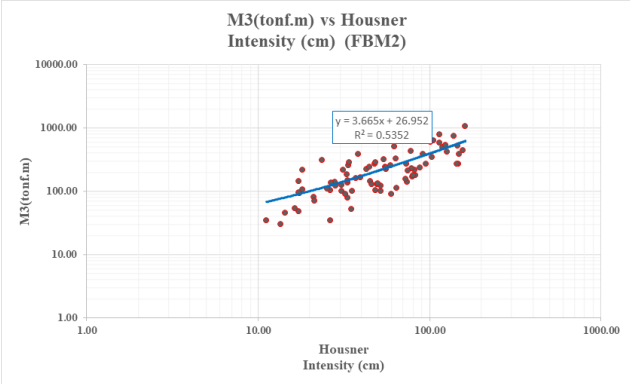


Figure A- 195:M3(tonf.m) in FBM2 vs HI (cm)

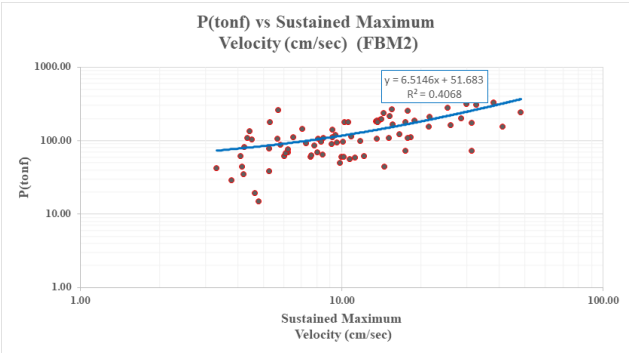


Figure A- 196:P(tonf) in FBM2 vs SMV (cm/sec)

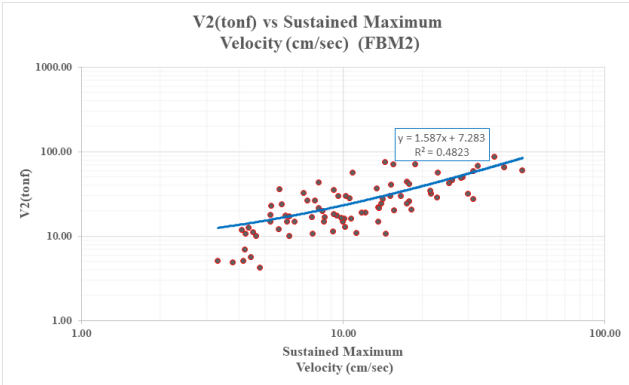


Figure A- 197:V2(tonf) in FBM2 vs SMV (cm/sec)

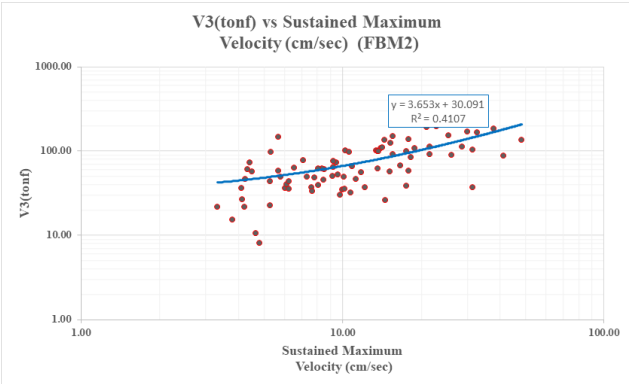


Figure A- 198:V3(tonf) in FBM2 vs SMV (cm/sec)

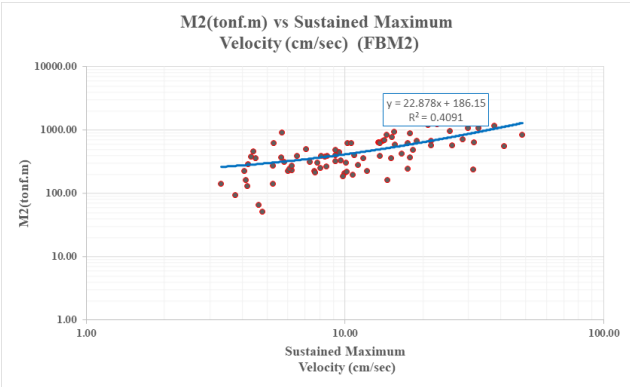


Figure A- 199:M2(tonf.m) in FBM2 vs SMV (cm/sec)

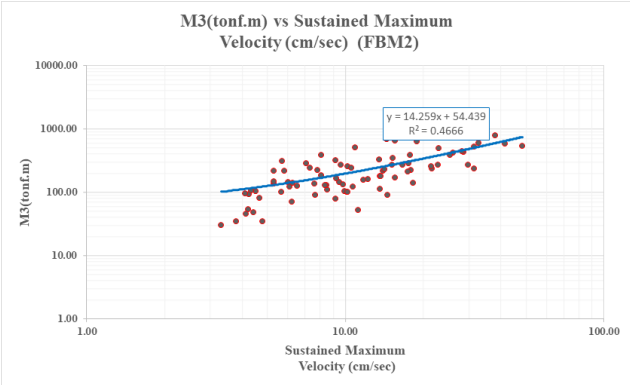


Figure A- 200:M3(tonf.m) in FBM2 vs SMV (cm/sec)

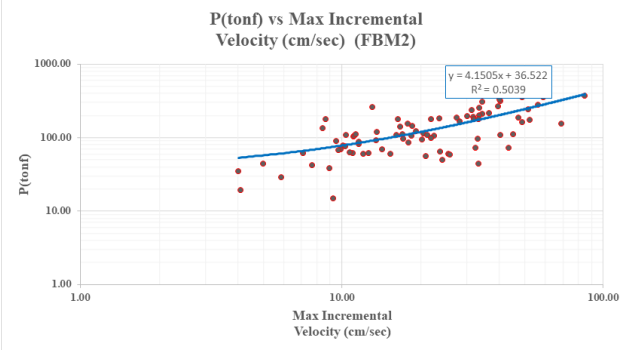


Figure A- 201:P(tonf) in FBM2 vs MIV (cm/sec)

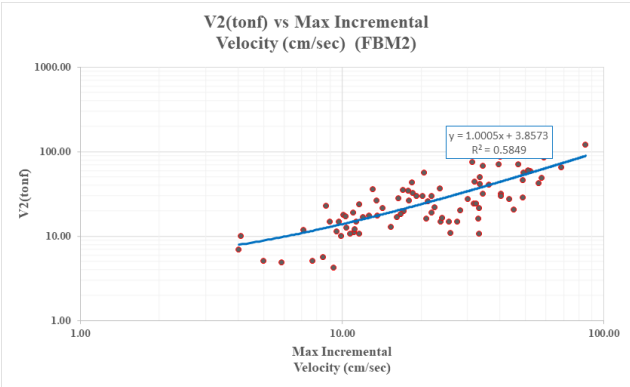


Figure A- 202:V2(tonf) in FBM2 vs MIV (cm/sec)

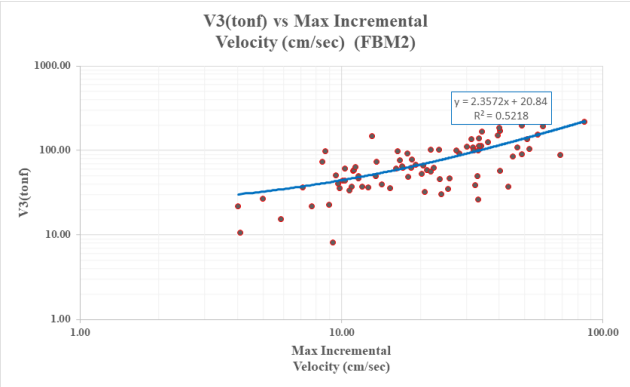


Figure A- 203:V3(tonf) in FBM2 vs MIV (cm/sec)

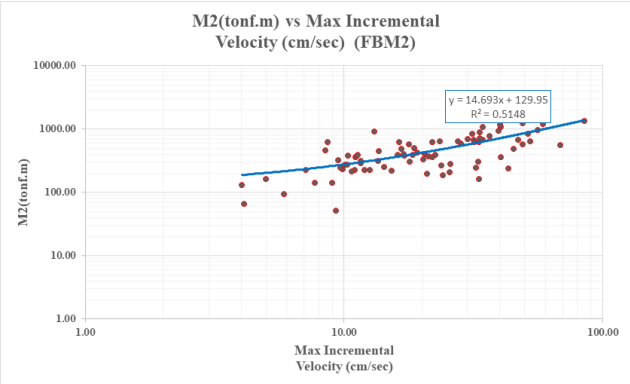


Figure A- 204:M2(tonf.m) in FBM2 vs MIV (cm/sec)

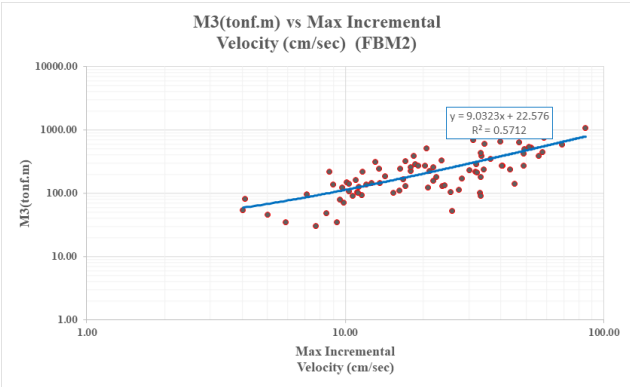


Figure A- 205:M3(tonf.m) in FBM2 vs MIV (cm/sec)

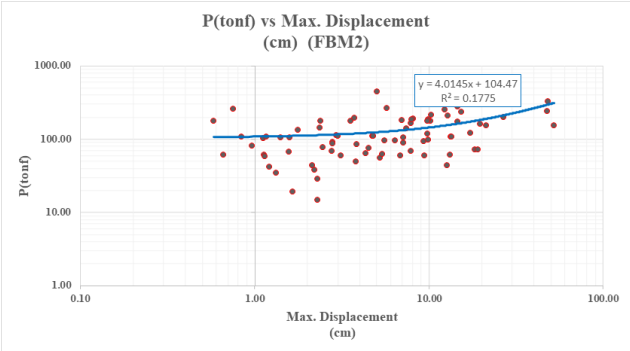


Figure A- 206:P(tonf) in FBM2 vs PGD (cm)

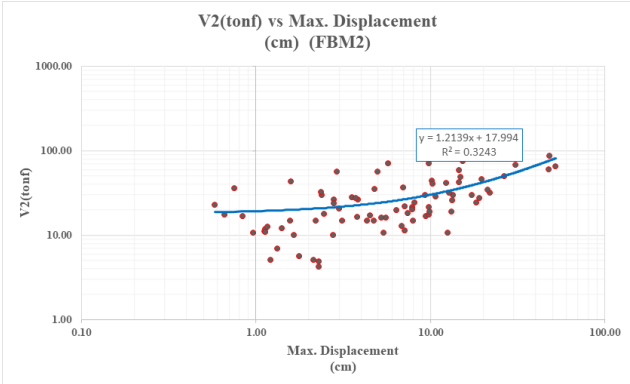


Figure A- 207:V2(tonf) in FBM2 vs PGD (cm)

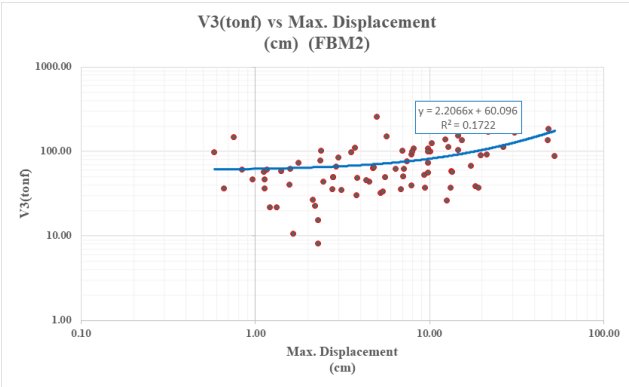


Figure A- 208:V3(tonf) in FBM2 vs PGD (cm)

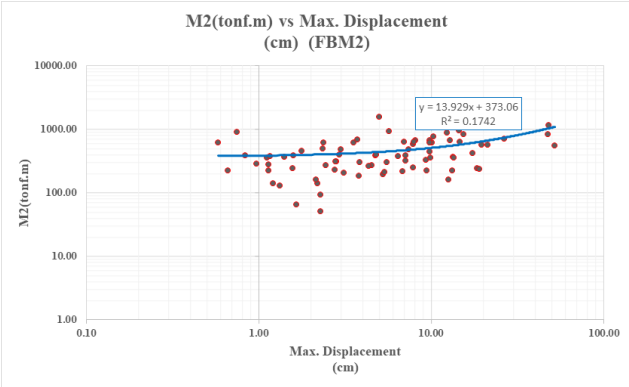


Figure A- 209:M2(tonf.m) in FBM2 vs PGD (cm)

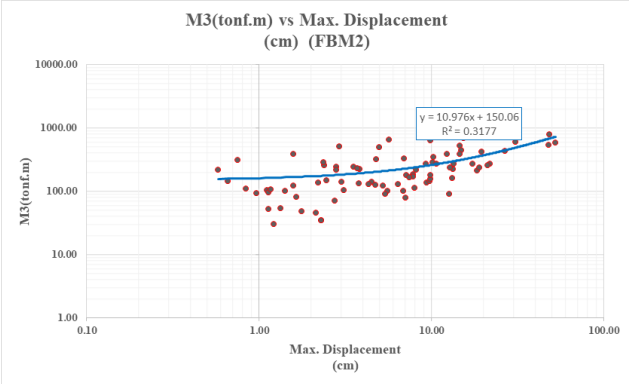


Figure A- 210:M3(tonf.m) in FBM2 vs PGD (cm)

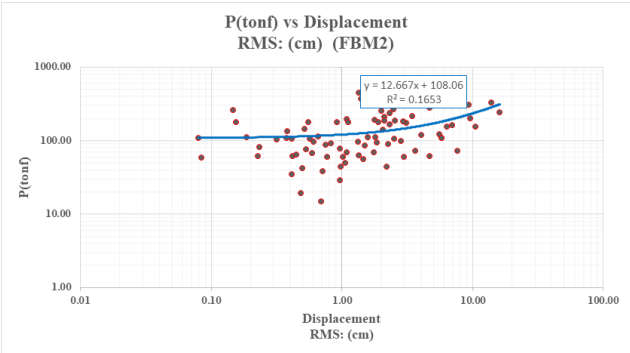


Figure A- 211:P(tonf) in FBM2 vs drms (cm)

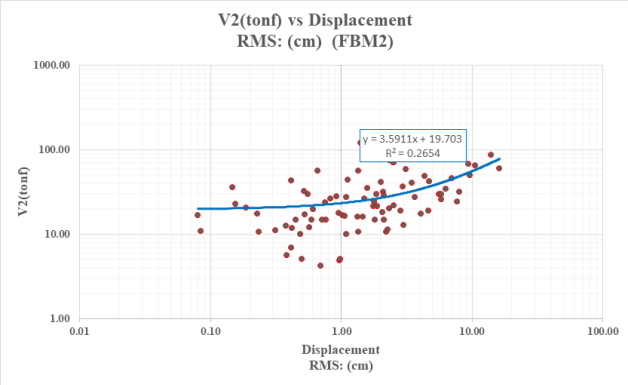


Figure A- 212:V2(tonf) in FBM2 vs drms (cm)

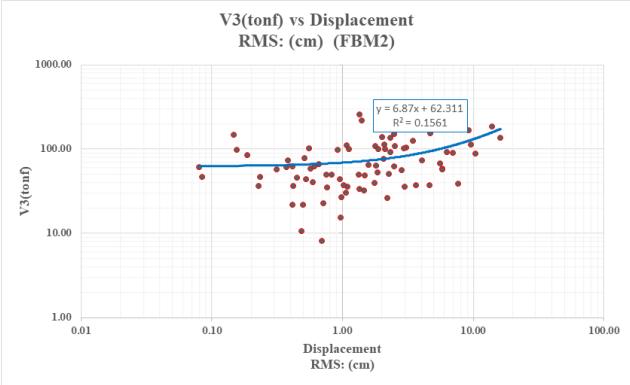


Figure A- 213:V3(tonf) in FBM2 vs drms (cm)

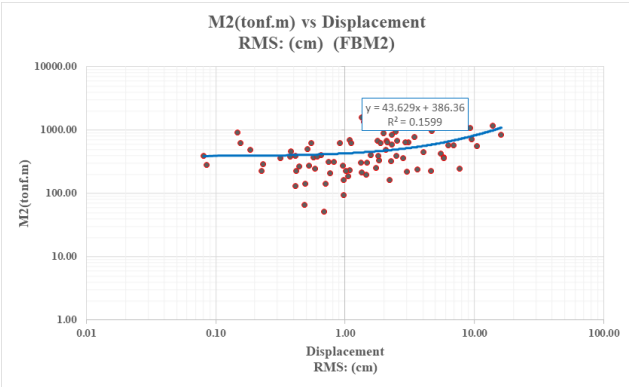


Figure A- 214:M2(tonf.m) in FBM2 vs drms (cm)

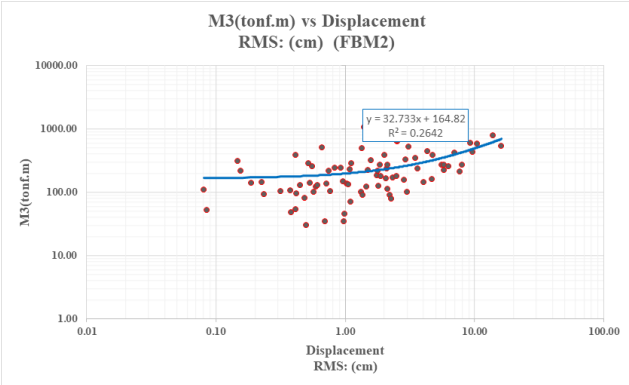


Figure A- 215:M3(tonf.m) in FBM2 vs drms (cm)

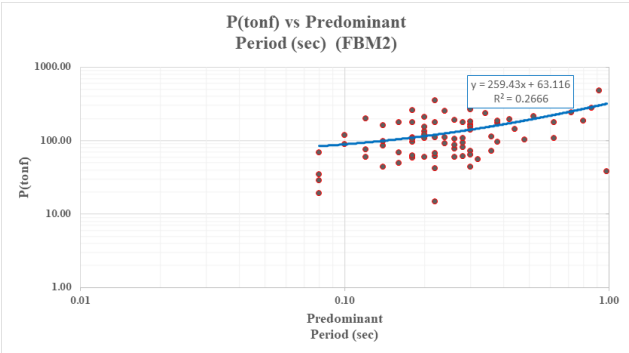


Figure A- 216:P(tonf) in FBM2 vs PP (sec)

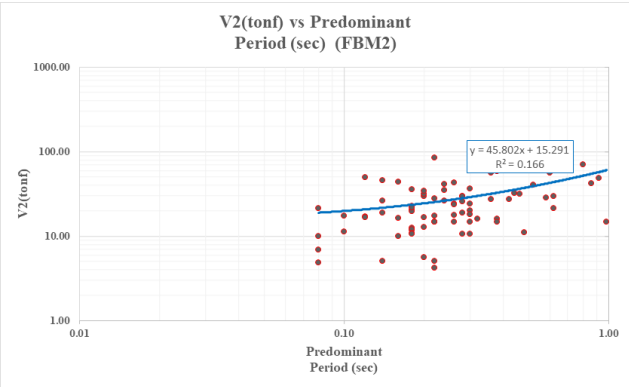


Figure A- 217:V2(tonf) in FBM2 vs PP (sec)

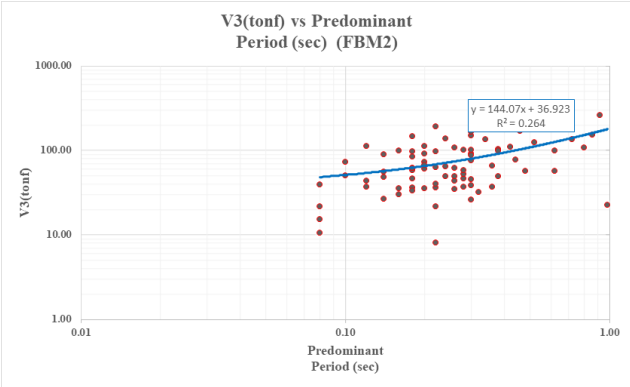


Figure A- 218:V3(tonf) in FBM2 vs PP (sec)

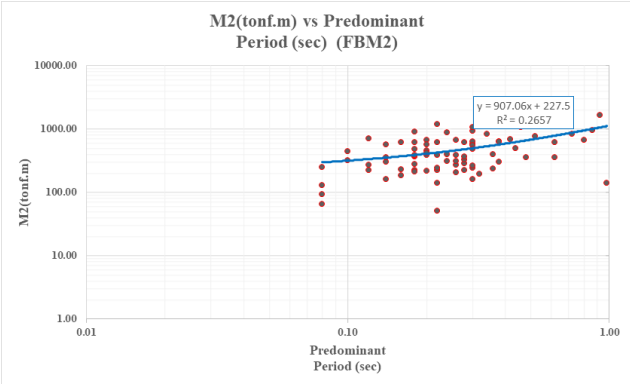


Figure A- 219:M2(tonf.m) in FBM2 vs PP (sec)

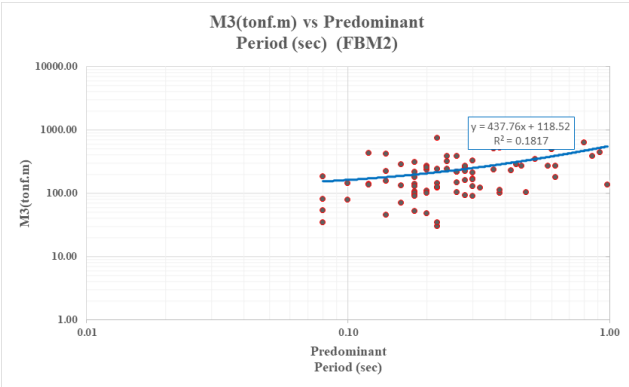


Figure A- 220:M3(tonf.m) in FBM2 vs PP (sec)

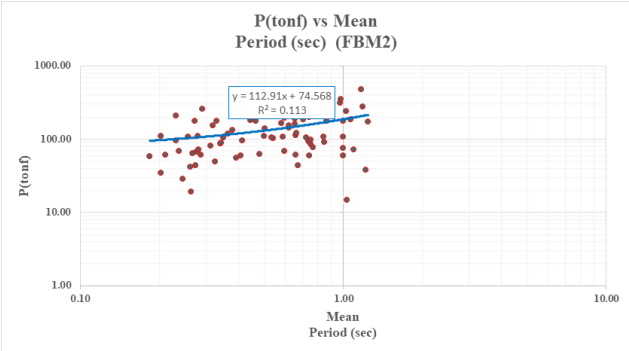


Figure A- 221:P(tonf) in FBM2 vs MP (sec)

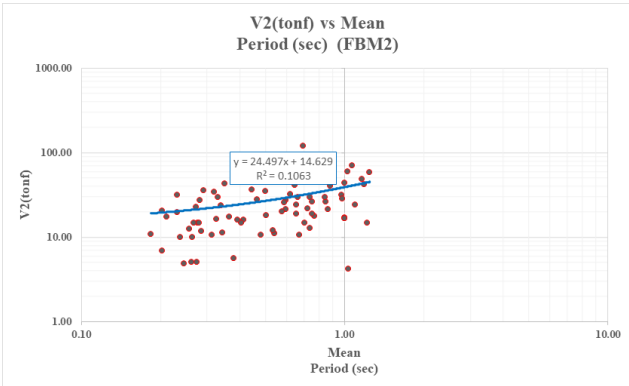


Figure A- 222:V2(tonf) in FBM2 vs MP (sec)

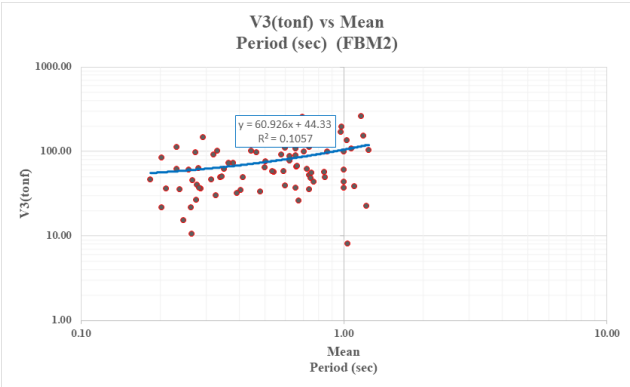


Figure A- 223:V3(tonf) in FBM2 vs MP (sec)

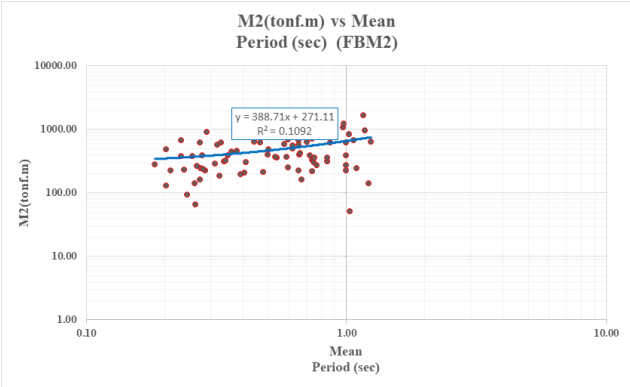


Figure A- 224:M2(tonf.m) in FBM2 vs MP (sec)

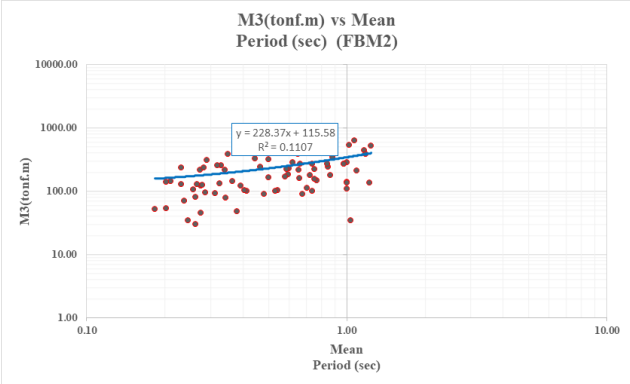


Figure A- 225:M3(tonf.m) in FBM2 vs MP (sec)

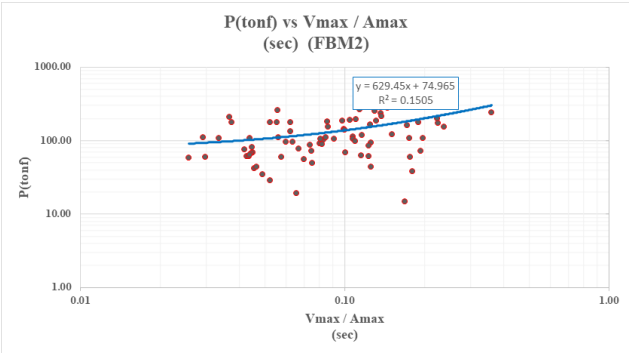


Figure A- 226:P(tonf) in FBM2 vs PGV/PGA(sec)

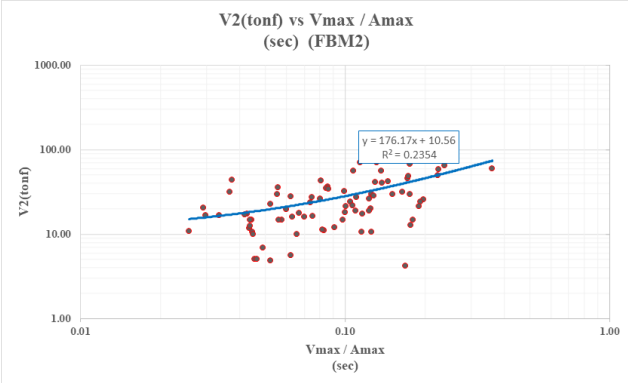


Figure A- 227:V2(tonf) in FBM2 vs PGV/PGA(sec)

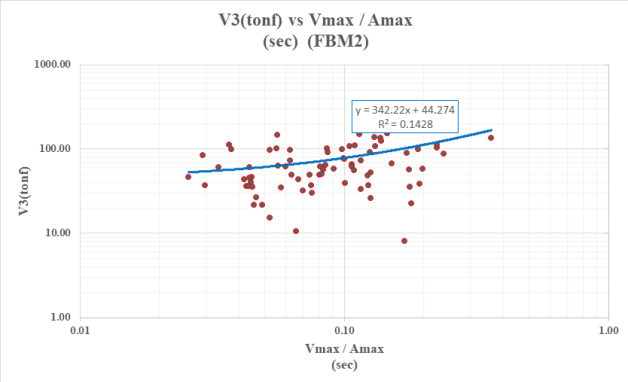


Figure A- 228:V3(tonf) in FBM2 vs PGV/PGA(sec)

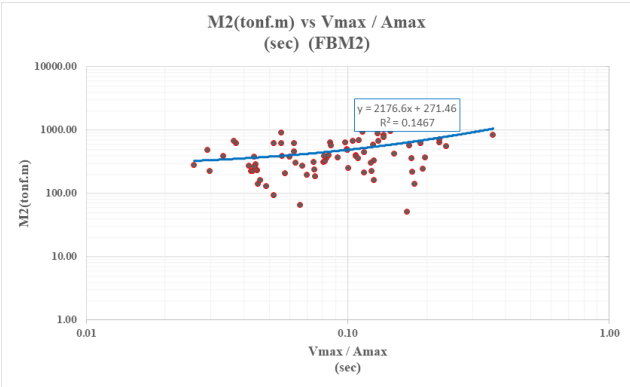


Figure A- 229:M2(tonf.m) in FBM2 vs PGV/PGA(sec)

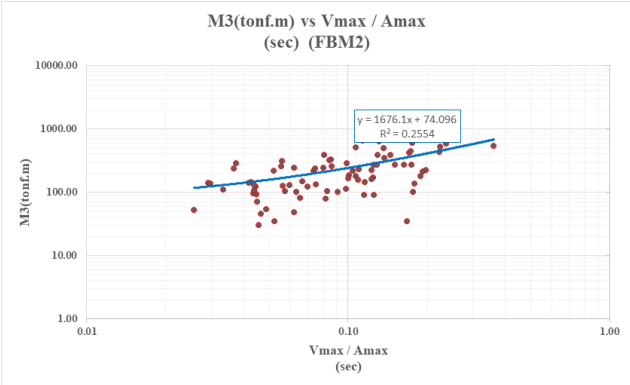


Figure A- 230:M3(tonf.m) in FBM2 vs PGV/PGA(sec)

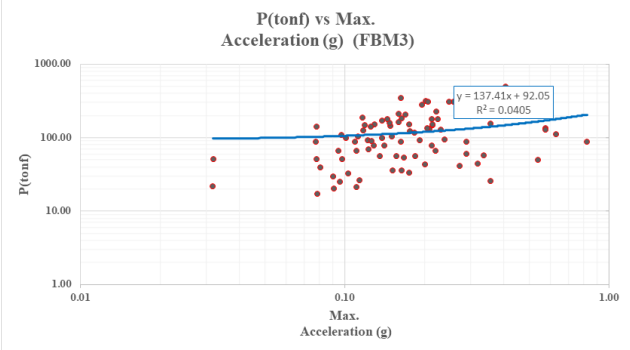


Figure A- 231:P(tonf) in FBM3 vs PGA(g)

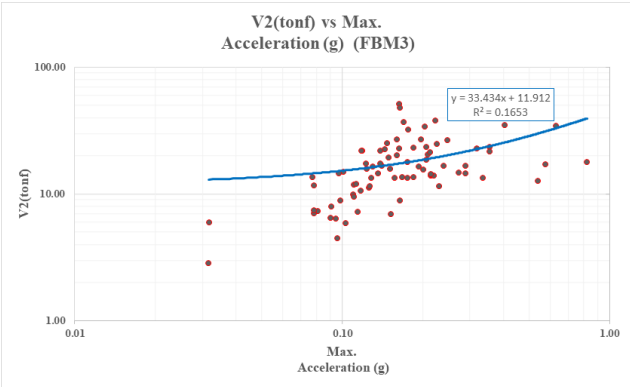


Figure A- 232:V2(tonf) in FBM3 vs PGA(g)

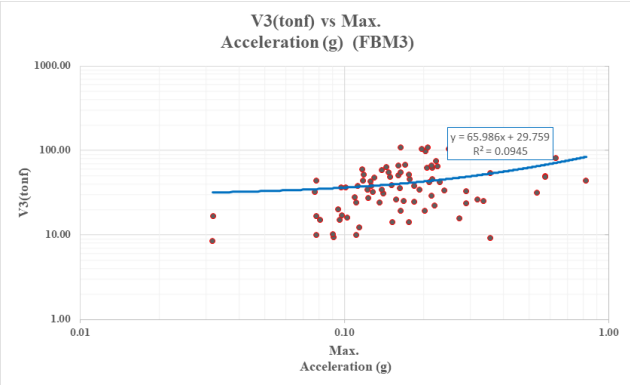


Figure A- 233:V3(tonf) in FBM3 vs PGA(g)g

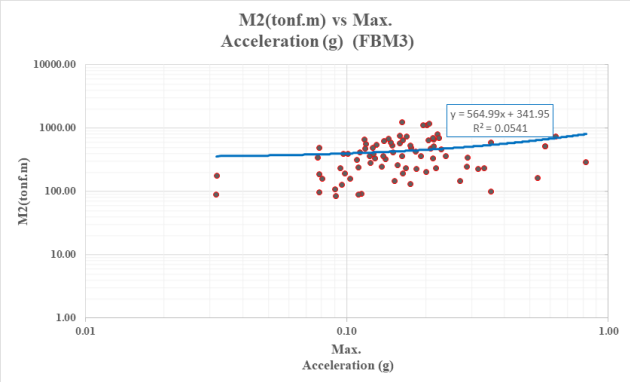


Figure A- 234:M2(tonf.m) in FBM3 vs PGA(g)

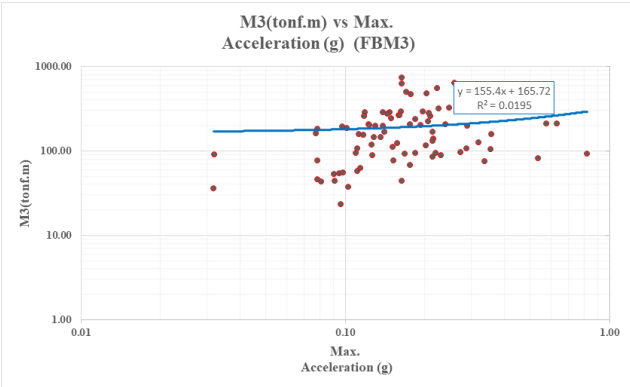


Figure A- 235:M3(tonf.m) in FBM3 vs PGA(g)

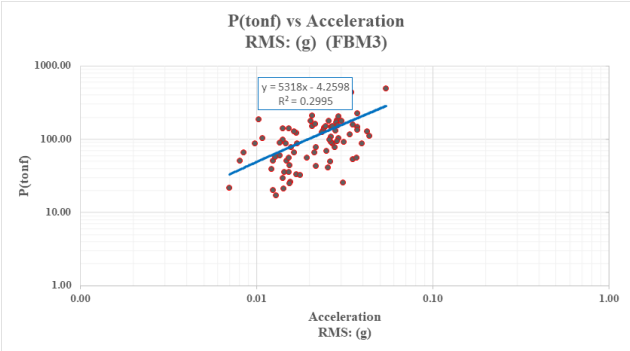


Figure A- 236:P(tonf) in FBM3 vs arms(g)

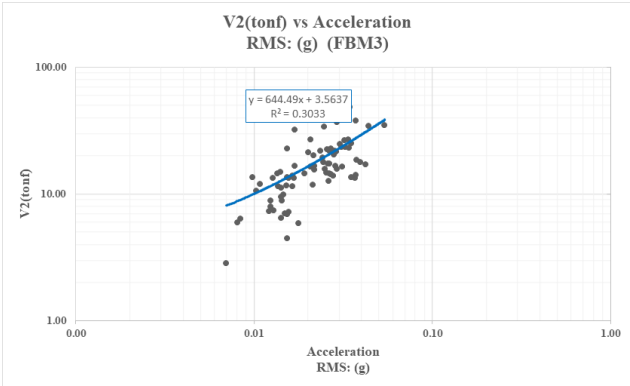


Figure A- 237:V2(tonf) in FBM3 vs arms(g)

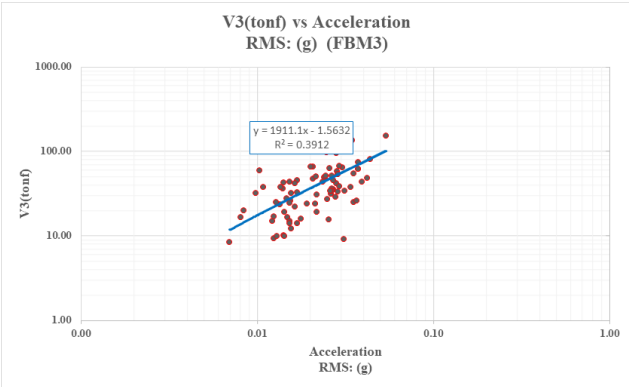


Figure A- 238:V3(tonf) in FBM3 vs arms(g)

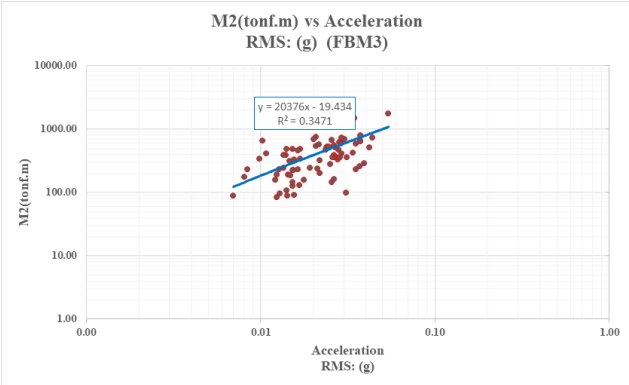


Figure A- 239:M2(tonf.m) in FBM3 vs arms(g)

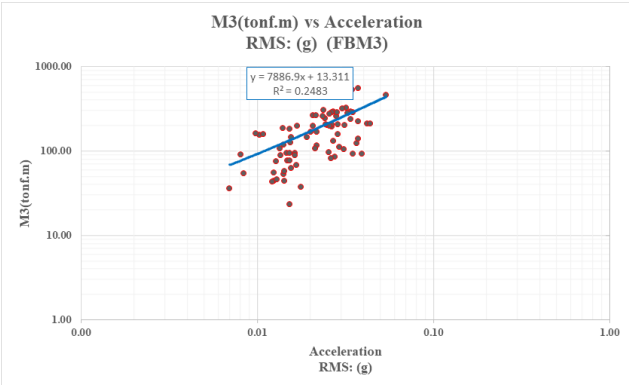


Figure A- 240:M3(tonf.m) in FBM3 vs arms(g)

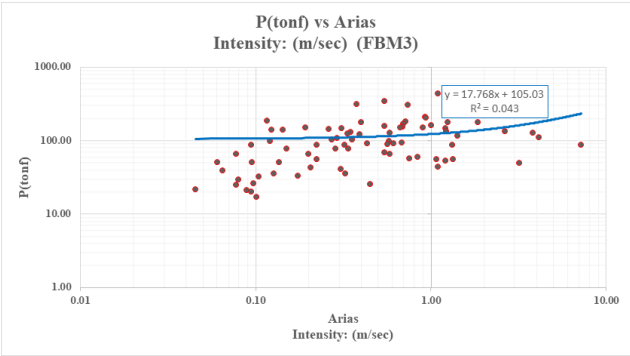


Figure A- 241:P(tonf) in FBM3 vs AI(m/sec)

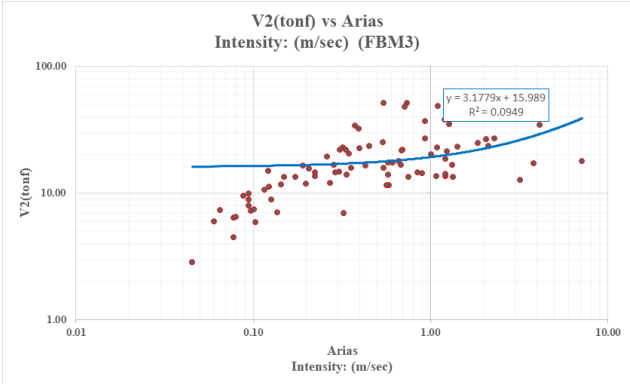


Figure A- 242:V2(tonf) in FBM3 vs AI(m/sec)

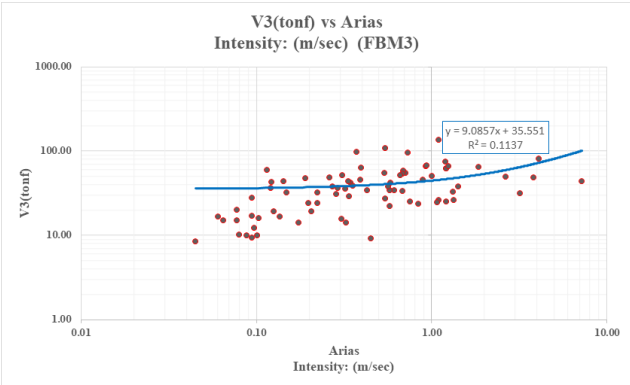


Figure A- 243:V3(tonf) in FBM3 vs AI(m/sec)

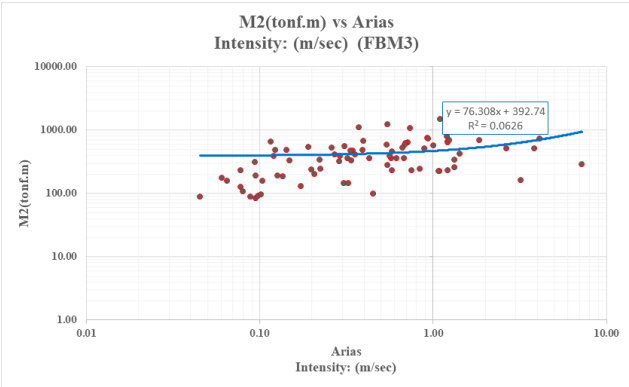


Figure A- 244:M2(tonf.m) in FBM3 vs AI(m/sec)

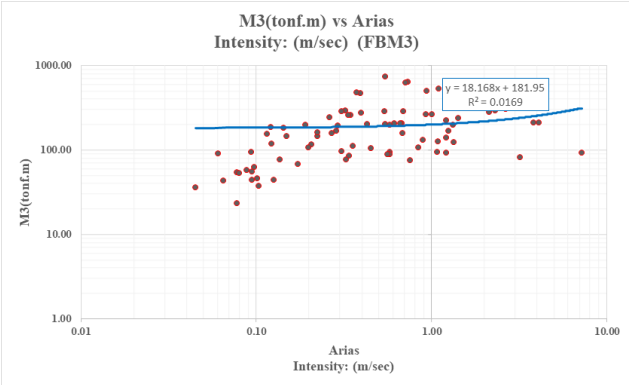


Figure A- 245:M3(tonf.m) in FBM3 vs AI(m/sec)

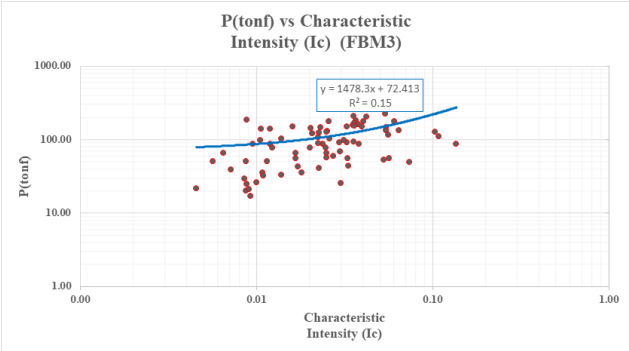


Figure A- 246:P(tonf) in FBM3 vs Ic

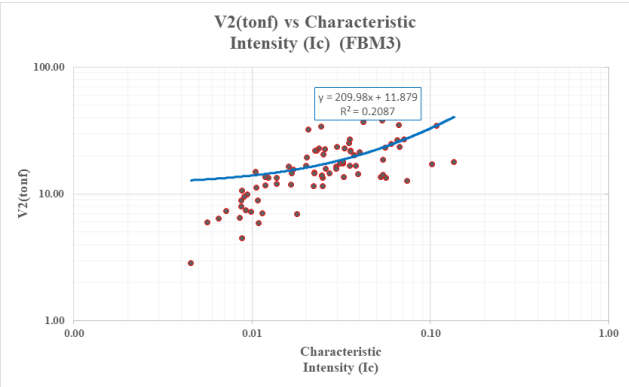


Figure A- 247:V2(tonf) in FBM3 vs Ic

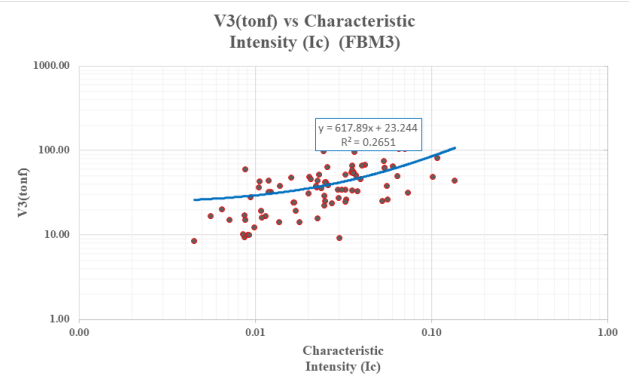


Figure A- 248:V3(tonf) in FBM3 vs Ic

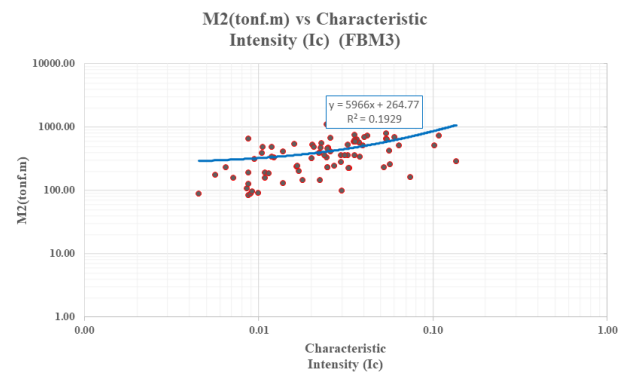


Figure A- 249:M2(tonf.m) in FBM3 vs Ic

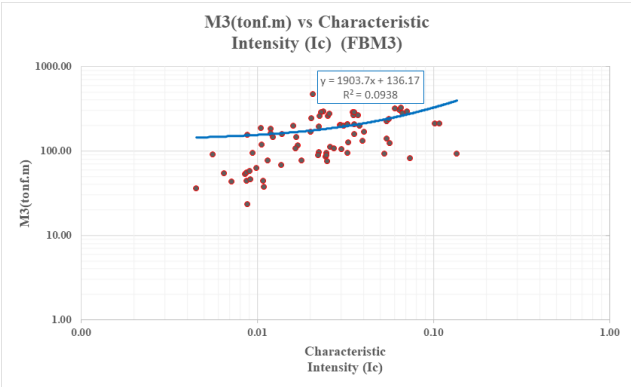


Figure A- 250:M3(tonf.m) in FBM3 vs Ic

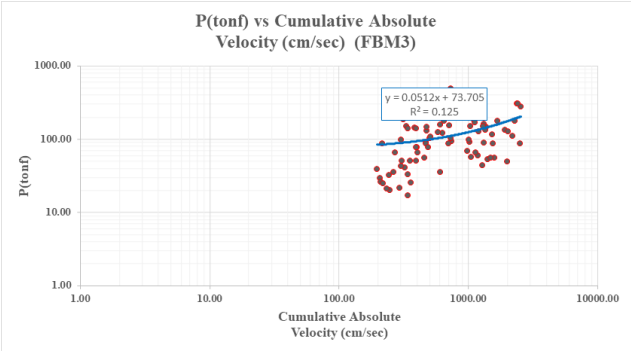


Figure A- 251:P(tonf) in FBM3 vs CAV (cm/sec)

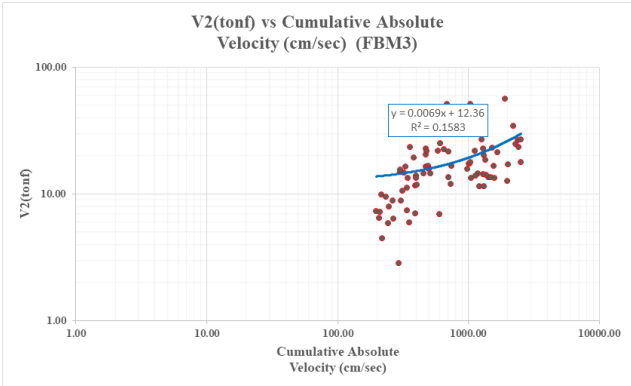


Figure A- 252:V2(tonf) in FBM3 vs CAV (cm/sec)

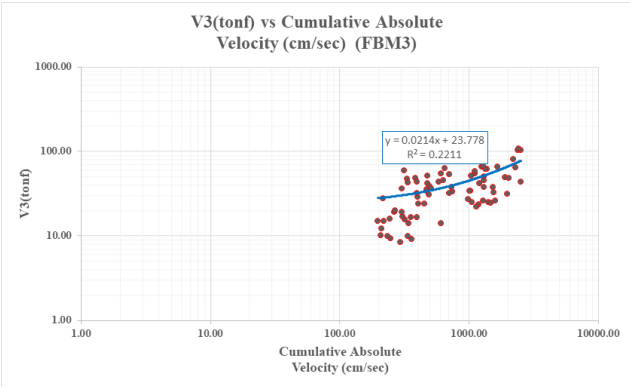


Figure A- 253:V3(tonf) in FBM3 vs CAV (cm/sec)

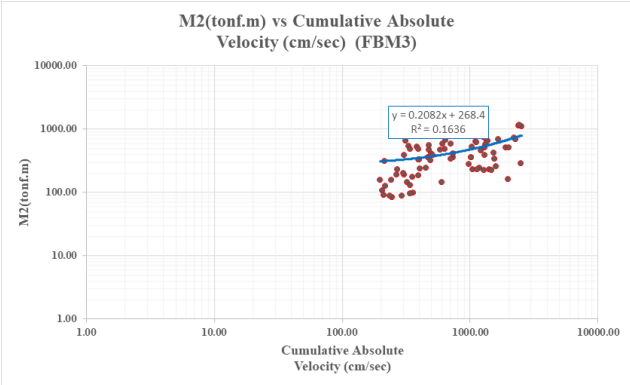


Figure A- 254:M2(tonf.m) in FBM3 vs CAV (cm/sec)

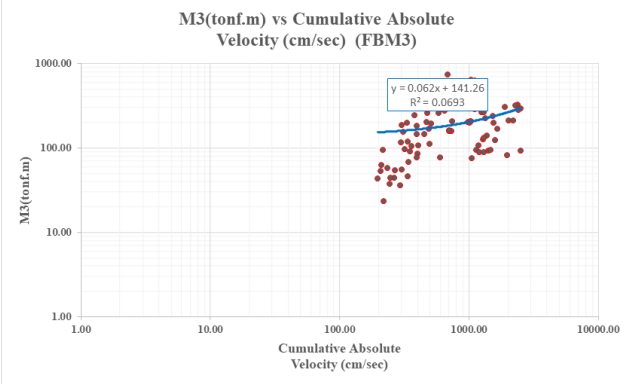


Figure A- 255:M3(tonf.m) in FBM3 vs CAV (cm/sec)

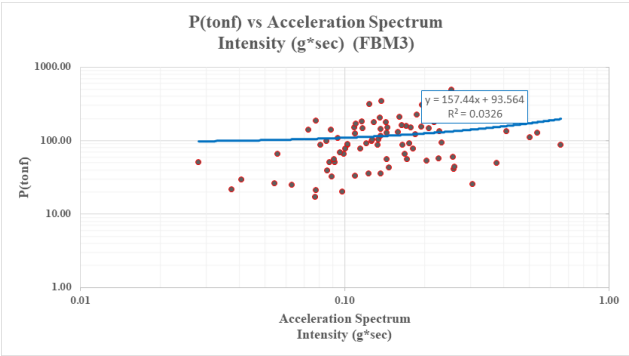


*Figure A- 256:P(tonf) in FBM3 vs ASI (g*sec)*

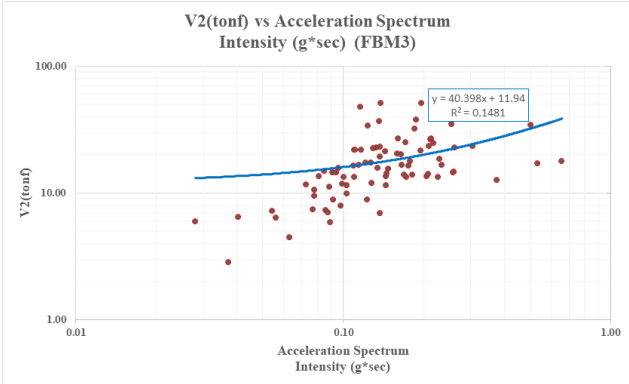


*Figure A- 257:V2(tonf) in FBM3 vs ASI (g*sec)*

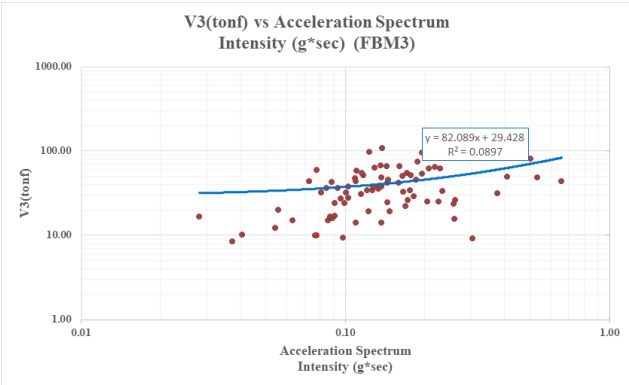


*Figure A- 258:V3(tonf) in FBM3 vs ASI (g*sec)*

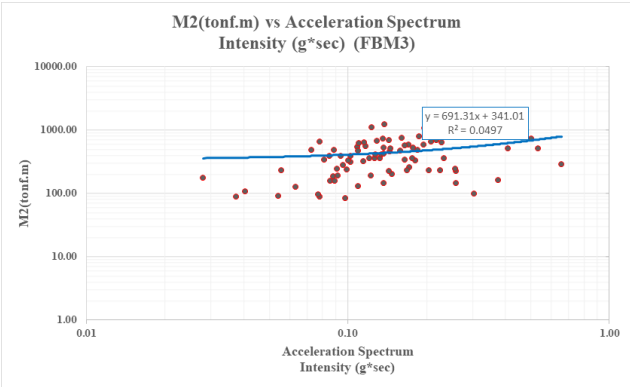


*Figure A- 259:M2(tonf.m) in FBM3 vs ASI (g*sec)*

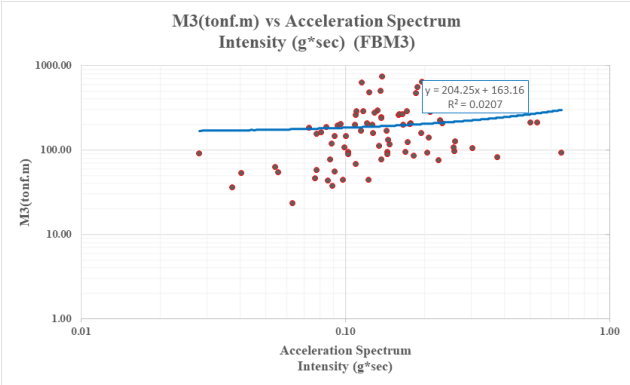


*Figure A- 260:M3(tonf.m) in FBM3 vs ASI (g*sec)*

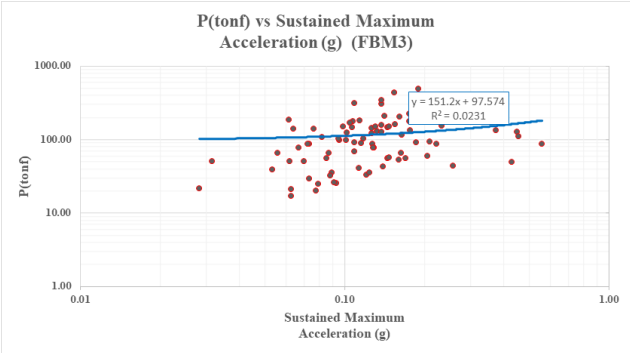


Figure A- 261:P(tonf) in FBM3 vs SMA (g)

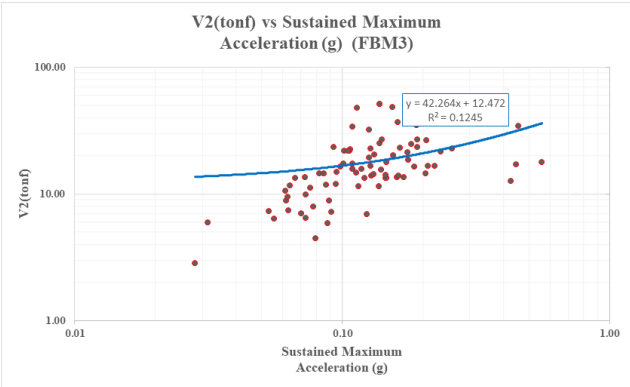


Figure A- 262:V2(tonf) in FBM3 vs SMA (g)

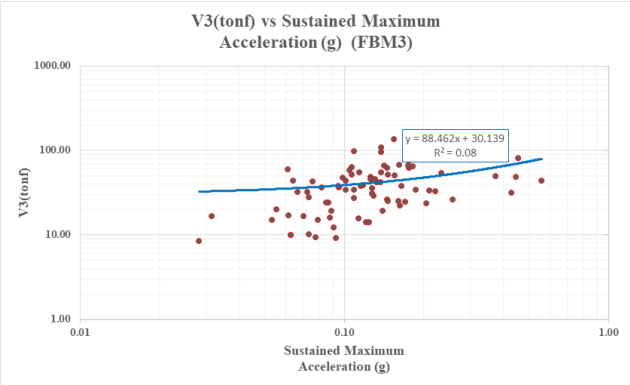


Figure A- 263:V3(tonf) in FBM3 vs SMA (g)

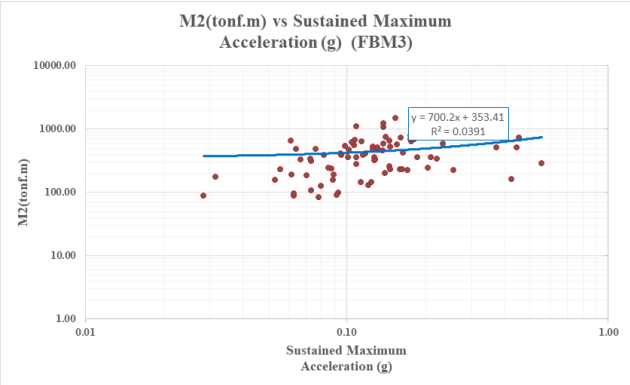


Figure A- 264:M2(tonf.m) in FBM3 vs SMA (g)

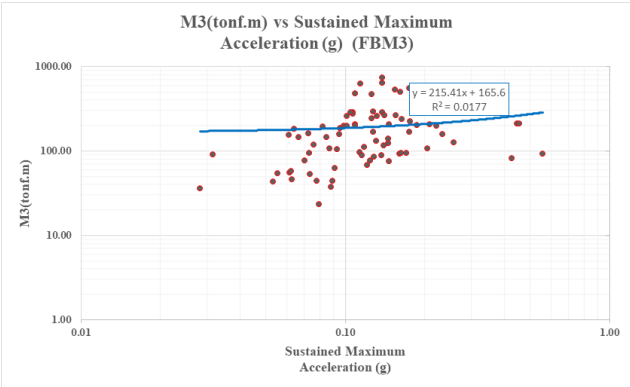


Figure A- 265:M3(tonf.m) in FBM3 vs SMA (g)

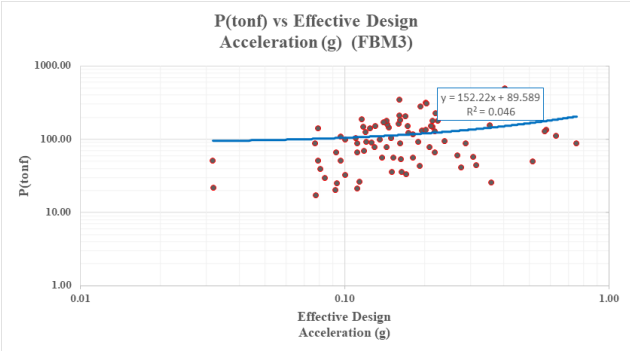


Figure A- 266:P(tonf) in FBM3 vs EDA (g)

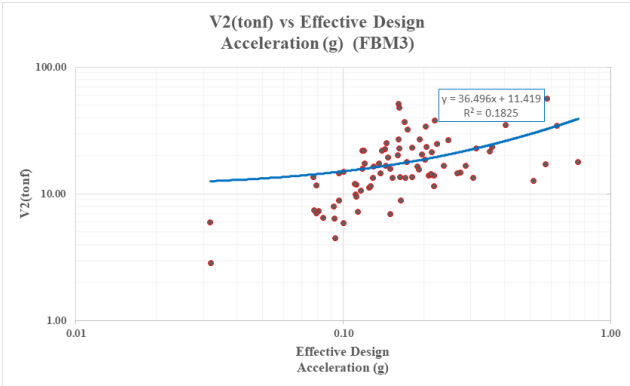


Figure A- 267:V2(tonf) in FBM3 vs EDA (g)

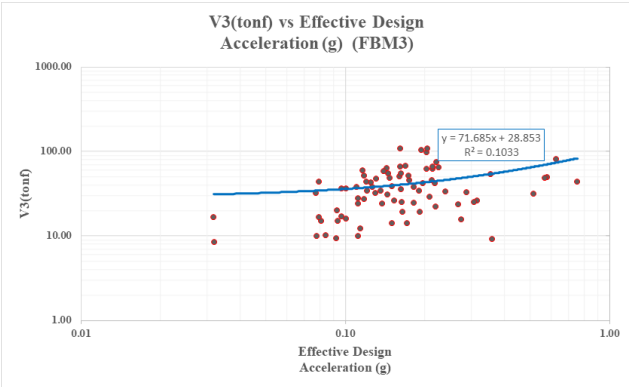


Figure A- 268:V3(tonf) in FBM3 vs EDA (g)

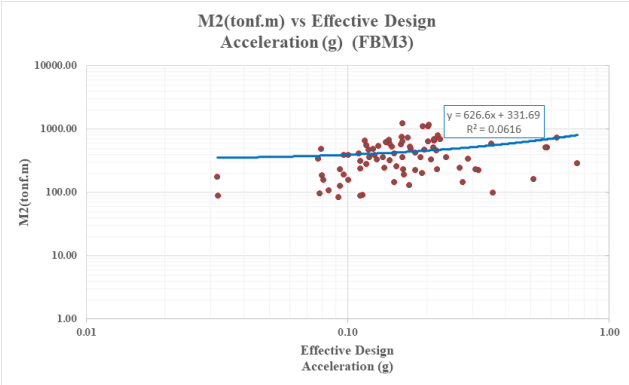


Figure A- 269:M2(tonf.m) in FBM3 vs EDA (g)

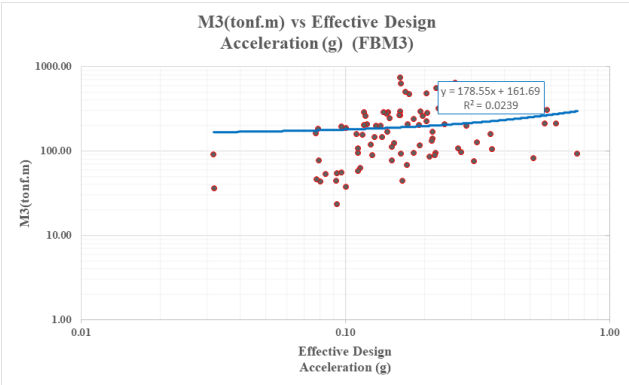


Figure A- 270:M3(tonf.m) in FBM3 vs EDA (g)

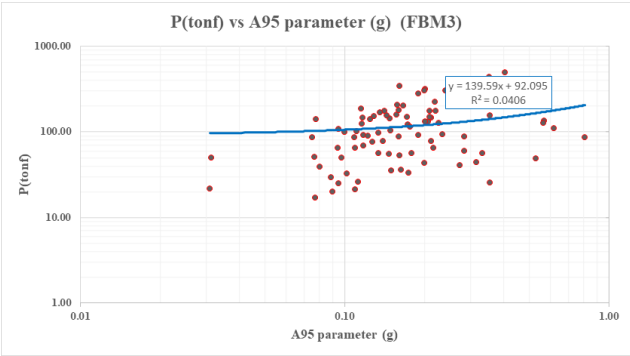


Figure A- 271:P(tonf) in FBM3 vs a95 (g)

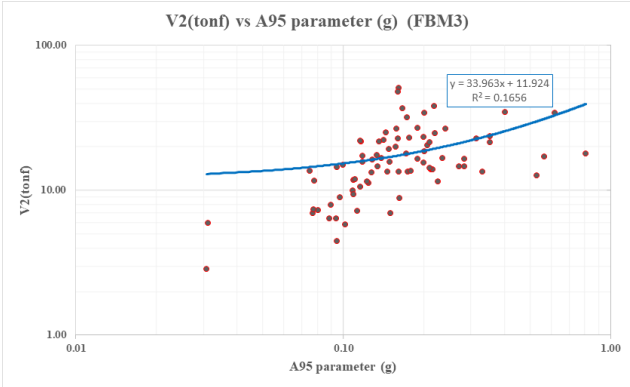


Figure A- 272:V2(tonf) in FBM3 vs a95 (g)

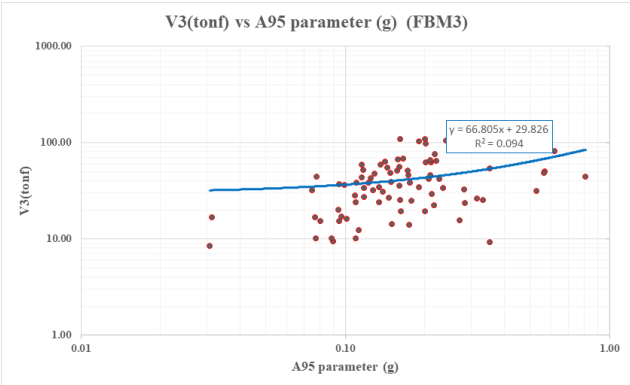


Figure A- 273:V3(tonf) in FBM3 vs a95 (g)

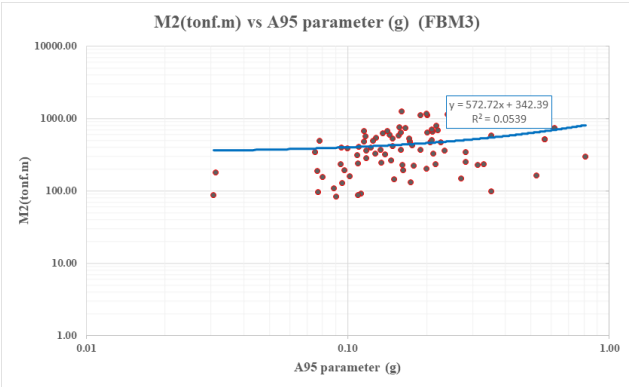


Figure A- 274:M2(tonf.m) in FBM3 vs a95 (g)

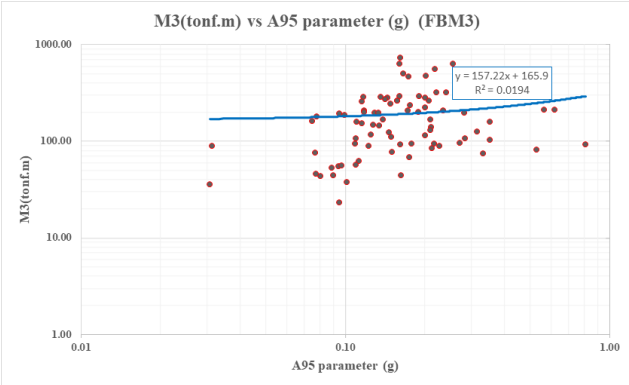


Figure A- 275:M3(tonf.m) in FBM3 vs a95 (g)

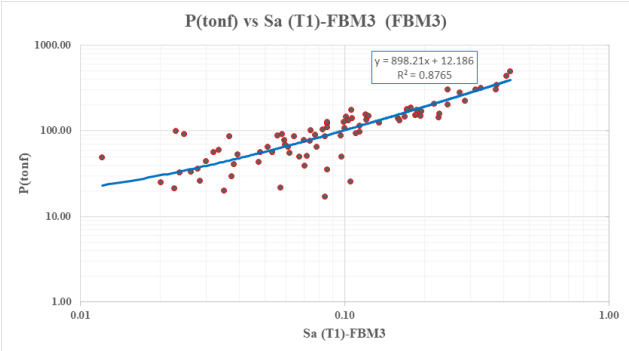


Figure A- 276:P(tonf) in FBM3 vs Sa (T1) (g)

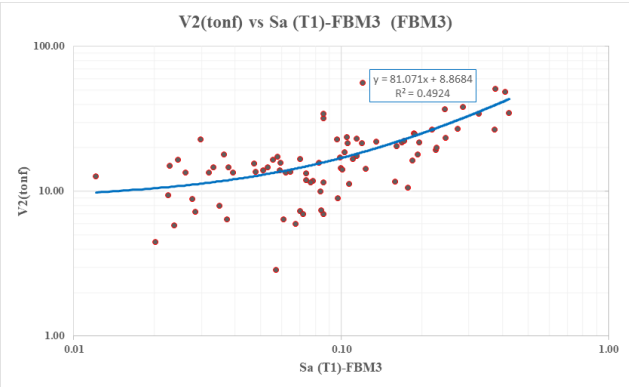


Figure A- 277:V2(tonf) in FBM3 vs Sa (T1) (g)

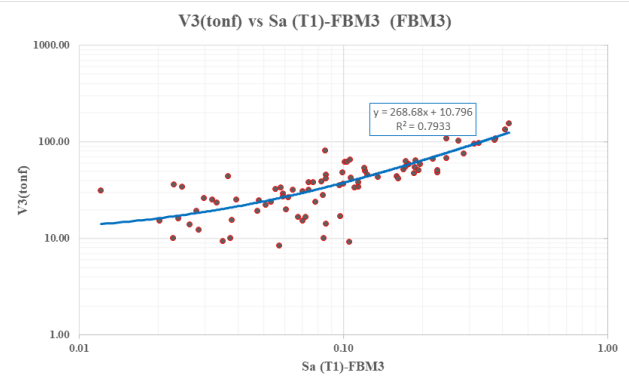


Figure A- 278:V3(tonf) in FBM3 vs Sa (T1) (g)

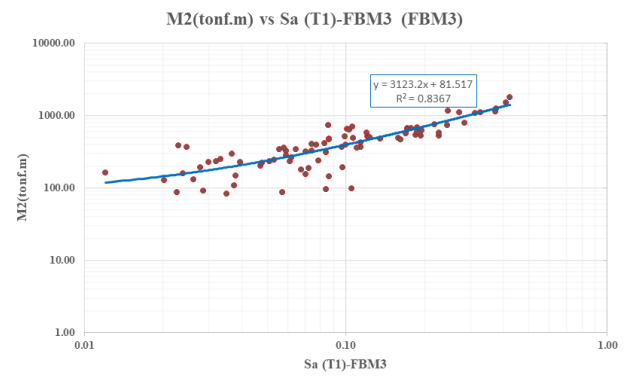


Figure A- 279:M2(tonf.m) in FBM3 vs Sa (T1) (g)

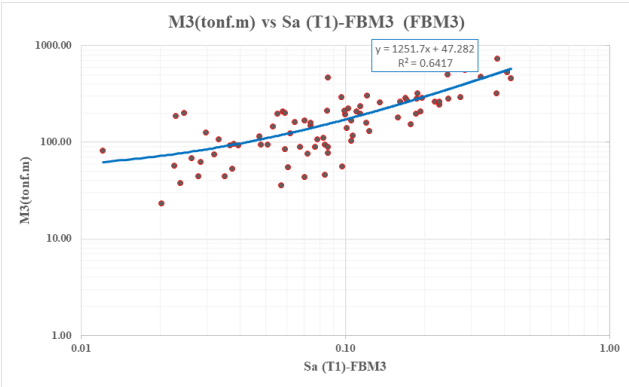


Figure A- 280:M3(tonf.m) in FBM3 vs Sa (T1) (g)

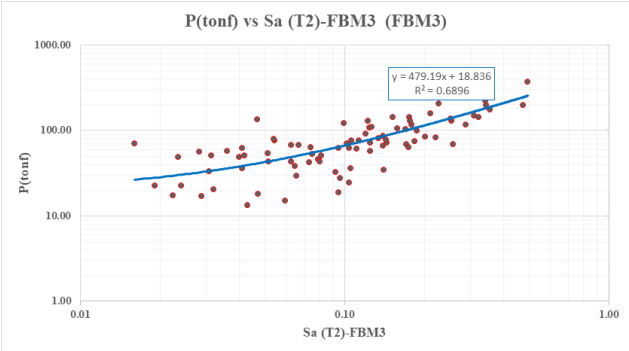


Figure A- 281:P(tonf) in FBM3 vs Sa (T2) (g)

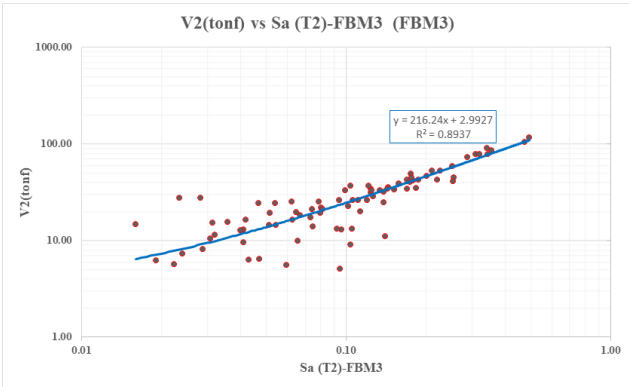


Figure A- 282:V2(tonf) in FBM3 vs Sa (T2) (g)

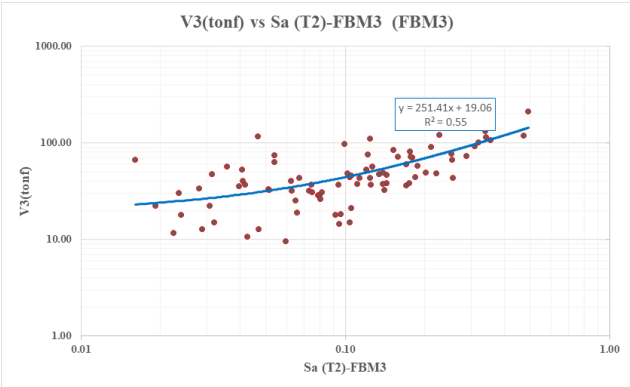


Figure A- 283:V3(tonf) in FBM3 vs Sa (T2) (g)

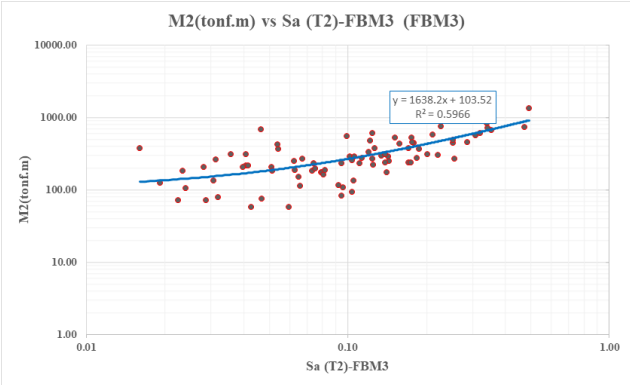


Figure A- 284:M2(tonf.m) in FBM3 vs Sa (T2) (g)

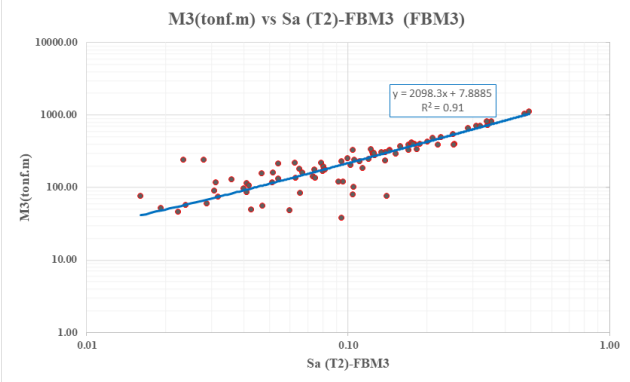


Figure A- 285:M3(tonf.m) in FBM3 vs Sa (T2) (g)

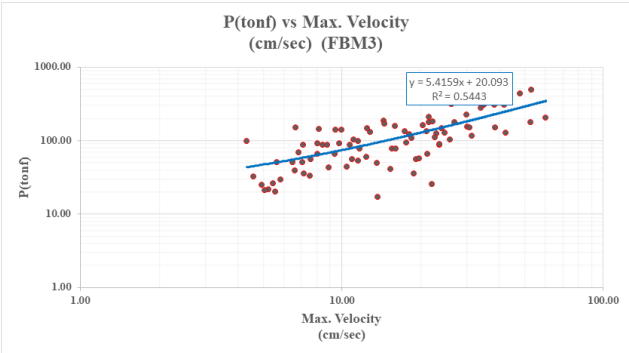


Figure A- 286:P(tonf) in FBM3 vs PGV (cm/sec)

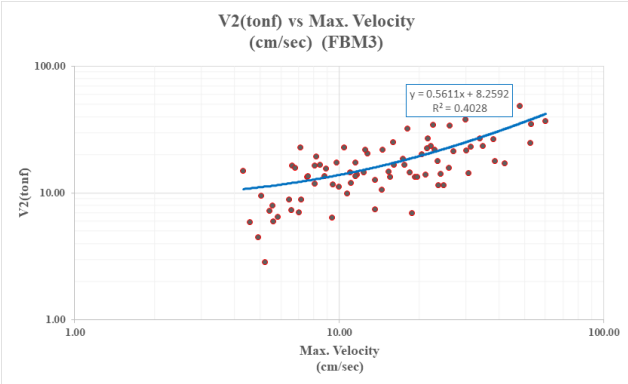


Figure A- 287:V2(tonf) in FBM3 vs PGV (cm/sec)

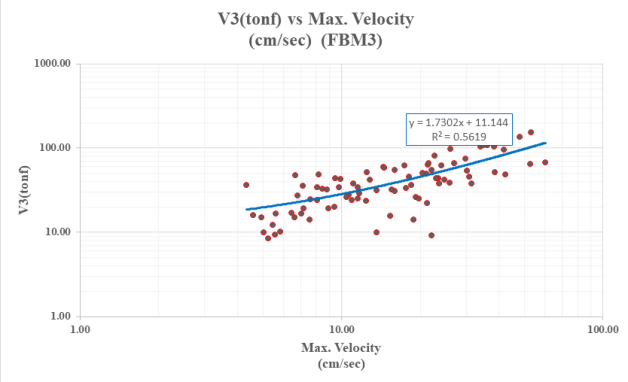


Figure A- 288:V3(tonf) in FBM3 vs PGV (cm/sec)

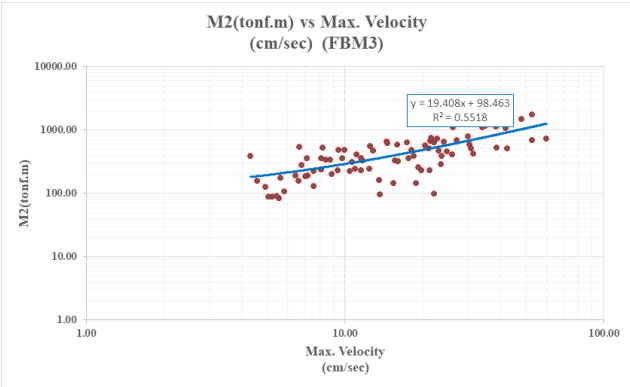


Figure A- 289:M2(tonf.m) in FBM3 vs PGV (cm/sec)

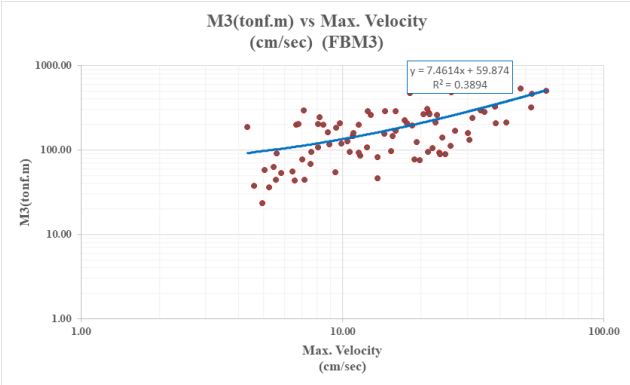


Figure A- 290:M3(tonf.m) in FBM3 vs PGV (cm/sec)

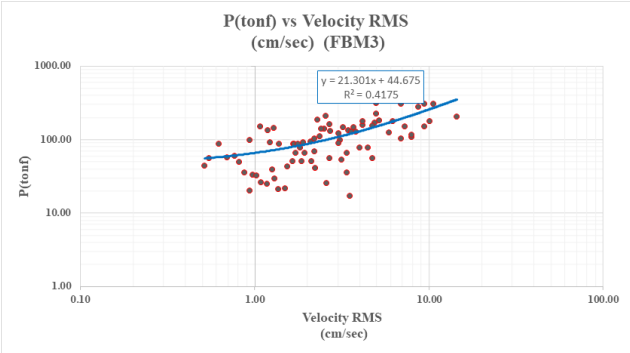


Figure A- 291:P(tonf) in FBM3 vs vrms (cm/sec)

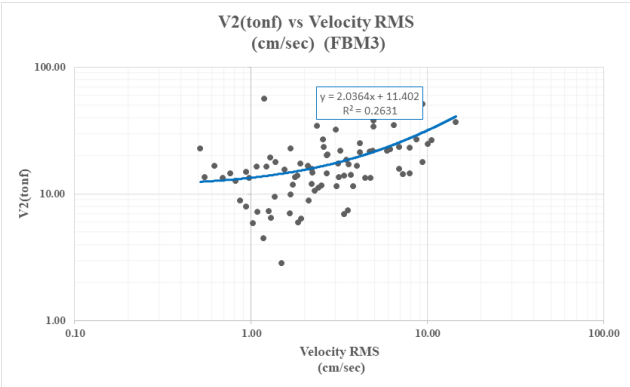


Figure A- 292:V2(tonf) in FBM3 vs vrms (cm/sec)

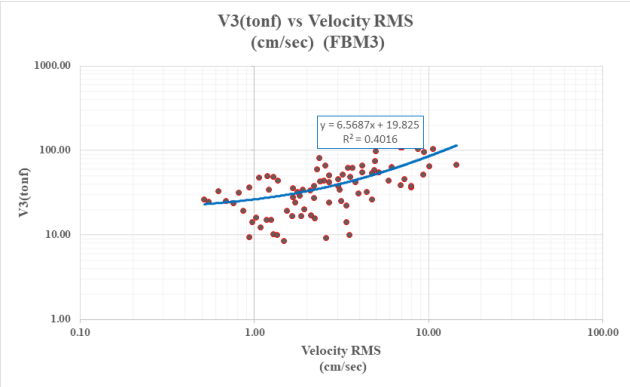


Figure A- 293:V3(tonf) in FBM3 vs vrms (cm/sec)

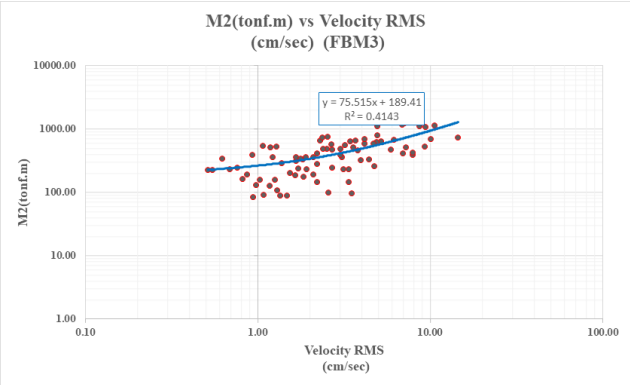


Figure A- 294:M2(tonf.m) in FBM3 vs vrms (cm/sec)

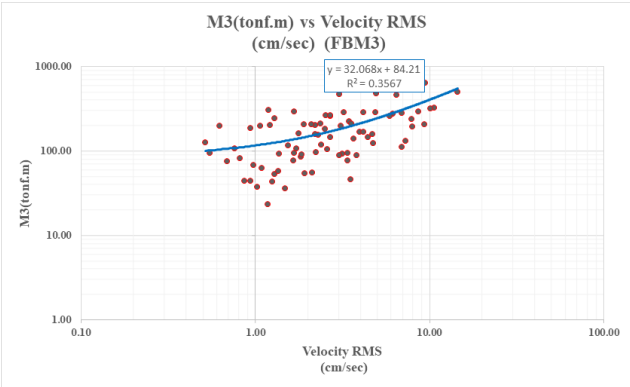


Figure A- 295:M3(tonf.m) in FBM3 vs vrms (cm/sec)

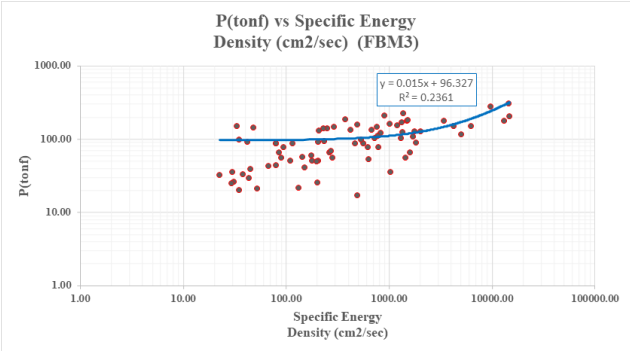


Figure A- 296:P(tonf) in FBM3 vs SED (cm²/sec)

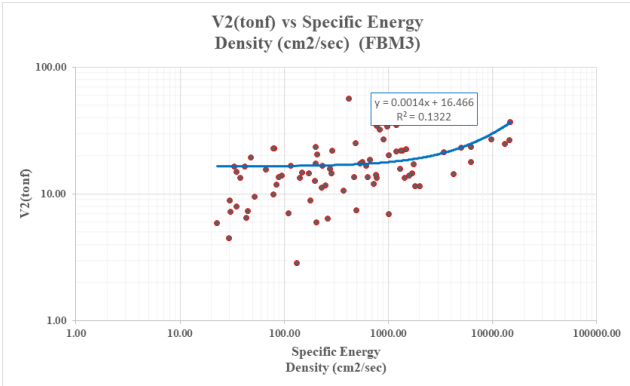


Figure A- 297:V2(tonf) in FBM3 vs SED (cm²/sec)

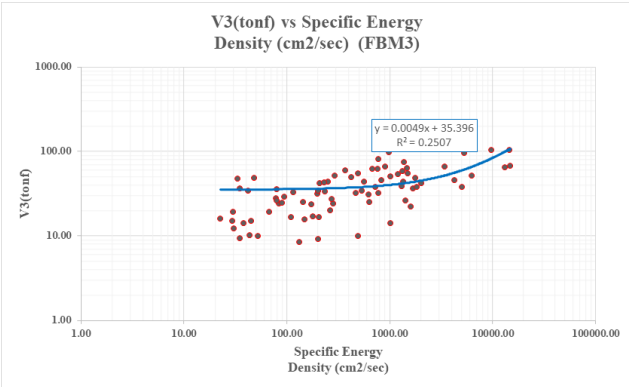


Figure A- 298:V3(tonf) in FBM3 vs SED (cm²/sec)

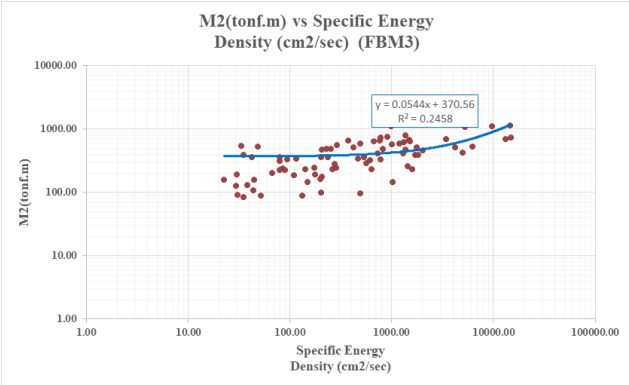


Figure A- 299:M2(tonf.m) in FBM3 vs SED (cm²/sec)

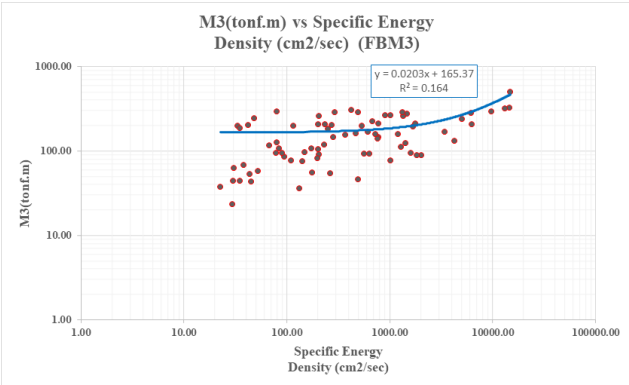


Figure A- 300:M3(tonf.m) in FBM3 vs SED (cm²/sec)

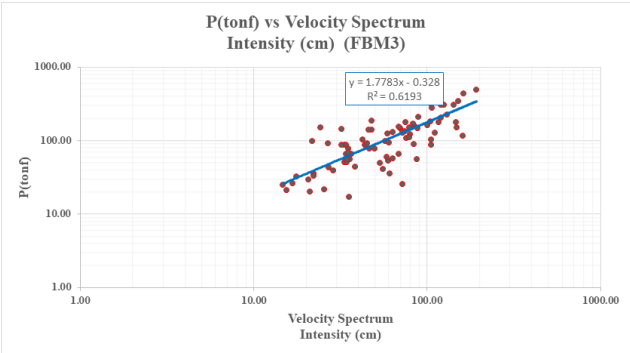


Figure A- 301:P(tonf) in FBM3 vs VSI (cm)

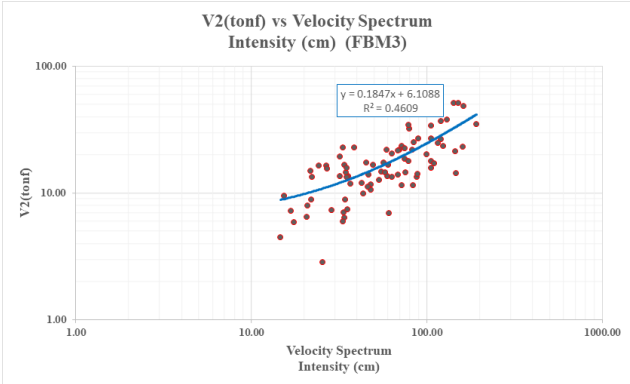


Figure A- 302:V2(tonf) in FBM3 vs VSI (cm)

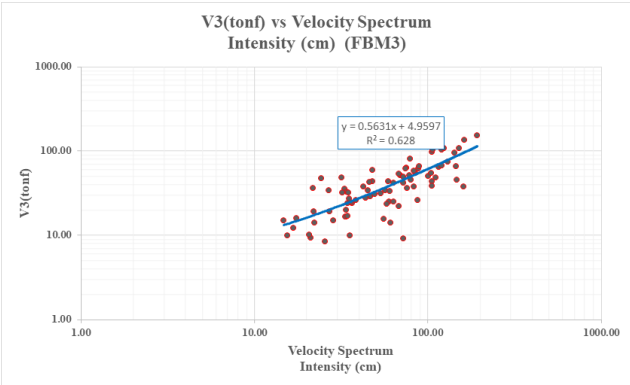


Figure A- 303:V3(tonf) in FBM3 vs VSI (cm)

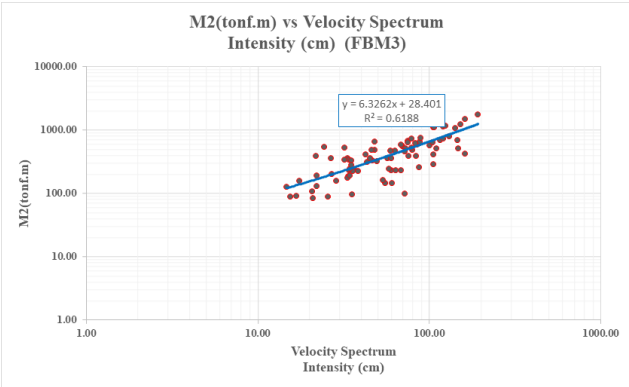


Figure A- 304:M2(tonf.m) in FBM3 vs VSI (cm)

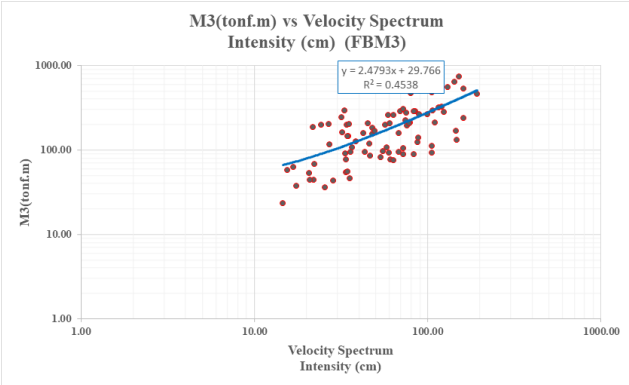


Figure A- 305:M3(tonf.m) in FBM3 vs VSI (cm)

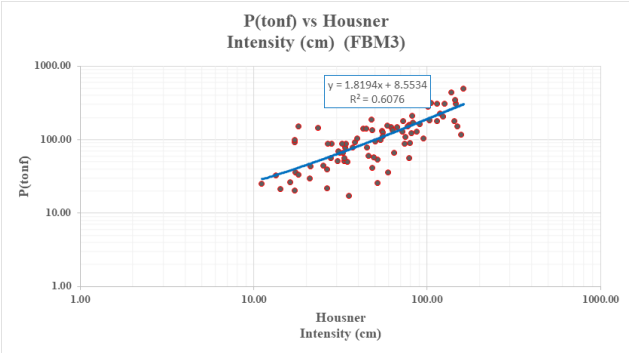


Figure A- 306:P(tonf) in FBM3 vs HI (cm)

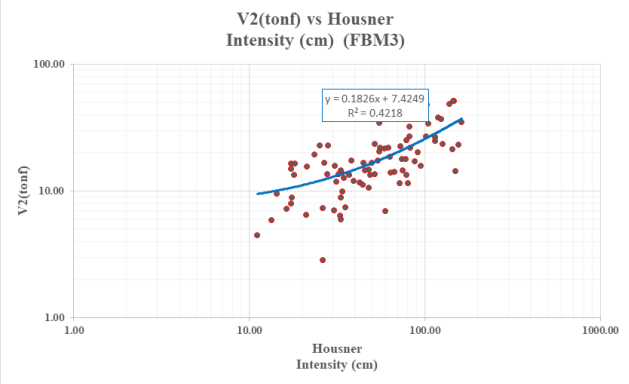


Figure A- 307:V2(tonf) in FBM3 vs HI (cm)

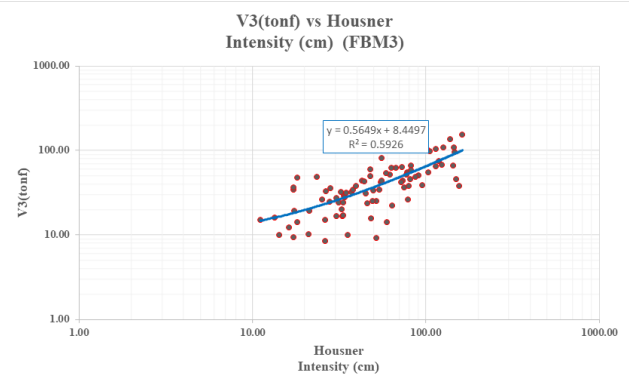


Figure A- 308:V3(tonf) in FBM3 vs HI (cm)

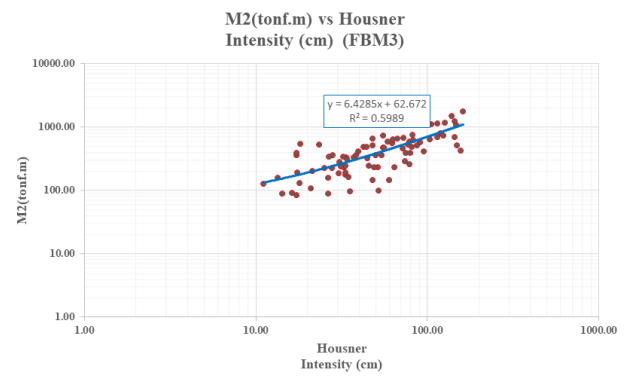


Figure A- 309:M2(tonf.m) in FBM3 vs HI (cm)

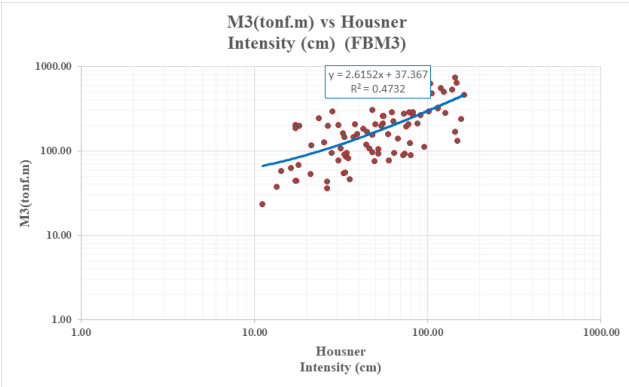


Figure A- 310:M3(tonf.m) in FBM3 vs HI (cm)

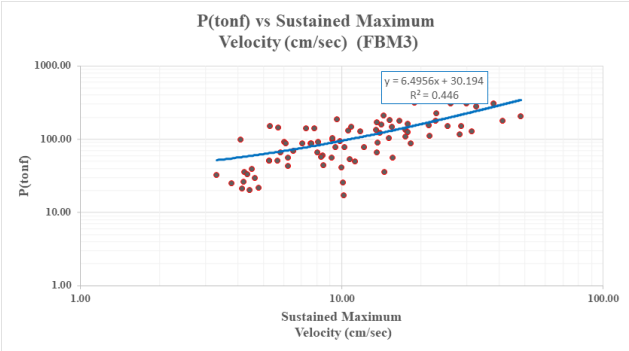


Figure A- 311:P(tonf) in FBM3 vs SMV (cm/sec)

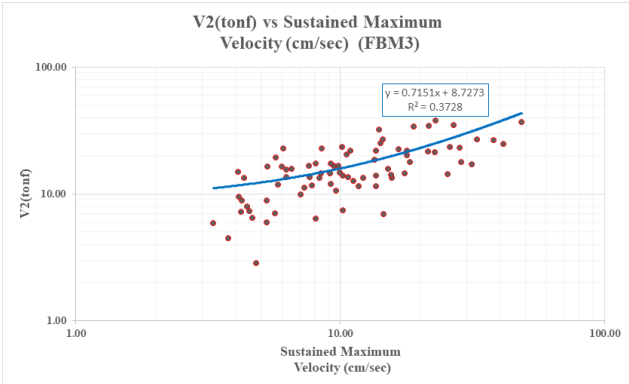


Figure A- 312:V2(tonf) in FBM3 vs SMV (cm/sec)

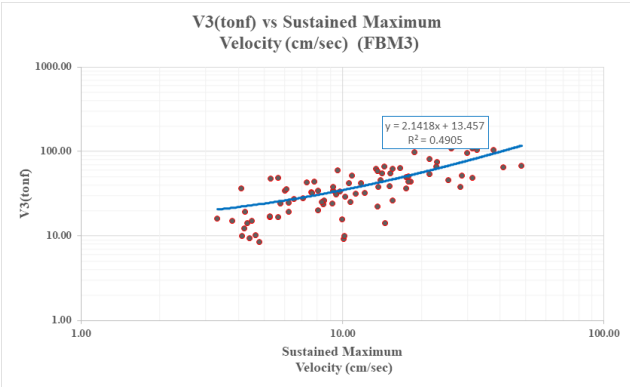


Figure A- 313:V3(tonf) in FBM3 vs SMV (cm/sec)

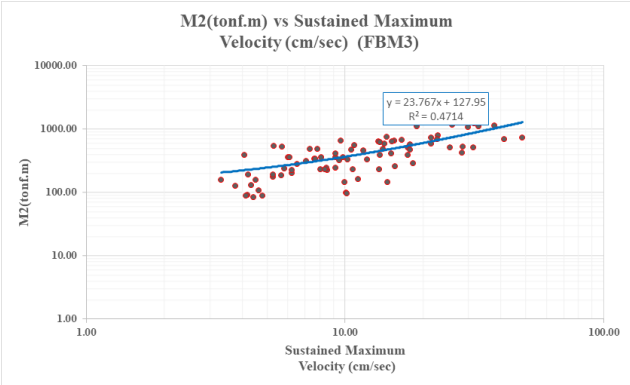


Figure A- 314:M2(tonf.m) in FBM3 vs SMV (cm/sec)

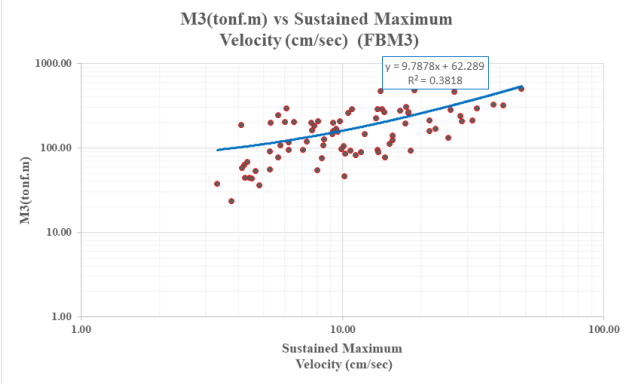


Figure A- 315:M3(tonf.m) in FBM3 vs SMV (cm/sec)

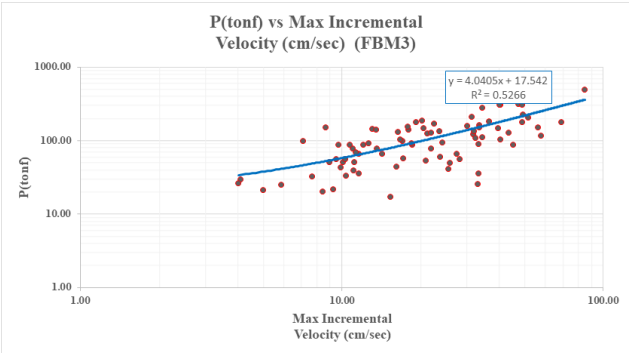


Figure A- 316:P(tonf) in FBM3 vs MIV (cm/sec)

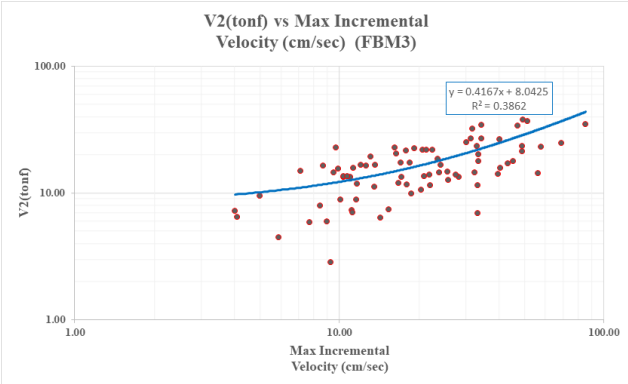


Figure A- 317:V2(tonf) in FBM3 vs MIV (cm/sec)

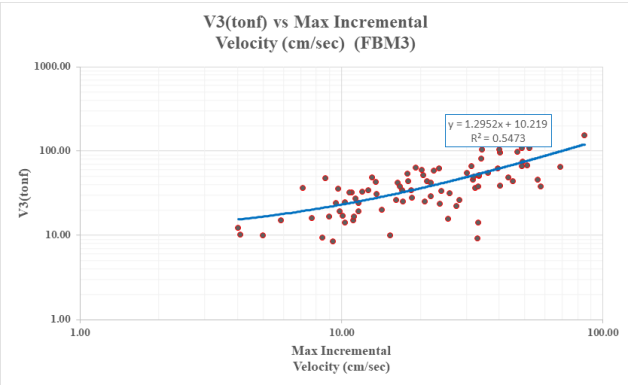


Figure A- 318:V3(tonf) in FBM3 vs MIV (cm/sec)

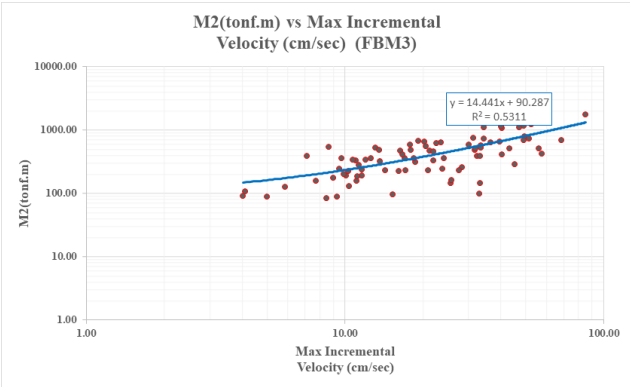


Figure A- 319:M2(tonf.m) in FBM3 vs MIV (cm/sec)

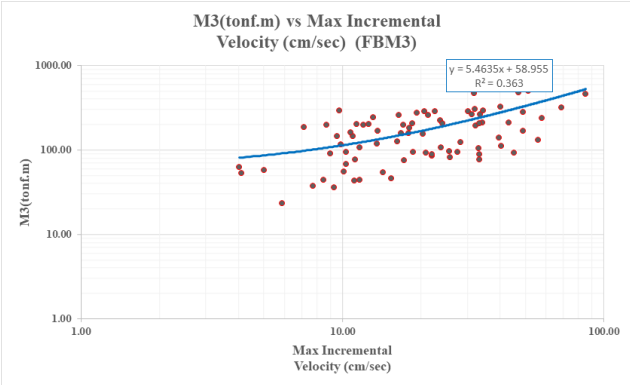


Figure A- 320:M3(tonf.m) in FBM3 vs MIV (cm/sec)

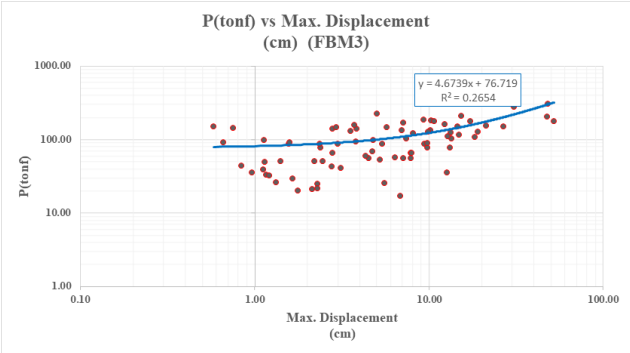


Figure A- 321:P(tonf) in FBM3 vs PGD (cm)

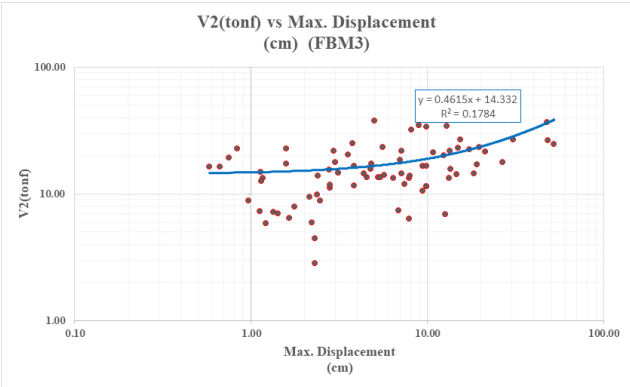


Figure A- 322:V2(tonf) in FBM3 vs PGD (cm)

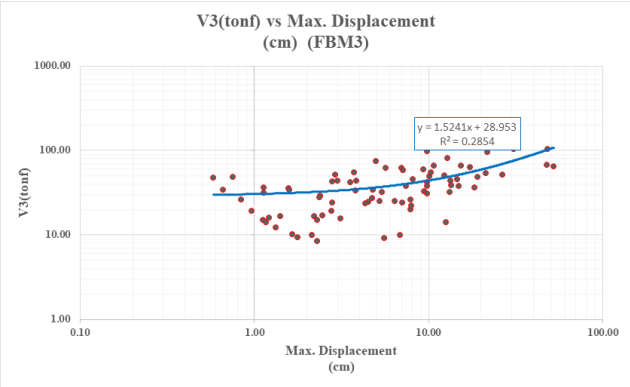


Figure A- 323:V3(tonf) in FBM3 vs PGD (cm)

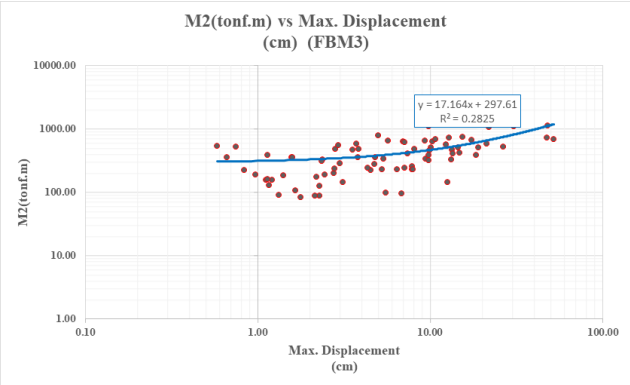


Figure A- 324:M2(tonf.m) in FBM3 vs PGD (cm)

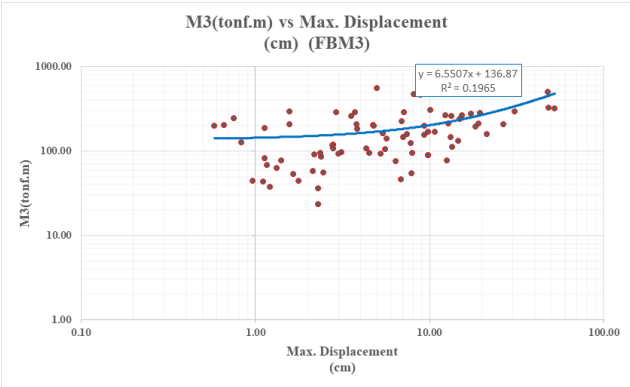


Figure A- 325:M3(tonf.m) in FBM3 vs PGD (cm)

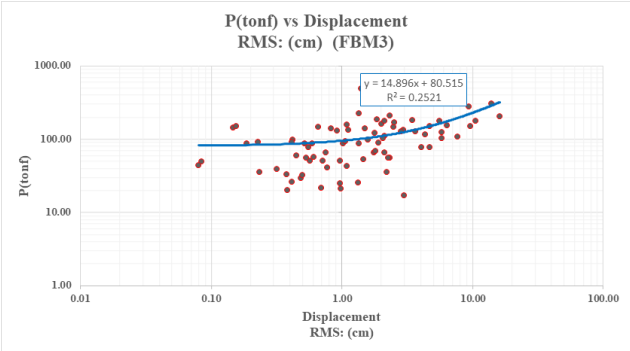


Figure A- 326:P(tonf) in FBM3 vs drms (cm)

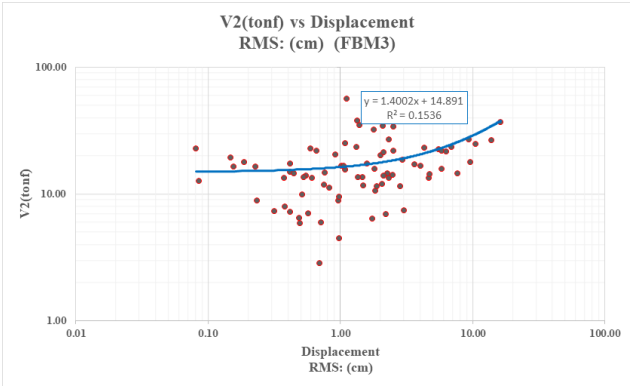


Figure A- 327:V2(tonf) in FBM3 vs drms (cm)

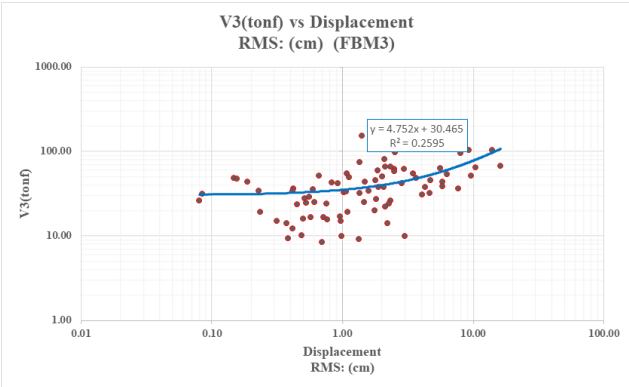


Figure A- 328:V3(tonf) in FBM3 vs drms (cm)

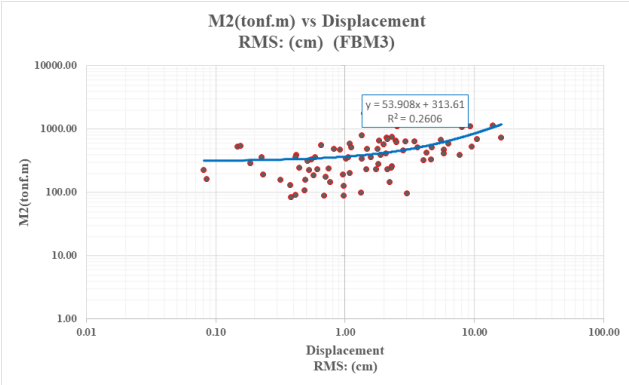


Figure A- 329:M2(tonf.m) in FBM3 vs drms (cm)

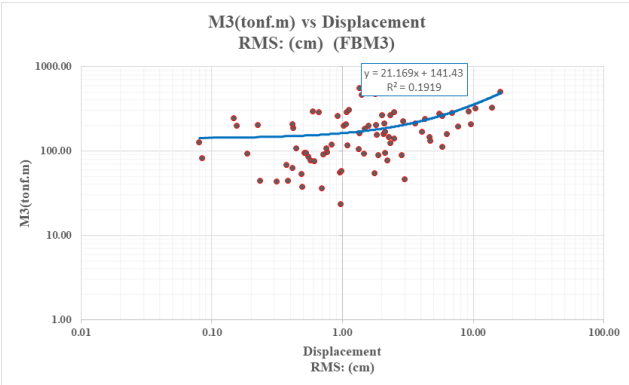


Figure A- 330:M3(tonf.m) in FBM3 vs drms (cm)

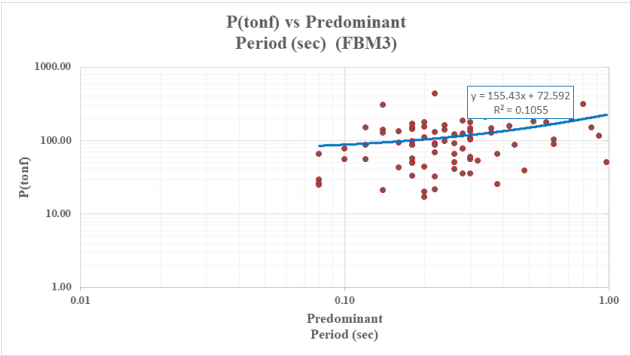


Figure A- 331:P(tonf) in FBM3 vs PP (sec)

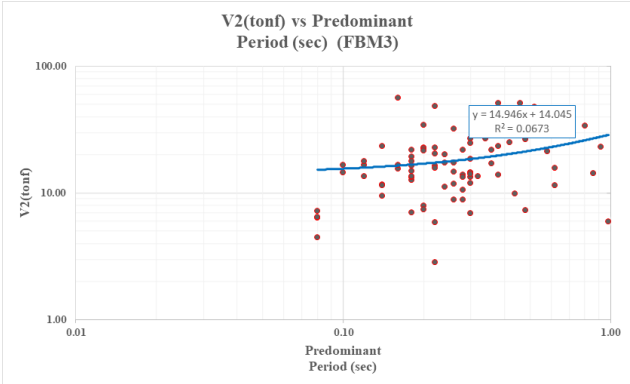


Figure A- 332:V2(tonf) in FBM3 vs PP (sec)

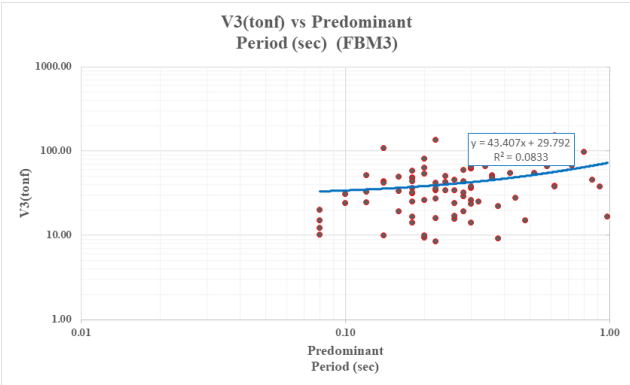


Figure A- 333:V3(tonf) in FBM3 vs PP (sec)

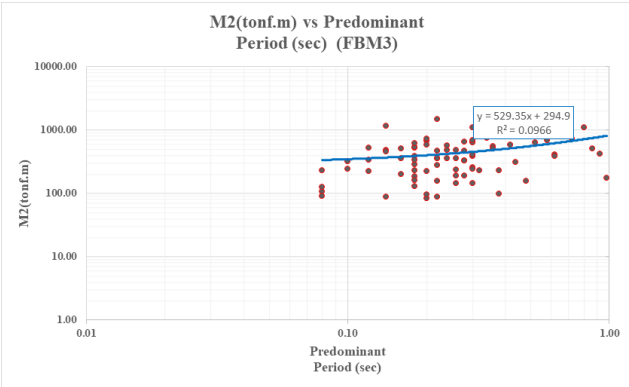


Figure A- 334:M2(tonf.m) in FBM3 vs PP (sec)

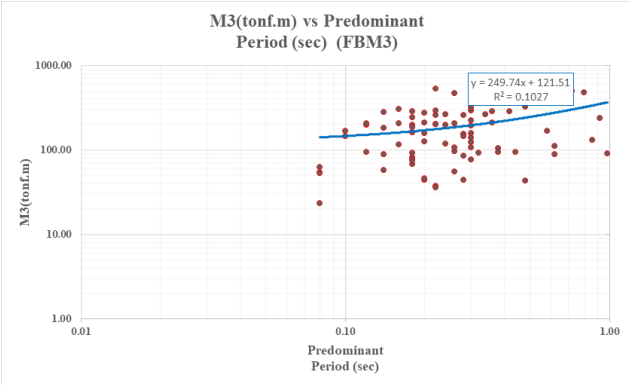


Figure A- 335:M3(tonf.m) in FBM3 vs PP (sec)

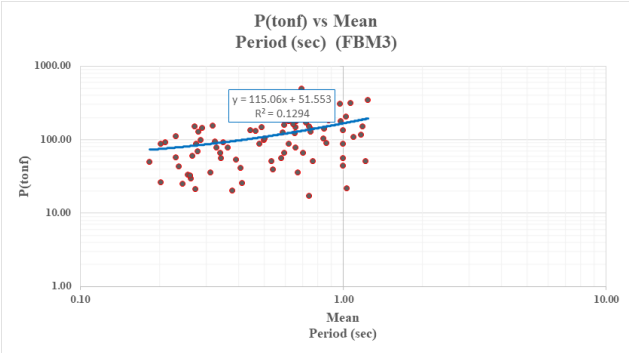


Figure A- 336:P(tonf) in FBM3 vs MP (sec)

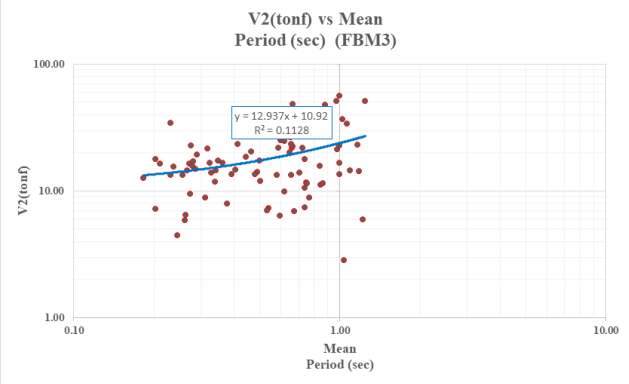


Figure A- 337:V2(tonf) in FBM3 vs MP (sec)

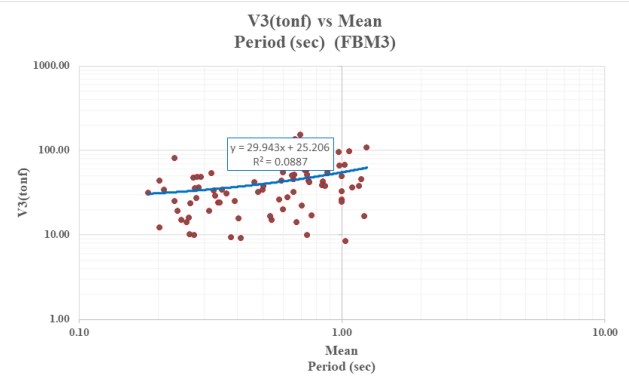


Figure A- 338:V3(tonf) in FBM3 vs MP (sec)

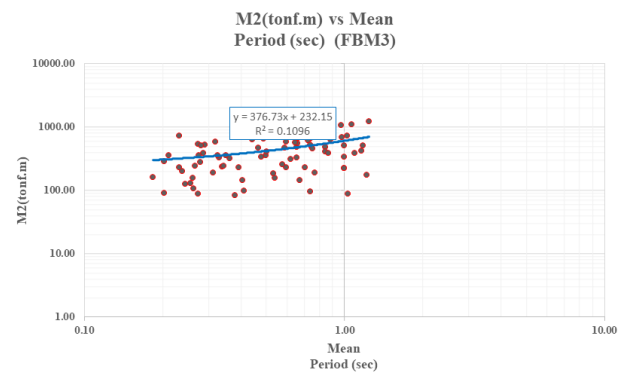


Figure A- 339:M2(tonf.m) in FBM3 vs MP (sec)

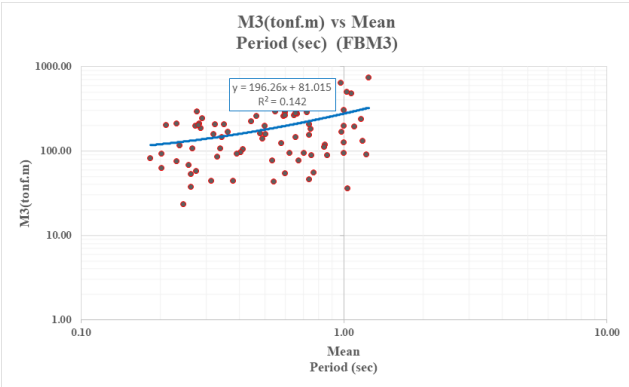


Figure A- 340:M3(tonf.m) in FBM3 vs MP (sec)

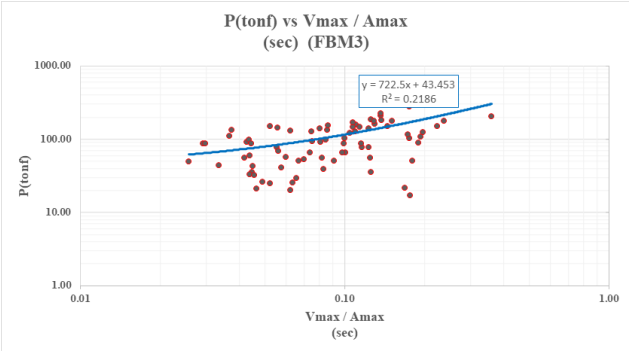


Figure A- 341:P(tonf) in FBM3 vs PGV/PGA(sec)

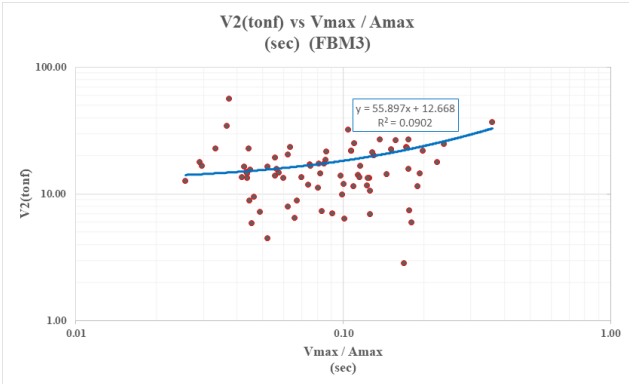


Figure A- 342:V2(tonf) in FBM3 vs PGV/PGA(sec)

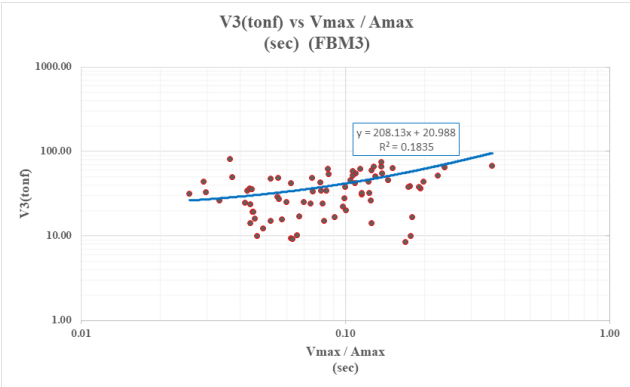


Figure A- 343:V3(tonf) in FBM3 vs PGV/PGA(sec)

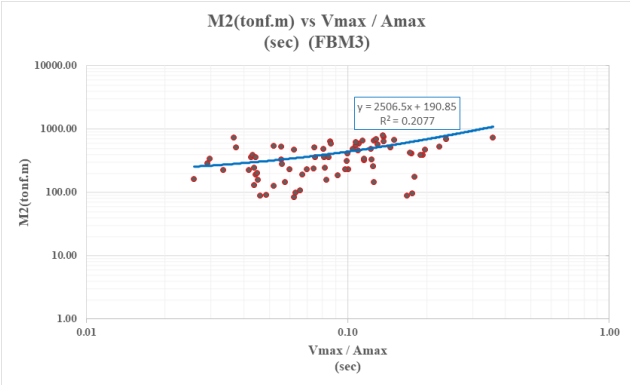


Figure A- 344:M2(tonf.m) in FBM3 vs PGV/PGA(sec)

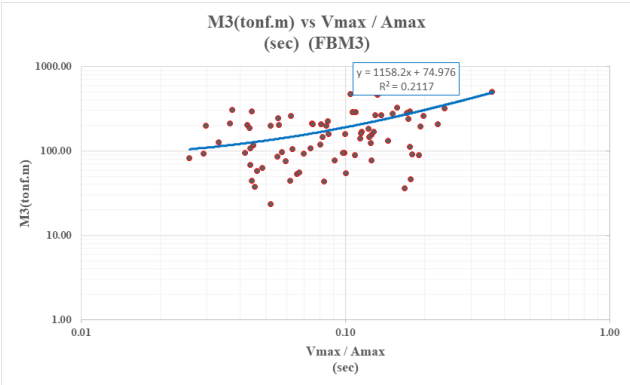


Figure A- 345:M3(tonf.m) in FBM3 vs PGV/PGA(sec)

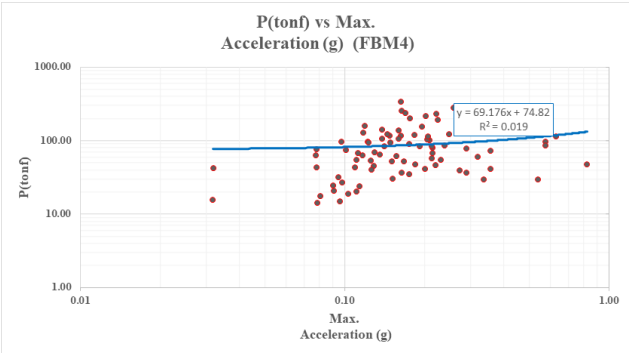


Figure A- 346:P(tonf) in FBM4 vs PGA(g)

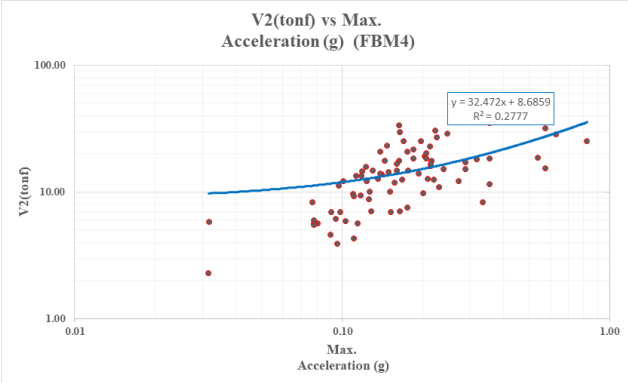


Figure A- 347:V2(tonf) in FBM4 vs PGA(g)

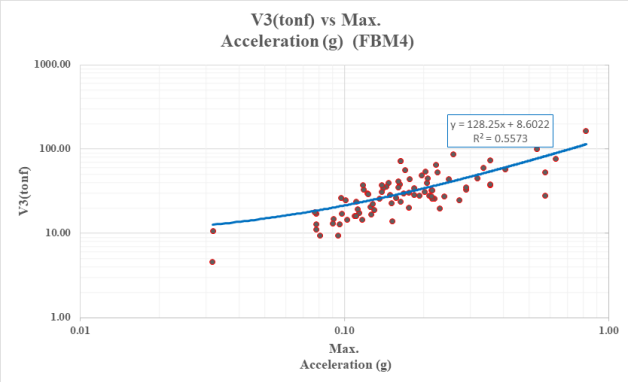


Figure A- 348:V3(tonf) in FBM4 vs PGA(g)

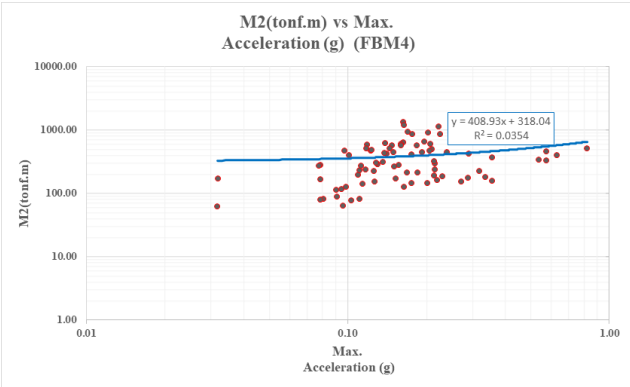


Figure A- 349:M2(tonf.m) in FBM4 vs PGA(g)

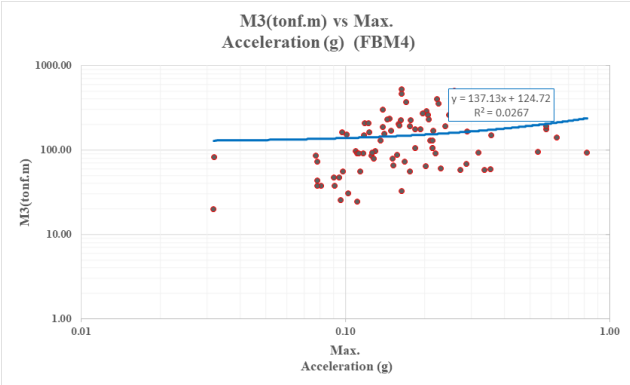


Figure A- 350:M3(tonf.m) in FBM4 vs PGA(g)

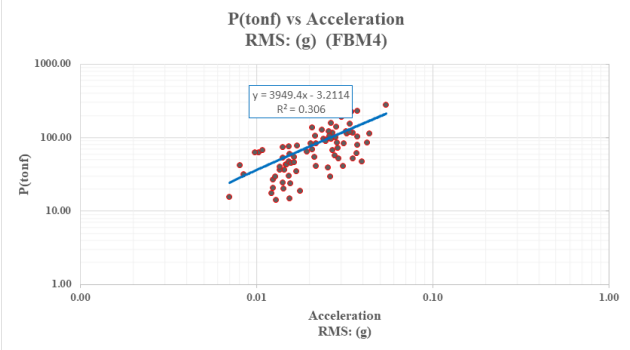


Figure A- 351:P(tonf) in FBM4 vs arms(g)

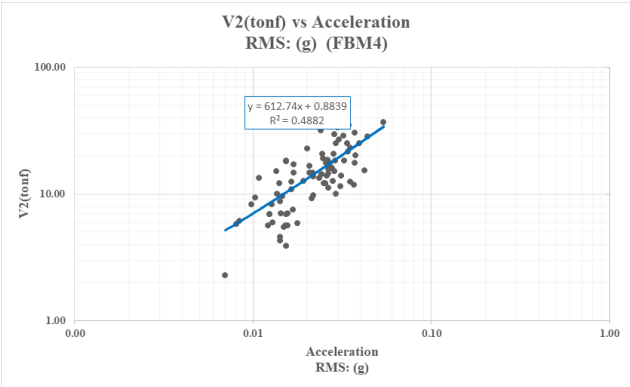


Figure A- 352:V2(tonf) in FBM4 vs arms(g)

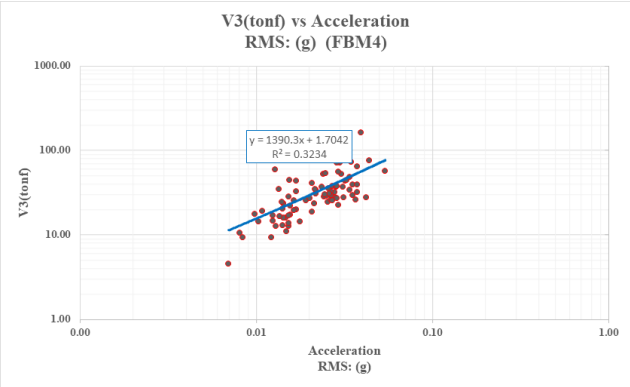


Figure A- 353:V3(tonf) in FBM4 vs arms(g)

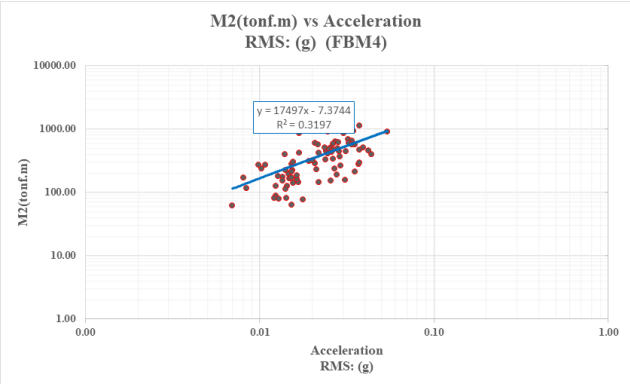


Figure A- 354:M2(tonf.m) in FBM4 vs arms(g)

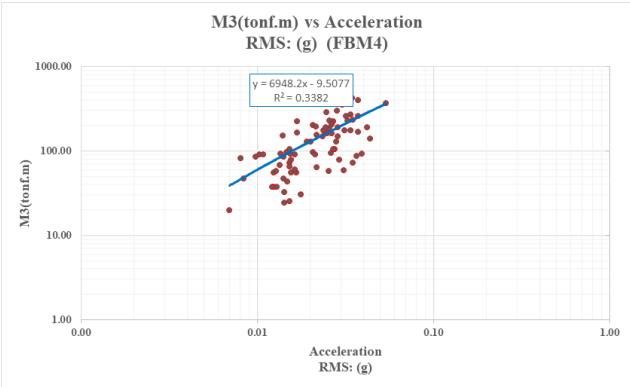


Figure A- 355:M3(tonf.m) in FBM4 vs arms(g)

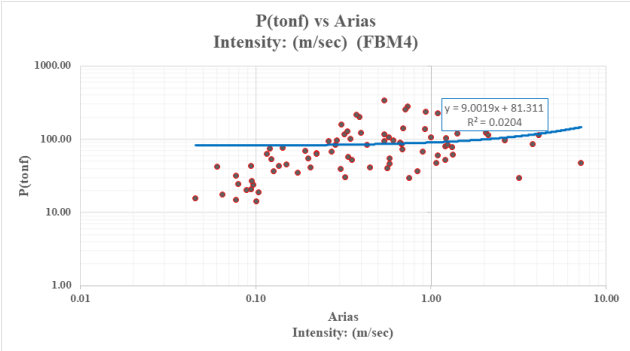


Figure A- 356:P(tonf) in FBM4 vs AI(m/sec)

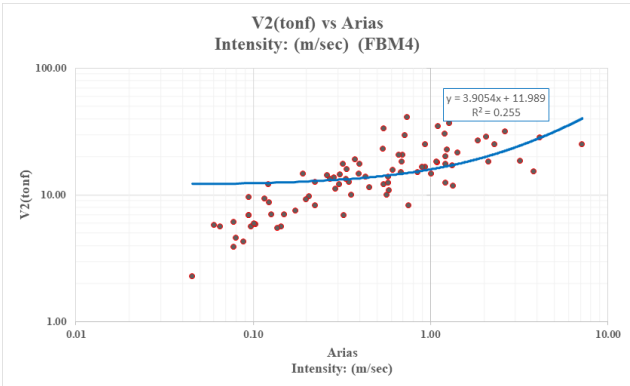


Figure A- 357:V2(tonf) in FBM4 vs AI(m/sec)

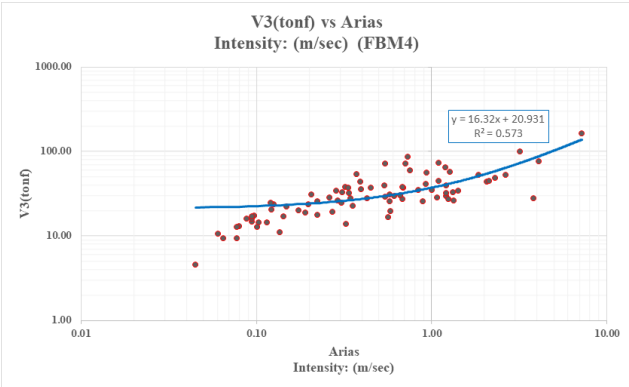


Figure A- 358:V3(tonf) in FBM4 vs AI(m/sec)

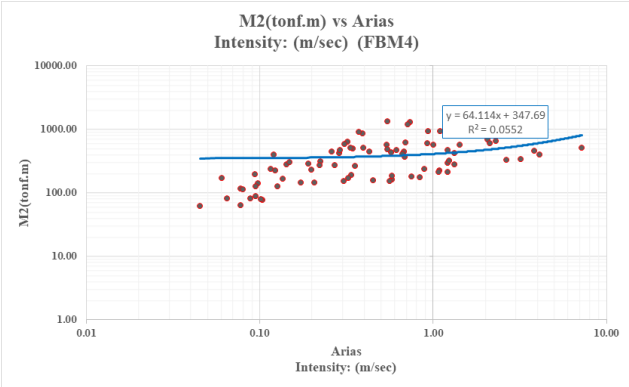


Figure A- 359:M2(tonf.m) in FBM4 vs AI(m/sec)

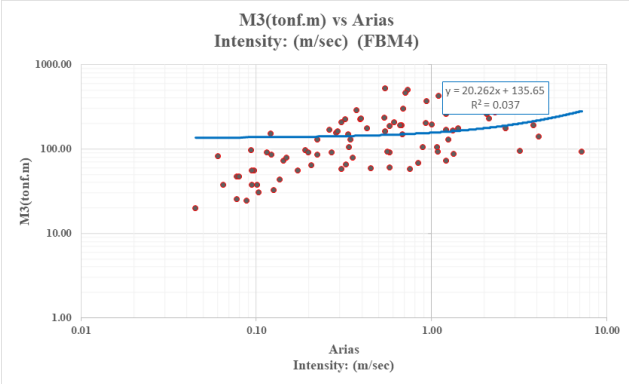


Figure A- 360:M3(tonf.m) in FBM4 vs AI(m/sec)

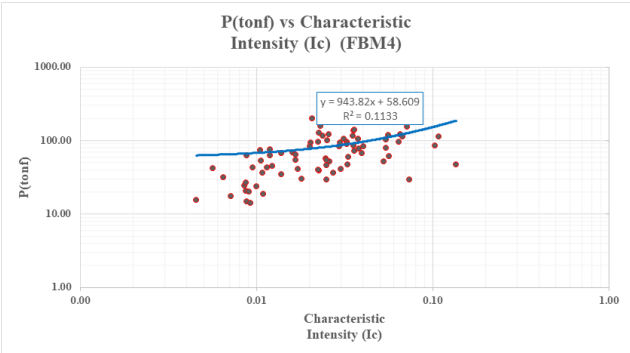


Figure A- 361:P(tonf) in FBM4 vs Ic

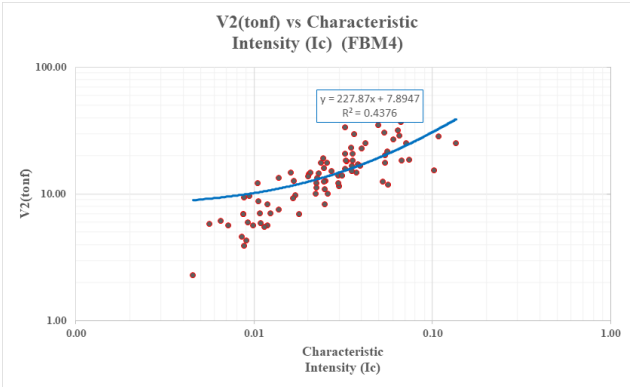


Figure A- 362:V2(tonf) in FBM4 vs Ic

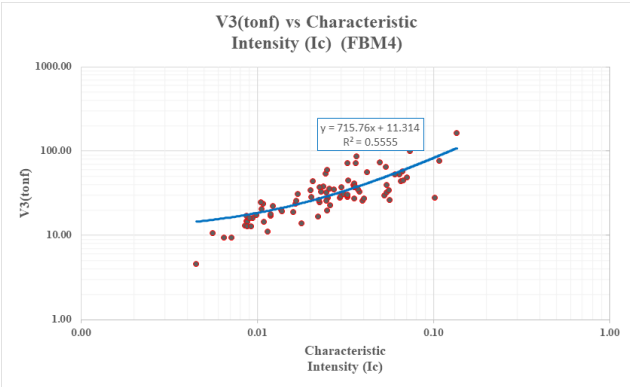


Figure A- 363:V3(tonf) in FBM4 vs Ic

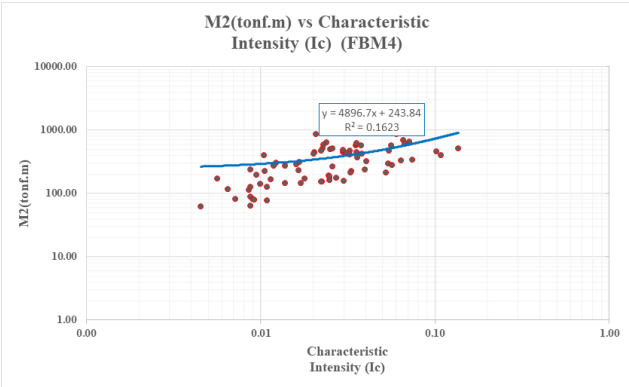


Figure A- 364:M2(tonf.m) in FBM4 vs Ic

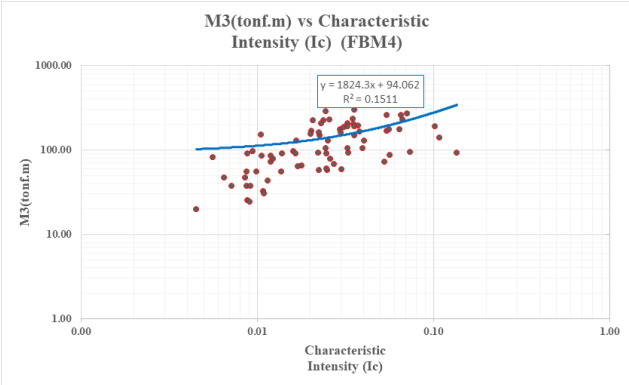


Figure A- 365:M3(tonf.m) in FBM4 vs Ic

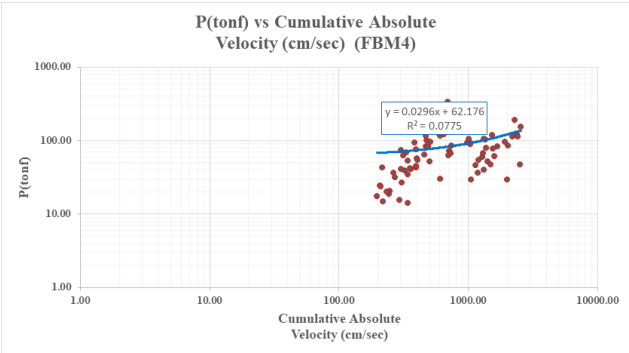


Figure A- 366:P(tonf) in FBM4 vs CAV (cm/sec)

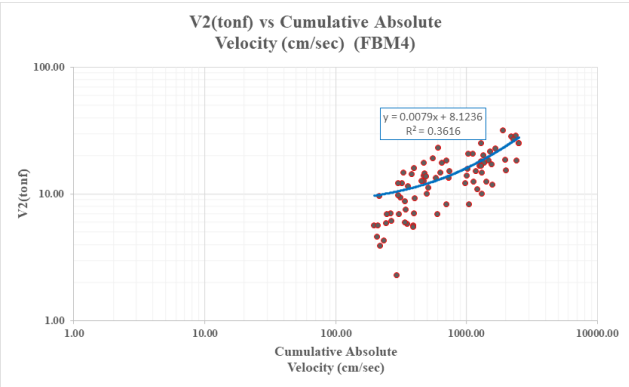


Figure A- 367:V2(tonf) in FBM4 vs CAV (cm/sec)

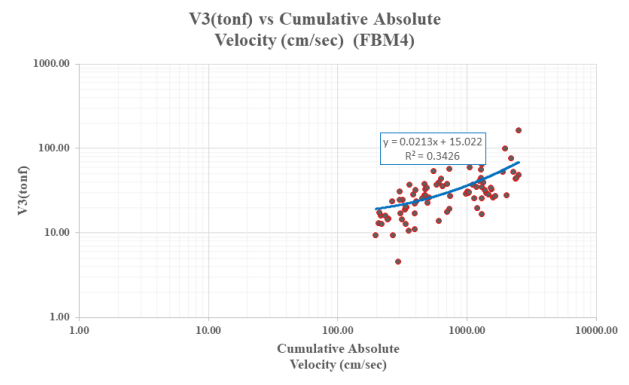


Figure A- 368:V3(tonf) in FBM4 vs CAV (cm/sec)

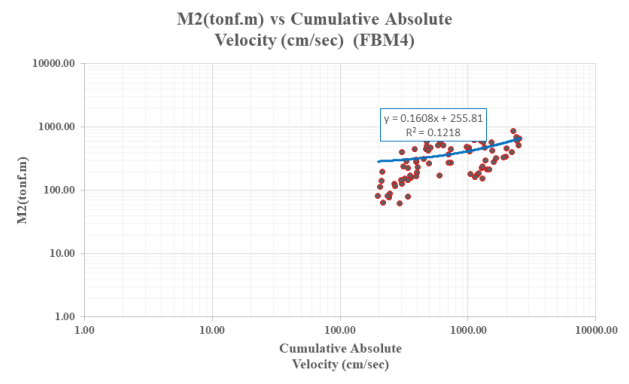


Figure A- 369:M2(tonf.m) in FBM4 vs CAV (cm/sec)

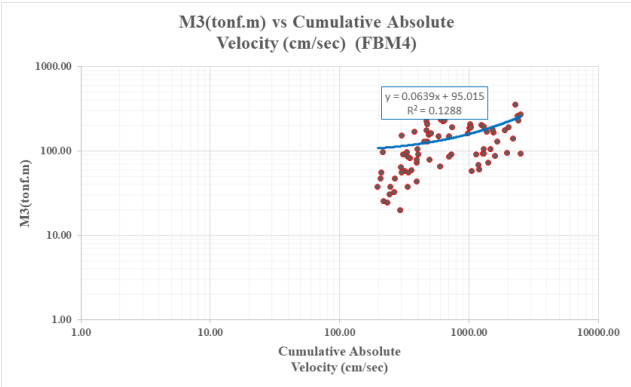


Figure A- 370:M3(tonf.m) in FBM4 vs CAV (cm/sec)

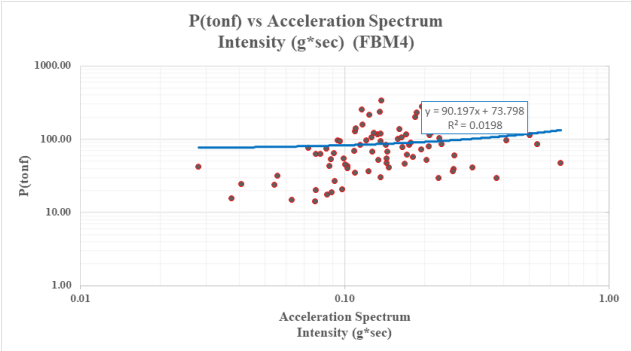


*Figure A- 371:P(tonf) in FBM4 vs ASI (g*sec)*

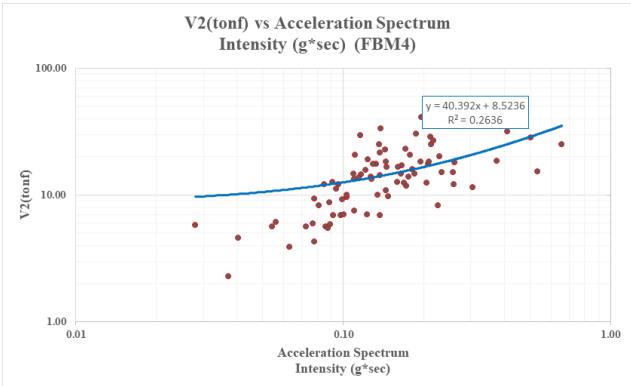


*Figure A- 372:V2(tonf) in FBM4 vs ASI (g*sec)*

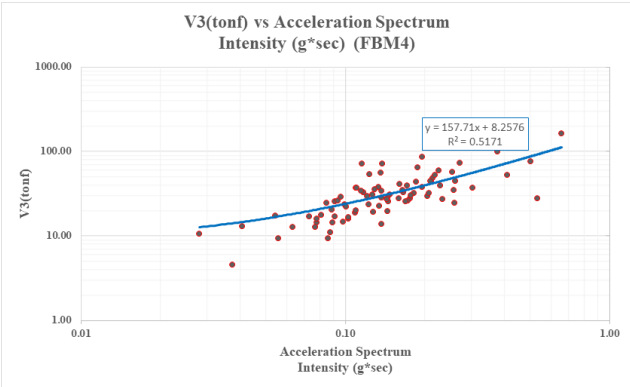


*Figure A- 373:V3(tonf) in FBM4 vs ASI (g*sec)*

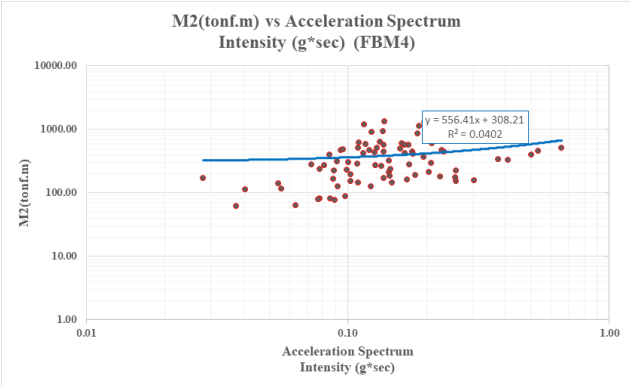


*Figure A- 374:M2(tonf.m) in FBM4 vs ASI (g*sec)*

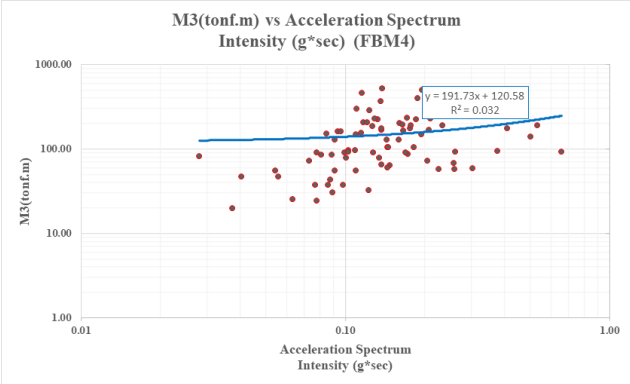


*Figure A- 375:M3(tonf.m) in FBM4 vs ASI (g*sec)*

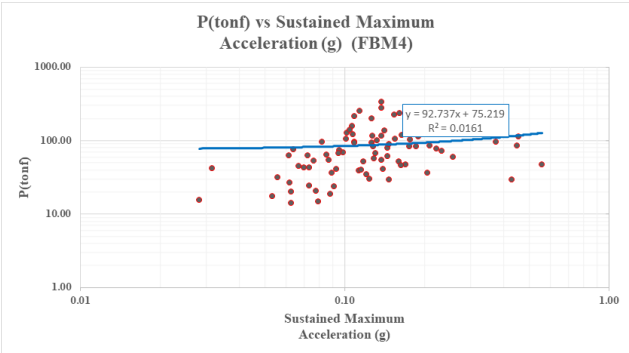


Figure A- 376:P(tonf) in FBM4 vs SMA (g)

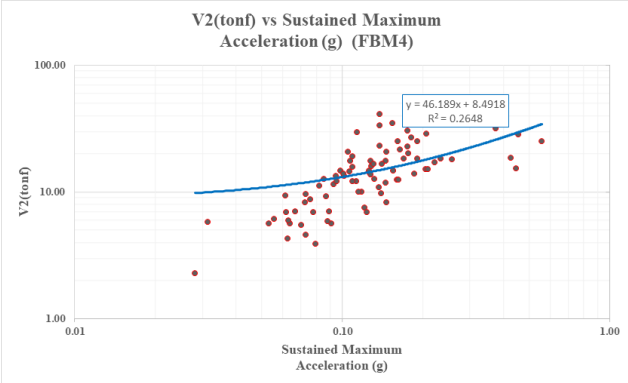


Figure A- 377:V2(tonf) in FBM4 vs SMA (g)

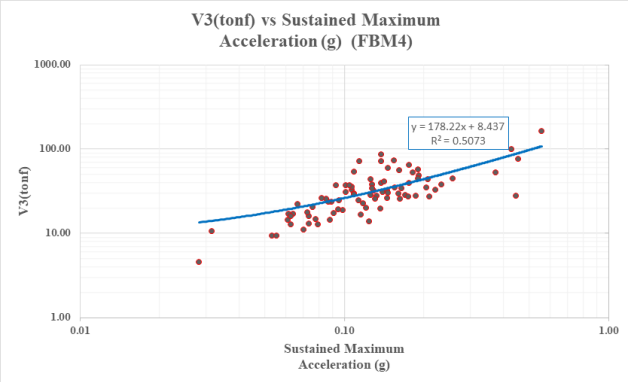


Figure A- 378:V3(tonf) in FBM4 vs SMA (g)

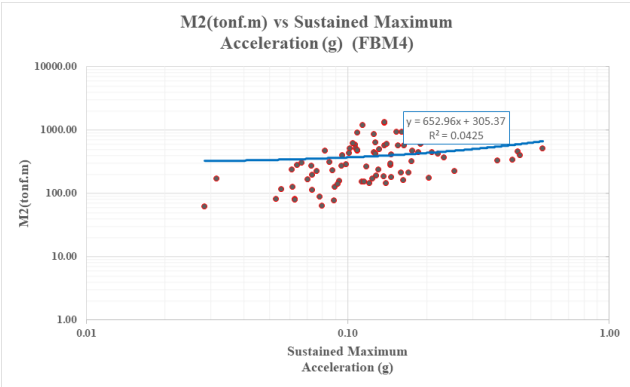


Figure A- 379:M2(tonf.m) in FBM4 vs SMA (g)

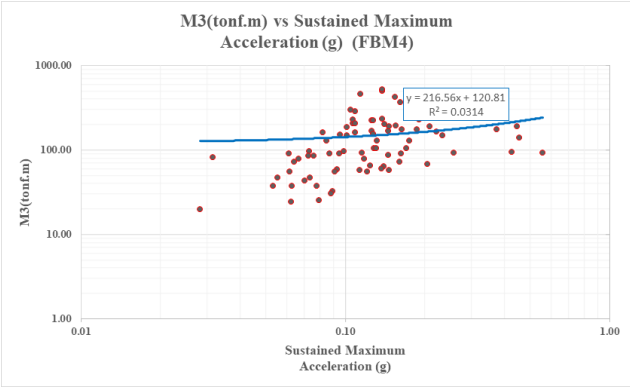


Figure A- 380:M3(tonf.m) in FBM4 vs SMA (g)

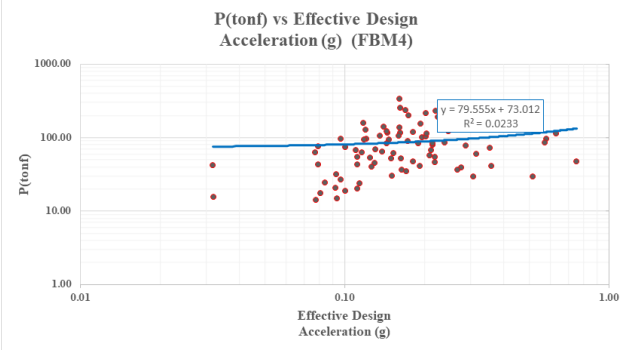


Figure A- 381:P(tonf) in FBM4 vs EDA (g)

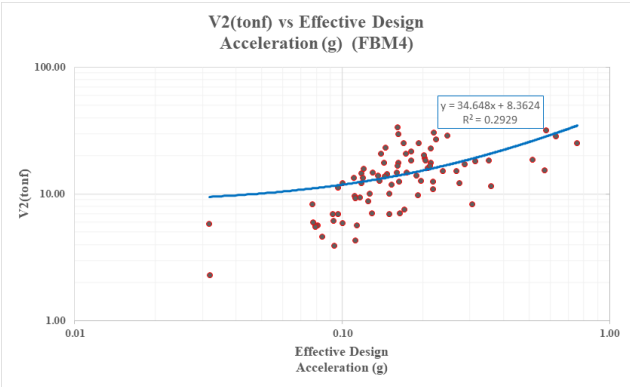


Figure A- 382:V2(tonf) in FBM4 vs EDA (g)

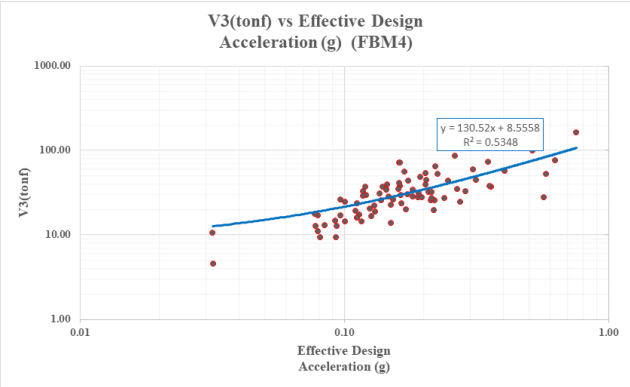


Figure A- 383:V3(tonf) in FBM4 vs EDA (g)

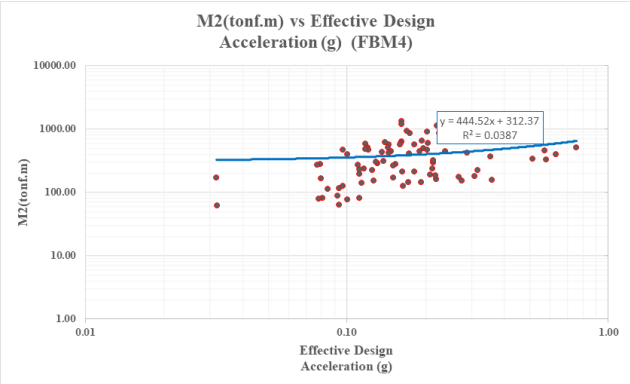


Figure A- 384:M2(tonf.m) in FBM4 vs EDA (g)

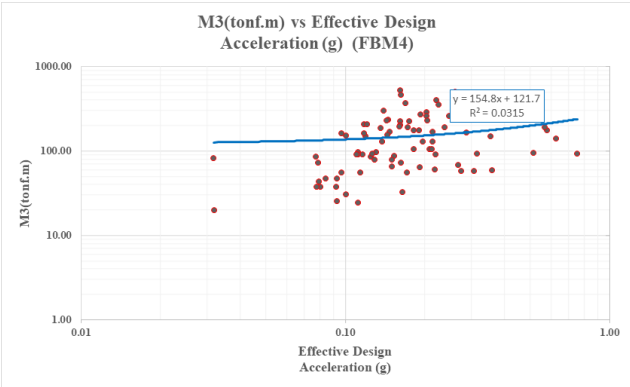


Figure A- 385:M3(tonf.m) in FBM4 vs EDA (g)

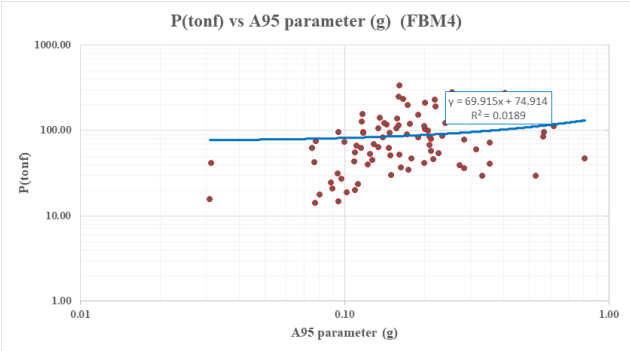


Figure A- 386:P(tonf) in FBM4 vs a95 (g)

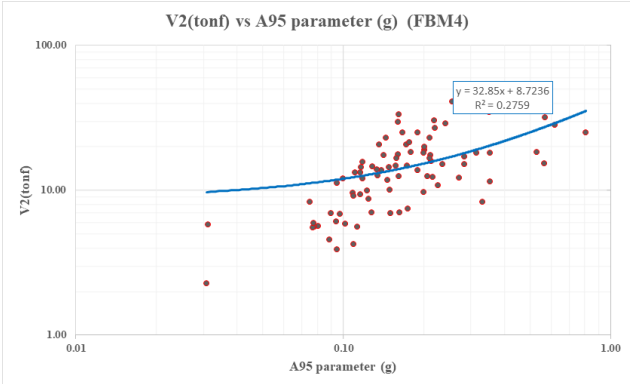


Figure A- 387:V2(tonf) in FBM4 vs a95 (g)

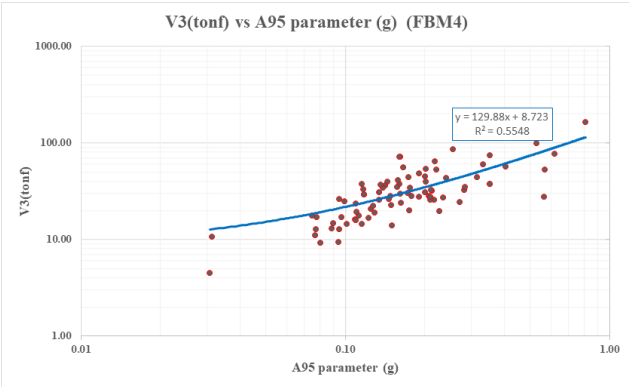


Figure A- 388:V3(tonf) in FBM4 vs a95 (g)

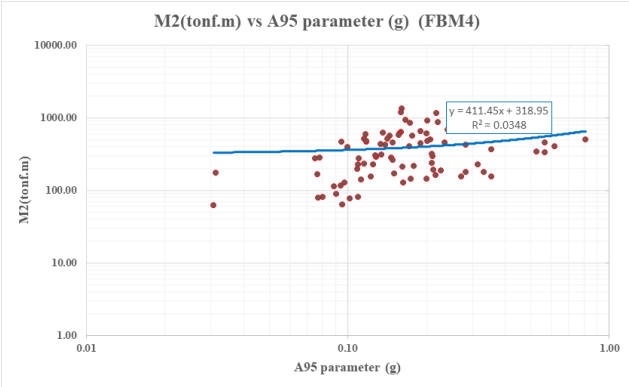


Figure A- 389:M2(tonf.m) in FBM4 vs a95 (g)

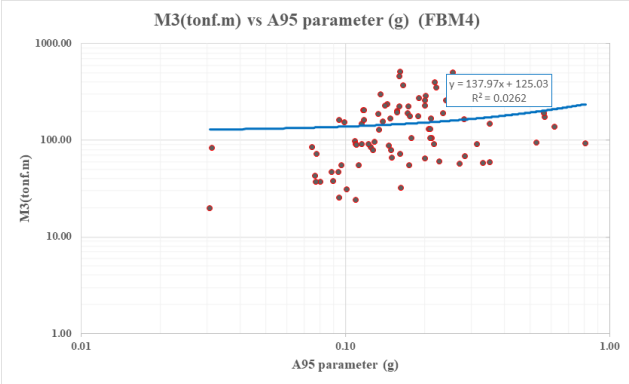


Figure A- 390:M3(tonf.m) in FBM4 vs a95 (g)

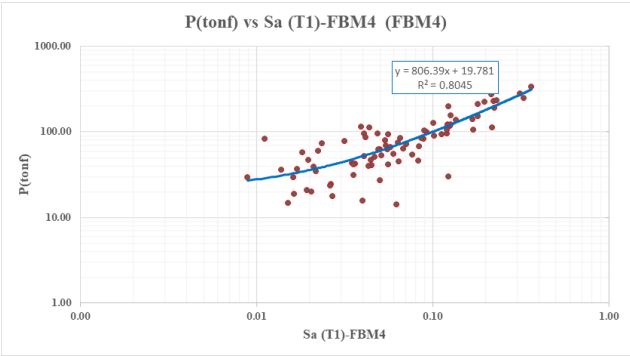


Figure A- 391:P(tonf) in FBM4 vs Sa (T1) (g)

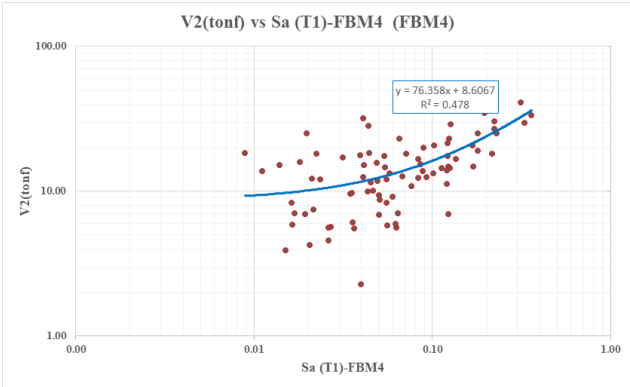


Figure A- 392:V2(tonf) in FBM4 vs Sa (T1) (g)

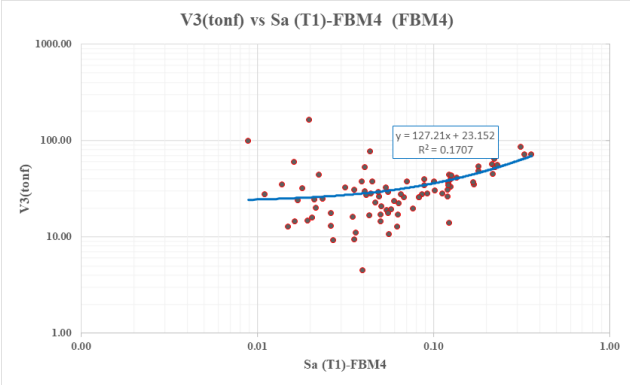


Figure A- 393:V3(tonf) in FBM4 vs Sa (T1) (g)

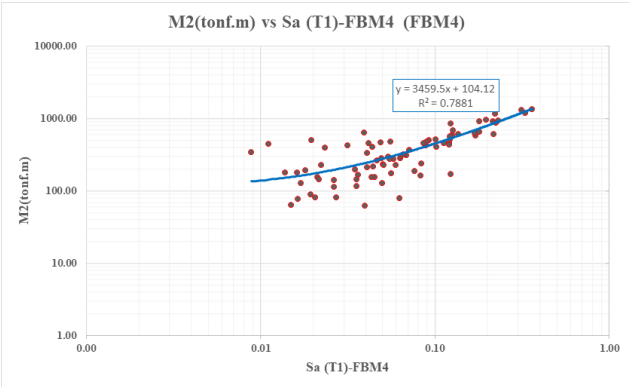


Figure A- 394:M2(tonf.m) in FBM4 vs Sa (T1) (g)

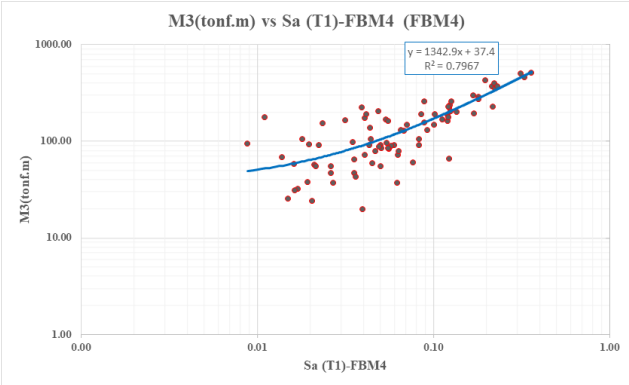


Figure A- 395:M3(tonf.m) in FBM4 vs Sa (T1) (g)

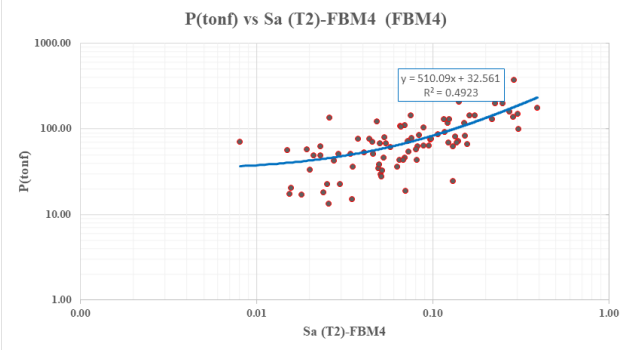


Figure A- 396:P(tonf) in FBM4 vs Sa (T2) (g)

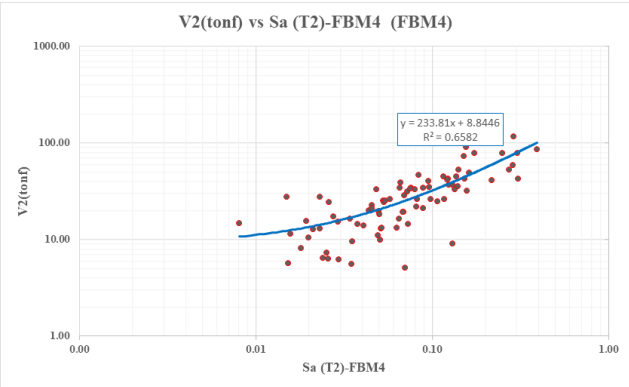


Figure A- 397:V2(tonf) in FBM4 vs Sa (T2) (g)

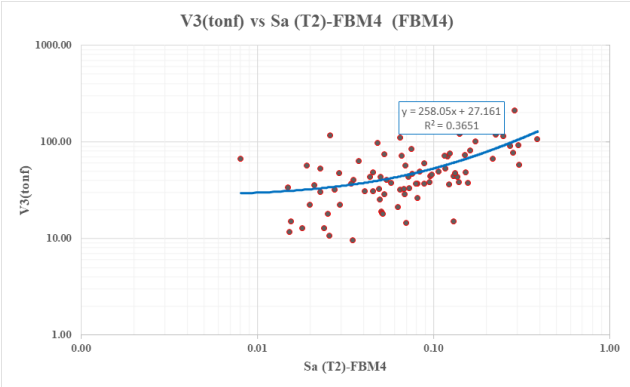


Figure A- 398:V3(tonf) in FBM4 vs Sa (T2) (g)

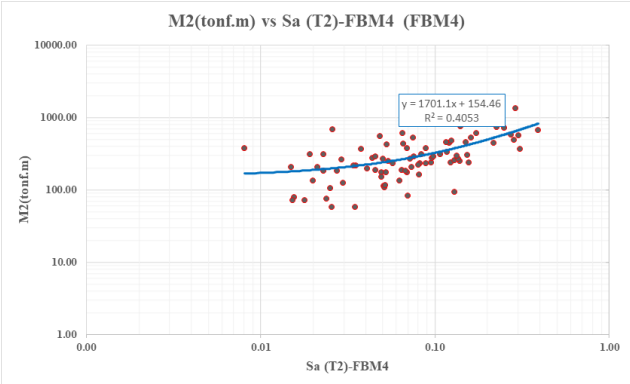


Figure A- 399:M2(tonf.m) in FBM4 vs Sa (T2) (g)

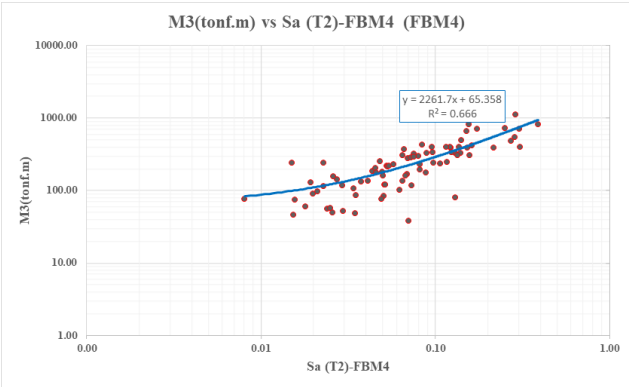


Figure A- 400:M3(tonf.m) in FBM4 vs Sa (T2) (g)

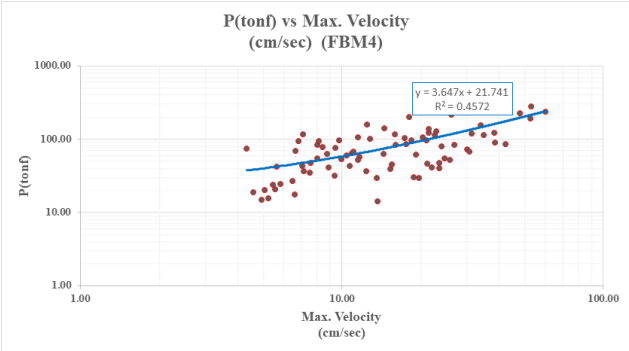


Figure A- 401:P(tonf) in FBM4 vs PGV (cm/sec)

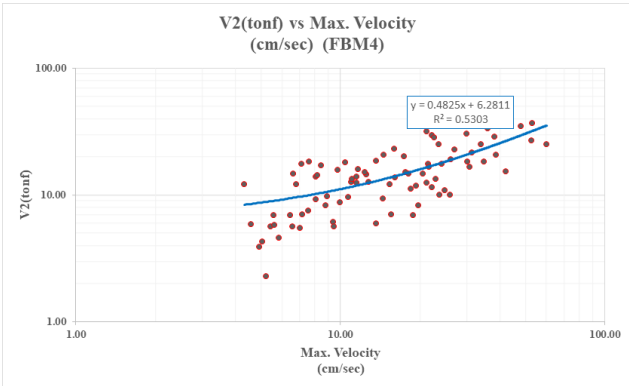


Figure A- 402:V2(tonf) in FBM4 vs PGV (cm/sec)

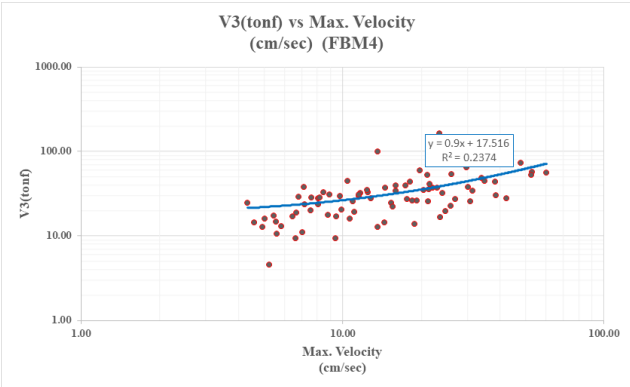


Figure A- 403:V3(tonf) in FBM4 vs PGV (cm/sec)

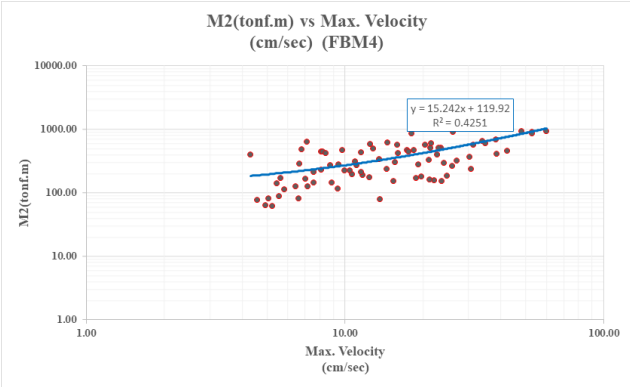


Figure A- 404:M2(tonf.m) in FBM4 vs PGV (cm/sec)

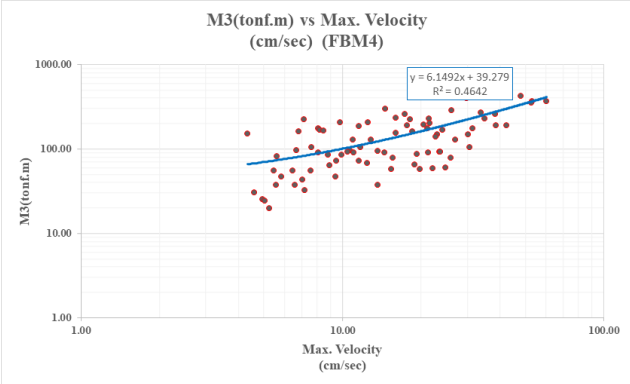


Figure A- 405:M3(tonf.m) in FBM4 vs PGV (cm/sec)

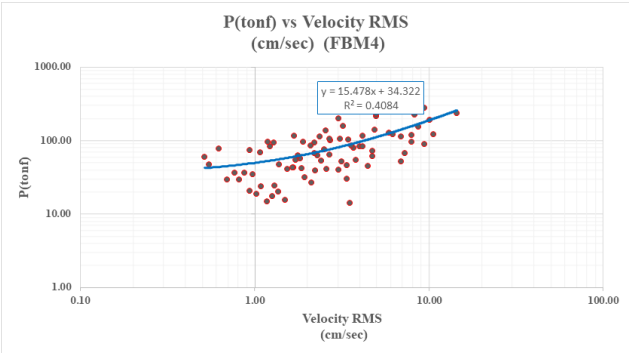


Figure A- 406:P(tonf) in FBM4 vs vrms (cm/sec)

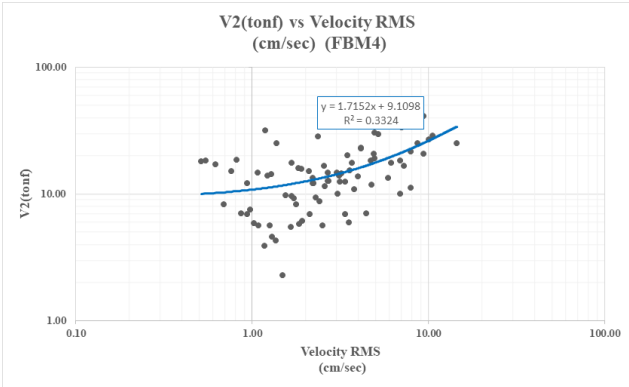


Figure A- 407:V2(tonf) in FBM4 vs vrms (cm/sec)

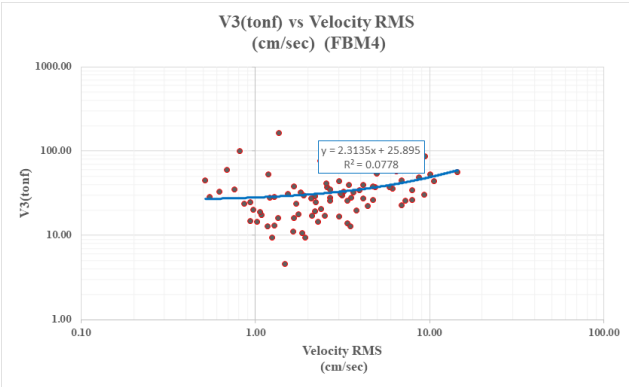


Figure A- 408:V3(tonf) in FBM4 vs vrms (cm/sec)

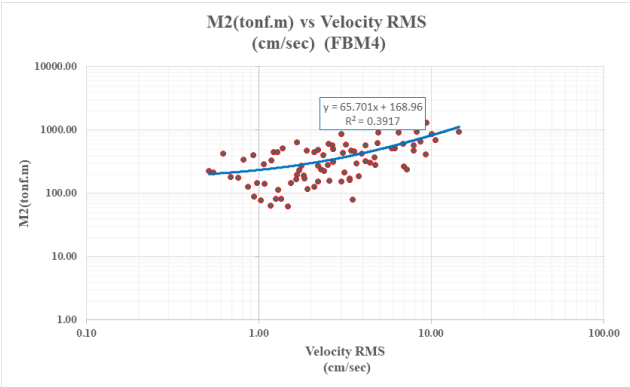


Figure A- 409:M2(tonf.m) in FBM4 vs vrms (cm/sec)

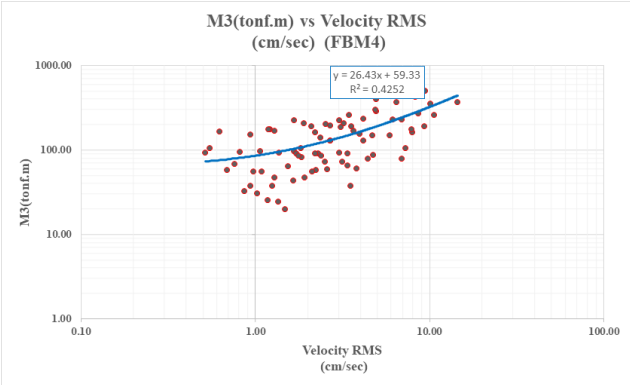


Figure A- 410:M3(tonf.m) in FBM4 vs vrms (cm/sec)

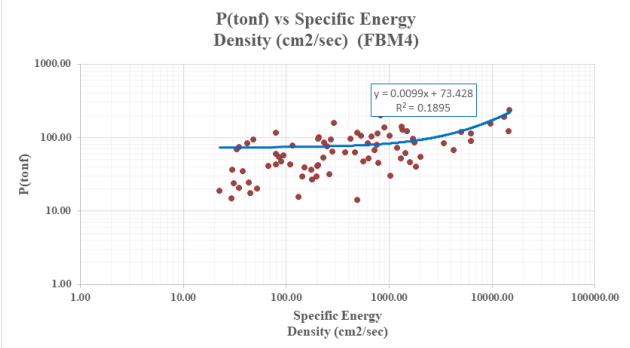


Figure A- 411:P(tonf) in FBM4 vs SED (cm²/sec)

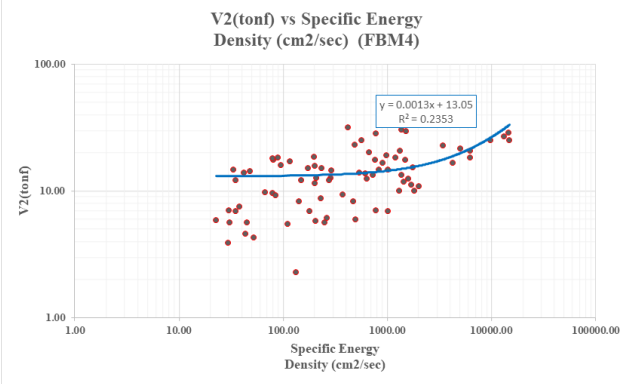


Figure A- 412:V2(tonf) in FBM4 vs SED (cm²/sec)

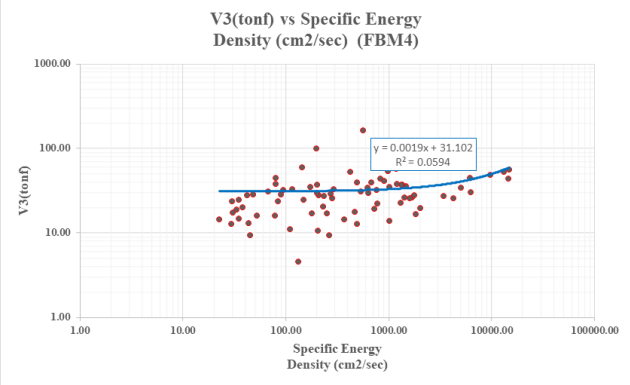


Figure A- 413:V3(tonf) in FBM4 vs SED (cm²/sec)

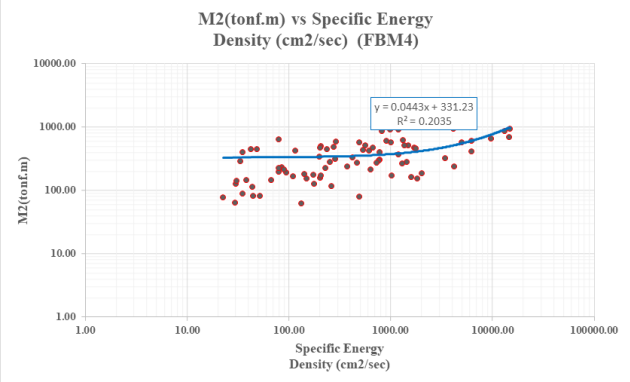


Figure A- 414:M2(tonf.m) in FBM4 vs SED (cm²/sec)

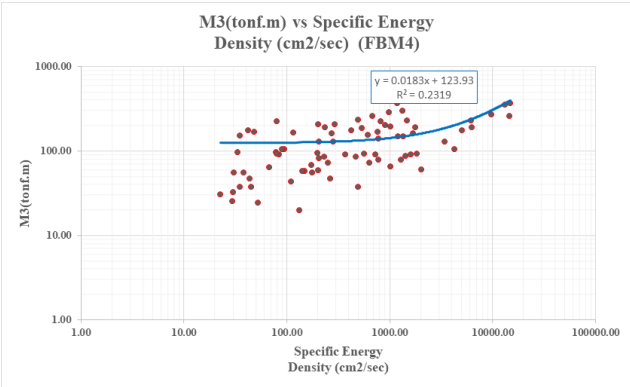


Figure A- 415:M3(tonf.m) in FBM4 vs SED (cm²/sec)

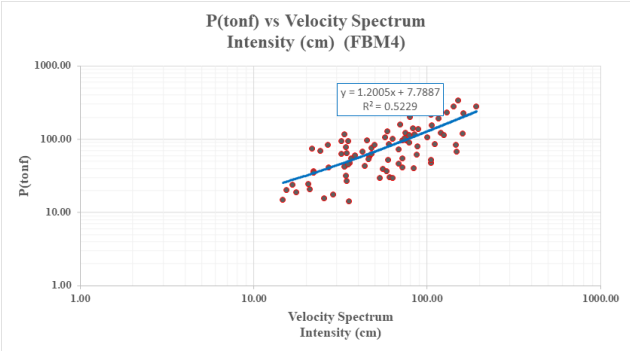


Figure A- 416:P(tonf) in FBM4 vs VSI (cm)

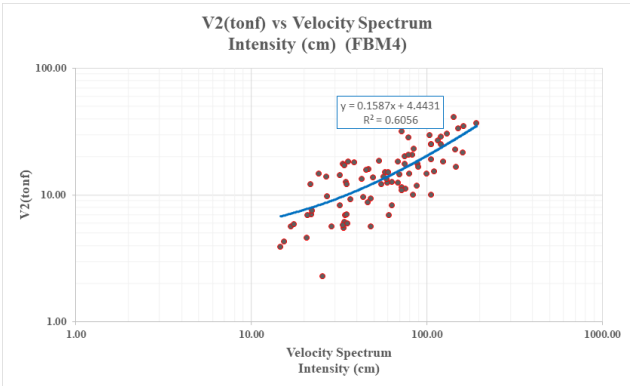


Figure A- 417:V2(tonf) in FBM4 vs VSI (cm)

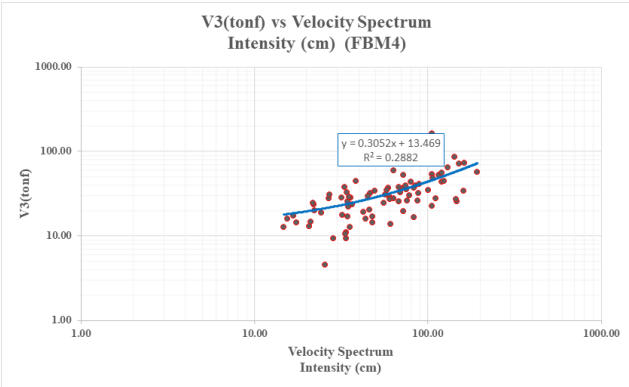


Figure A- 418:V3(tonf) in FBM4 vs VSI (cm)

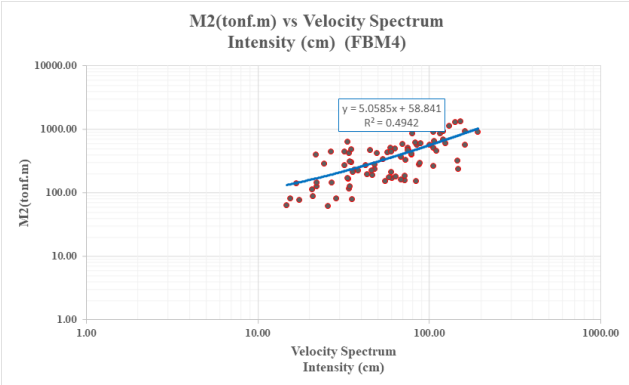


Figure A- 419:M2(tonf.m) in FBM4 vs VSI (cm)

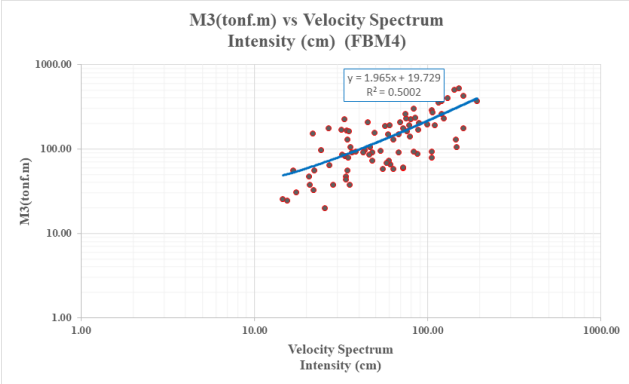


Figure A- 420:M3(tonf.m) in FBM4 vs VSI (cm)

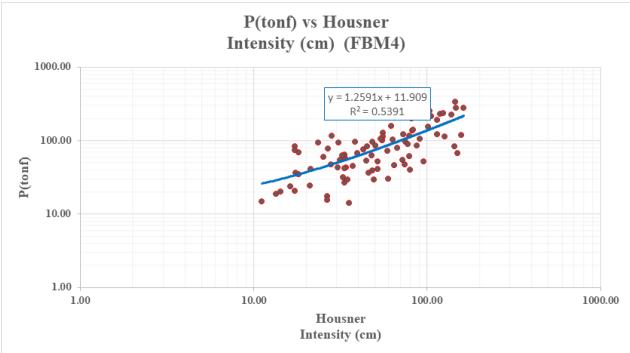


Figure A- 421:P(tonf) in FBM4 vs HI (cm)

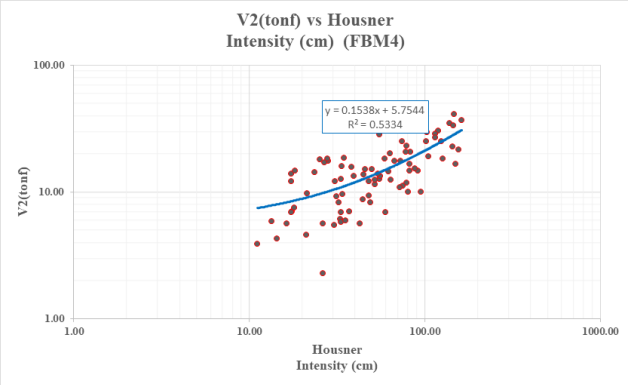


Figure A- 422:V2(tonf) in FBM4 vs HI (cm)

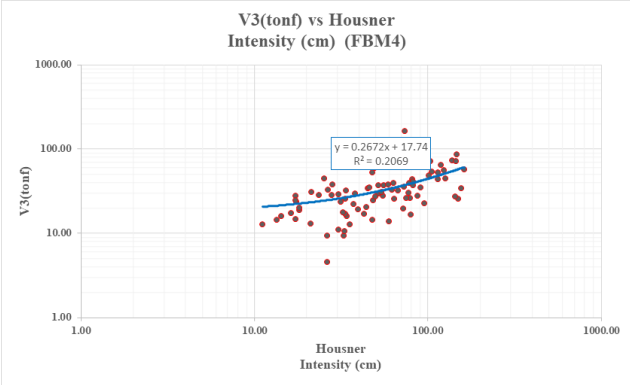


Figure A- 423:V3(tonf) in FBM4 vs HI (cm)

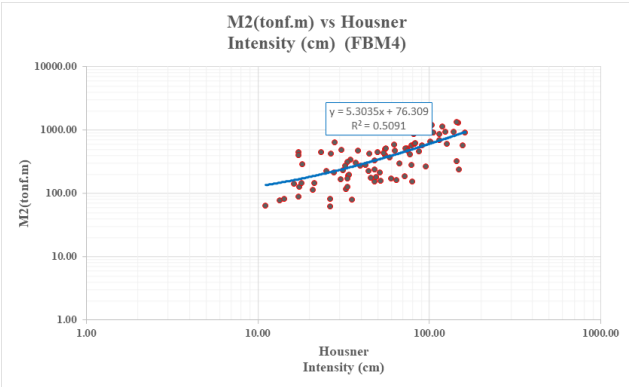


Figure A- 424:M2(tonf.m) in FBM4 vs HI (cm)

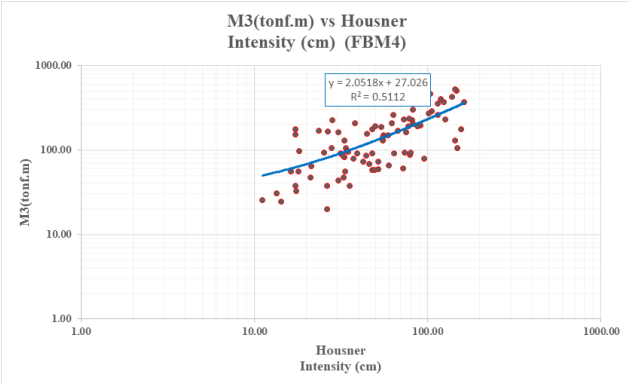


Figure A- 425:M3(tonf.m) in FBM4 vs HI (cm)

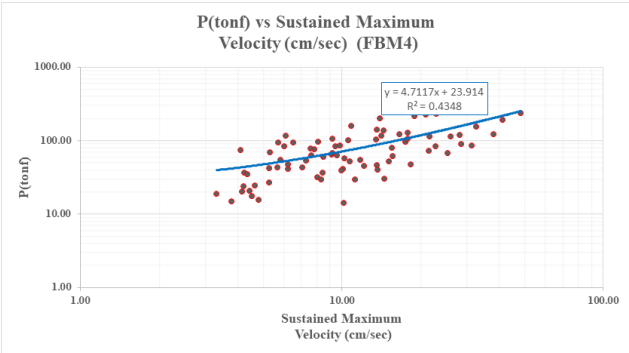


Figure A- 426:P(tonf) in FBM4 vs SMV (cm/sec)

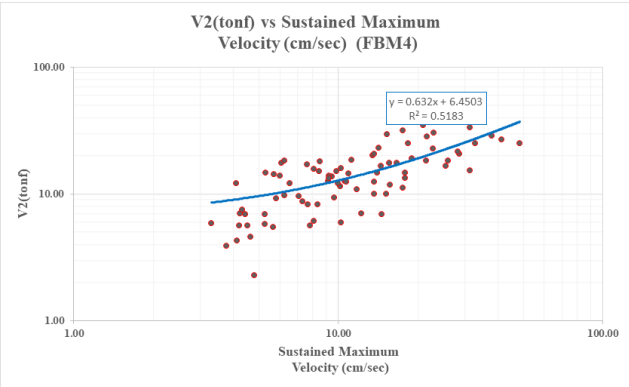


Figure A- 427:V2(tonf) in FBM4 vs SMV (cm/sec)

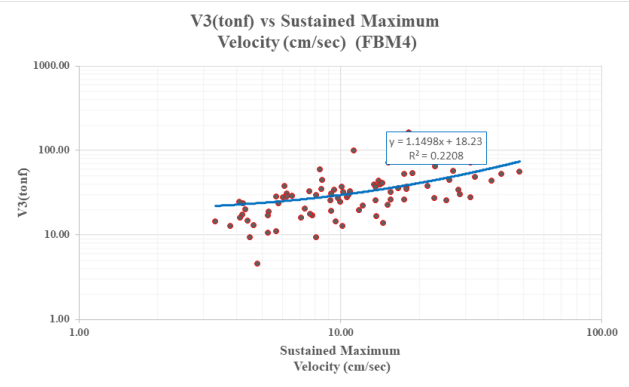


Figure A- 428:V3(tonf) in FBM4 vs SMV (cm/sec)

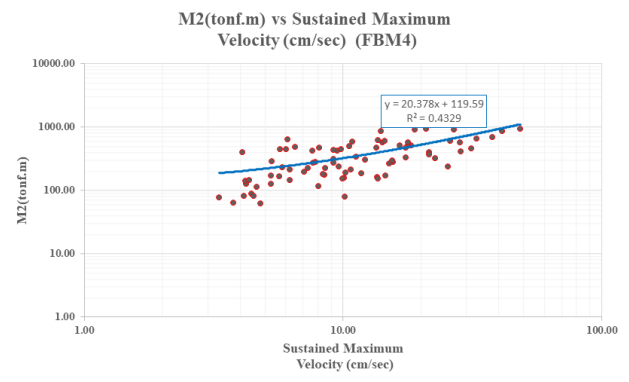


Figure A- 429:M2(tonf.m) in FBM4 vs SMV (cm/sec)

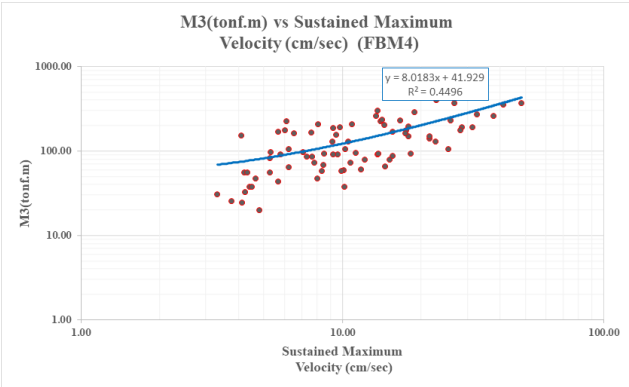


Figure A- 430:M3(tonf.m) in FBM4 vs SMV (cm/sec)

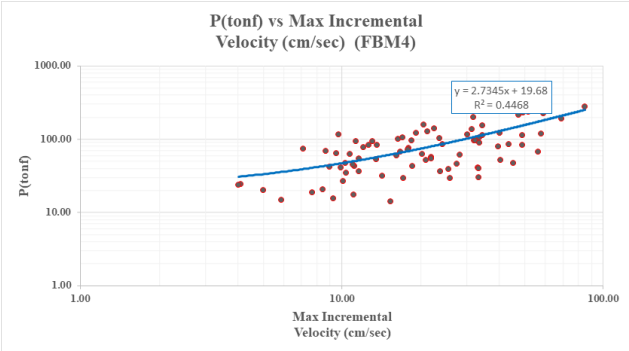


Figure A- 431:P(tonf) in FBM4 vs MIV (cm/sec)

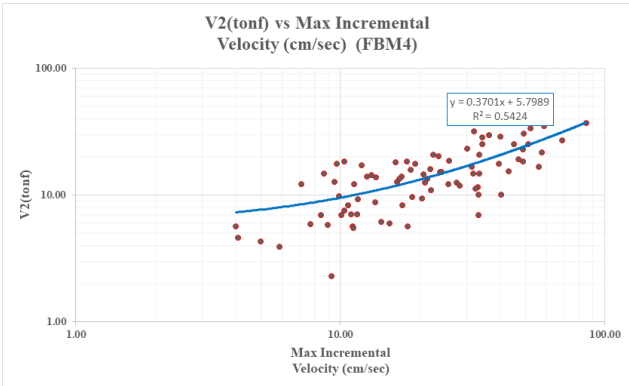


Figure A- 432:V2(tonf) in FBM4 vs MIV (cm/sec)

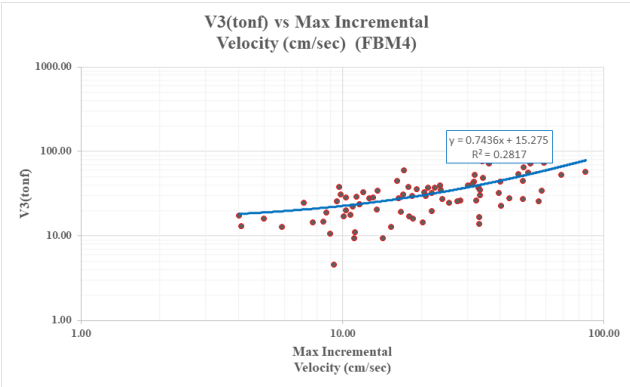


Figure A- 433:V3(tonf) in FBM4 vs MIV (cm/sec)

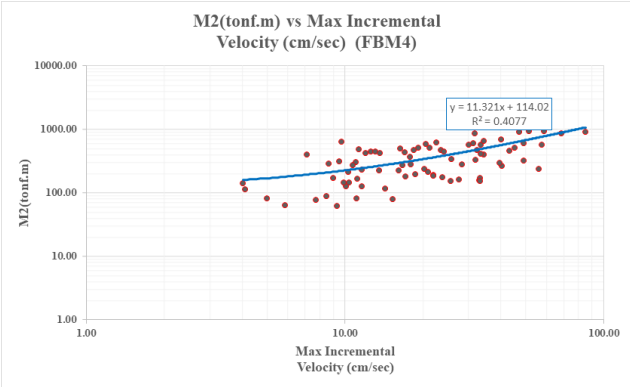


Figure A- 434:M2(tonf.m) in FBM4 vs MIV (cm/sec)

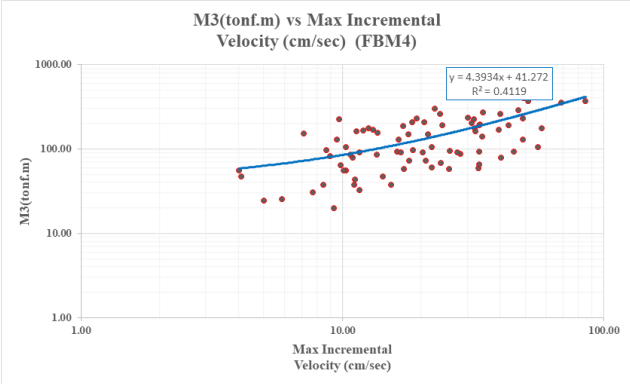


Figure A- 435:M3(tonf.m) in FBM4 vs MIV (cm/sec)

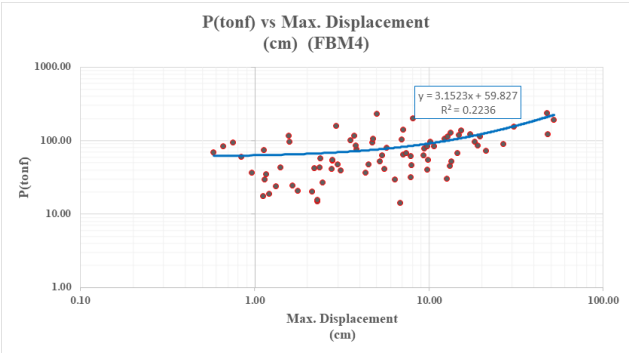


Figure A- 436:P(tonf) in FBM4 vs PGD (cm)

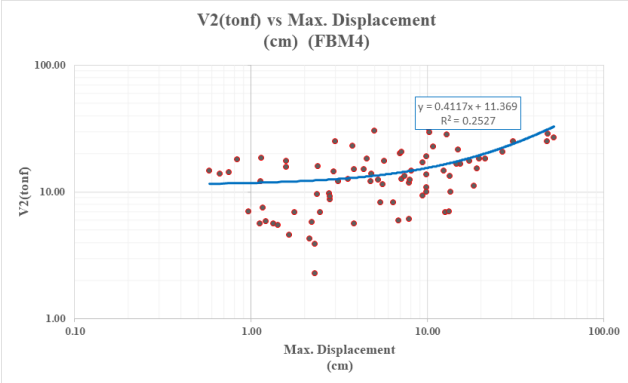


Figure A- 437:V2(tonf) in FBM4 vs PGD (cm)

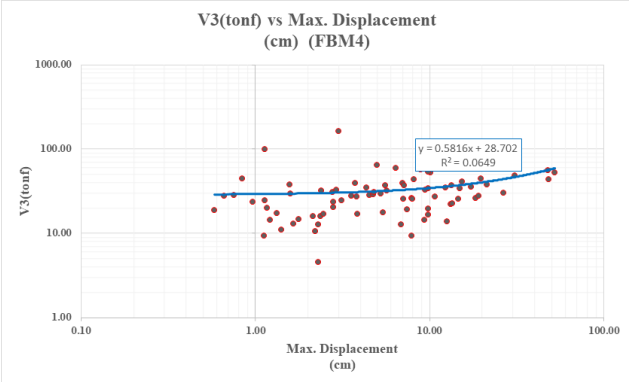


Figure A- 438:V3(tonf) in FBM4 vs PGD (cm)

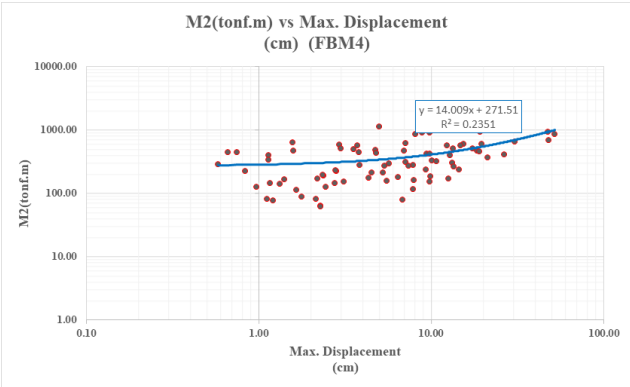


Figure A- 439:M2(tonf.m) in FBM4 vs PGD (cm)

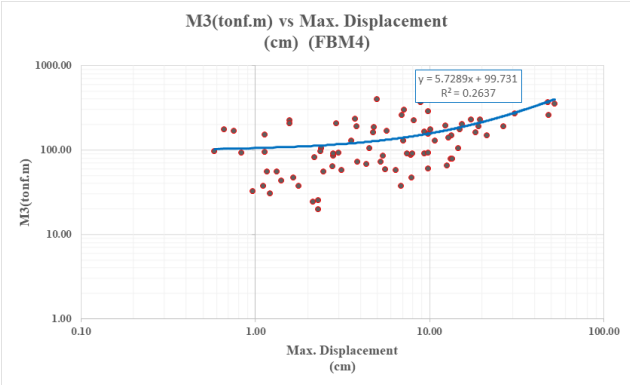


Figure A- 440:M3(tonf.m) in FBM4 vs PGD (cm)

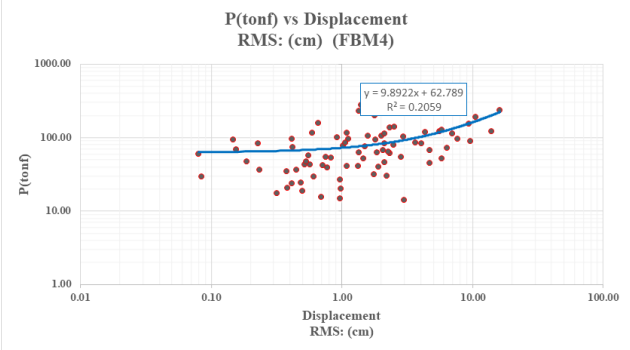


Figure A- 441:P(tonf) in FBM4 vs drms (cm)

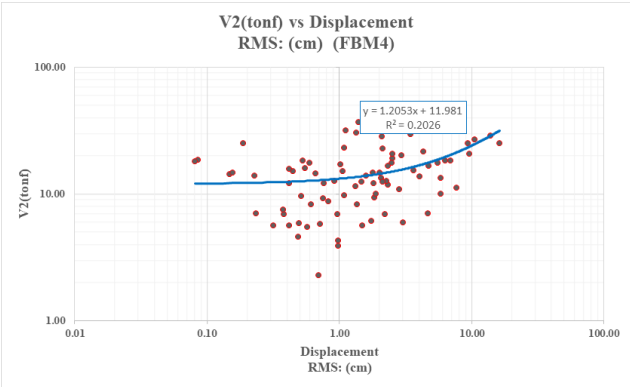


Figure A- 442:V2(tonf) in FBM4 vs drms (cm)

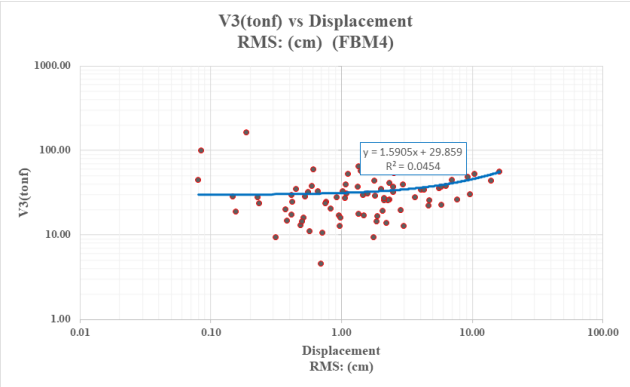


Figure A- 443:V3(tonf) in FBM4 vs drms (cm)

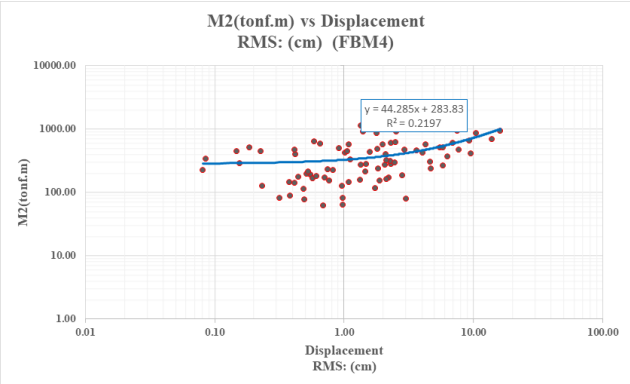


Figure A- 444:M2(tonf.m) in FBM4 vs drms (cm)

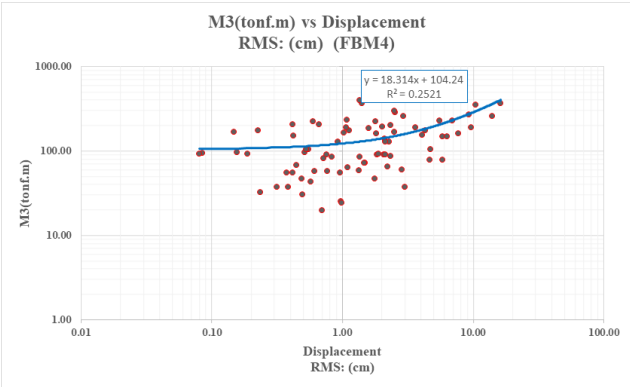


Figure A- 445:M3(tonf.m) in FBM4 vs drms (cm)

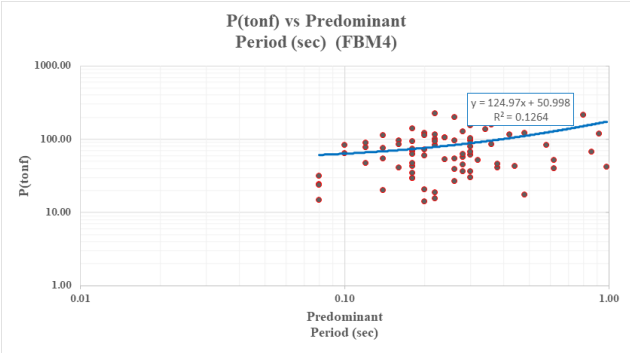


Figure A- 446:P(tonf) in FBM4 vs PP (sec)

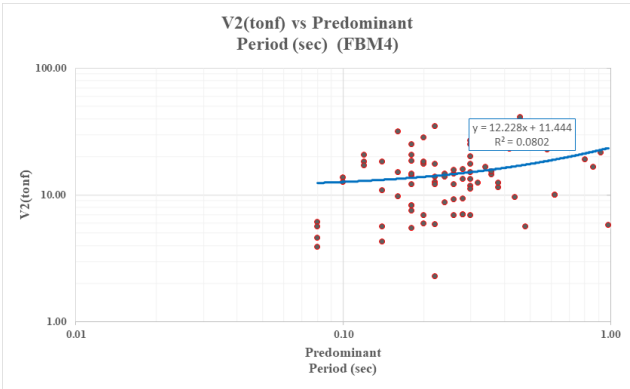


Figure A- 447:V2(tonf) in FBM4 vs PP (sec)

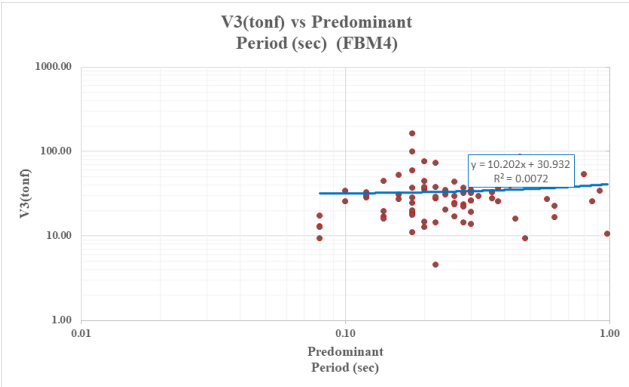


Figure A- 448:V3(tonf) in FBM4 vs PP (sec)

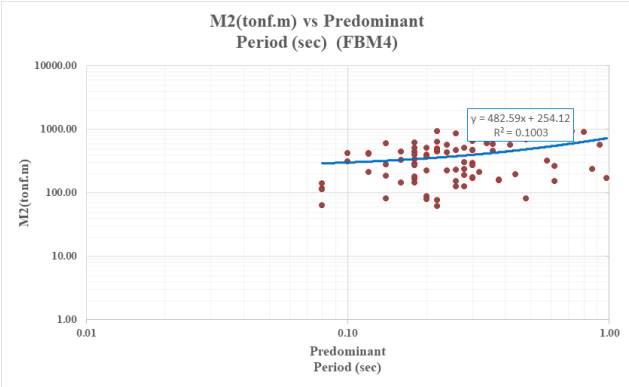


Figure A- 449:M2(tonf.m) in FBM4 vs PP (sec)

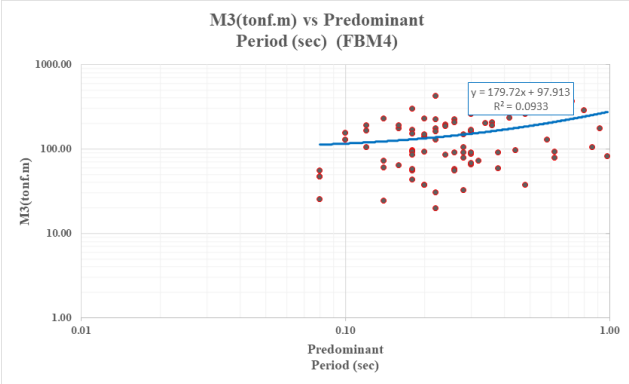


Figure A- 450:M3(tonf.m) in FBM4 vs PP (sec)

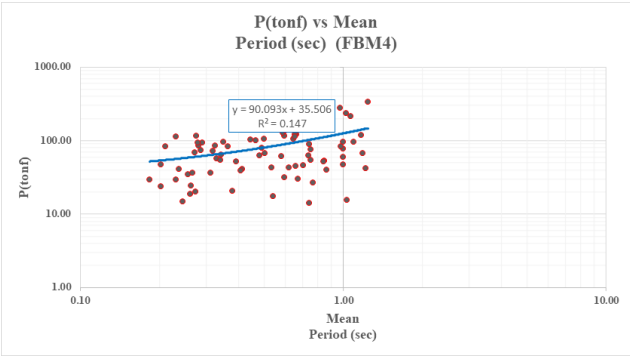


Figure A- 451:P(tonf) in FBM4 vs MP (sec)

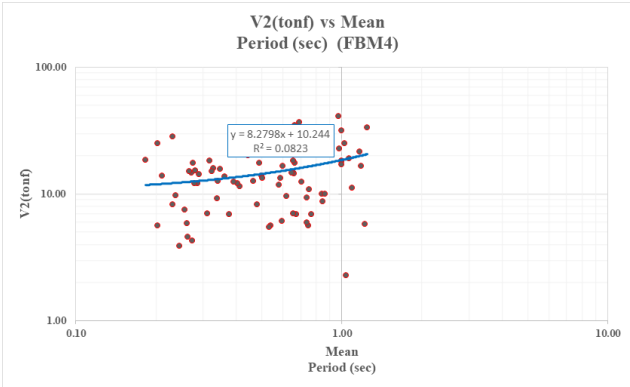


Figure A- 452:V2(tonf) in FBM4 vs MP (sec)

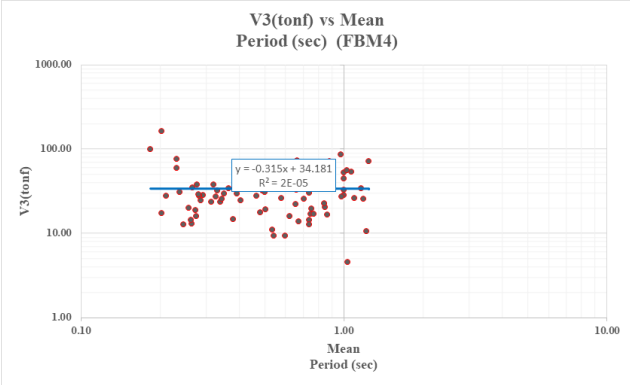


Figure A- 453:V3(tonf) in FBM4 vs MP (sec)

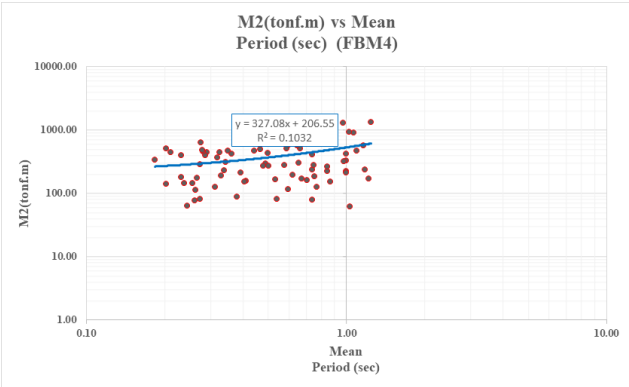


Figure A- 454:M2(tonf.m) in FBM4 vs MP (sec)

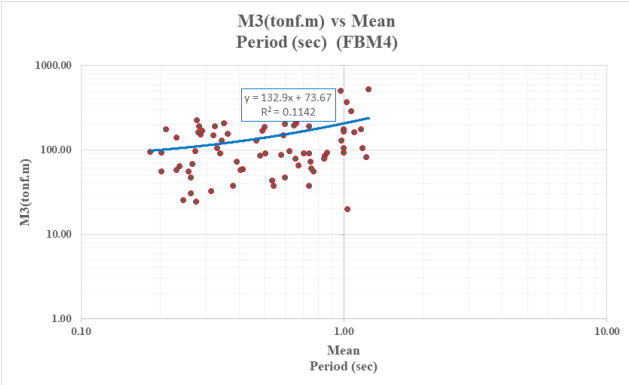


Figure A- 455:M3(tonf.m) in FBM4 vs MP (sec)

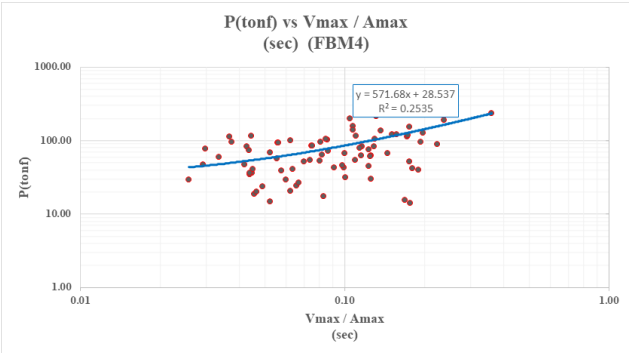


Figure A- 456:P(tonf) in FBM4 vs PGV/PGA(sec)

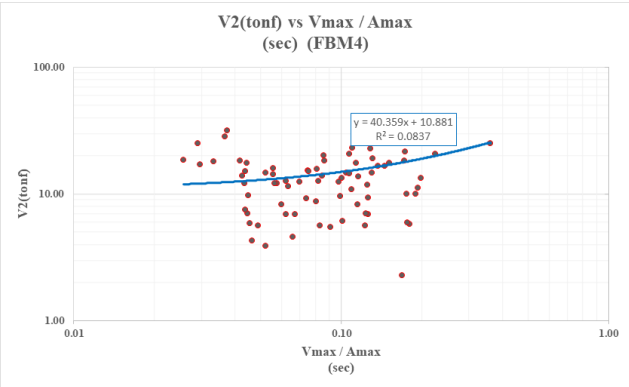


Figure A- 457:V2(tonf) in FBM4 vs PGV/PGA(sec)

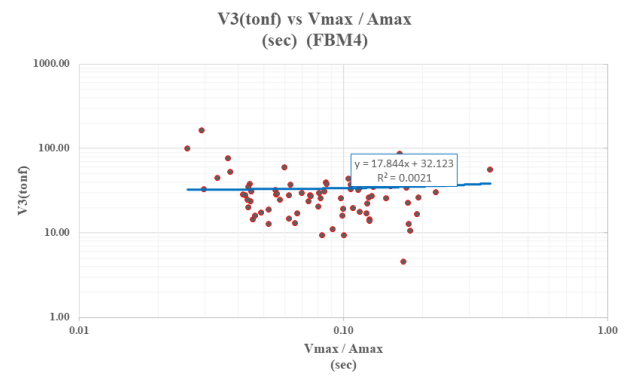


Figure A- 458:V3(tonf) in FBM4 vs PGV/PGA(sec)

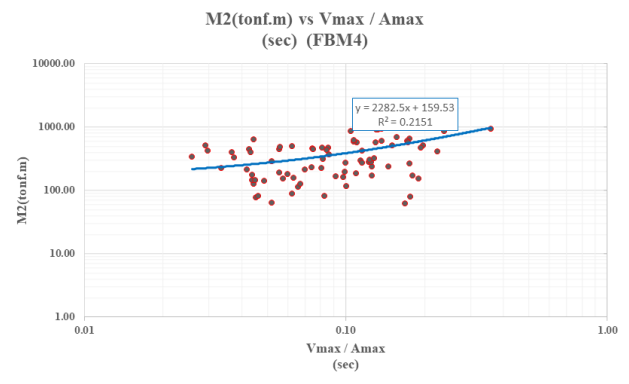


Figure A- 459:M2(tonf.m) in FBM4 vs PGV/PGA(sec)

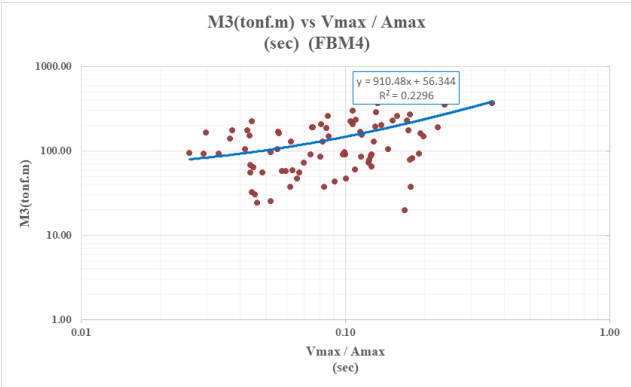


Figure A- 460:M3(tonf.m) in FBM4 vs PGV/PGA(sec)

B. Correlation Graphs Between Ground Motion Intensity Measures and Seismic Demand Parameters

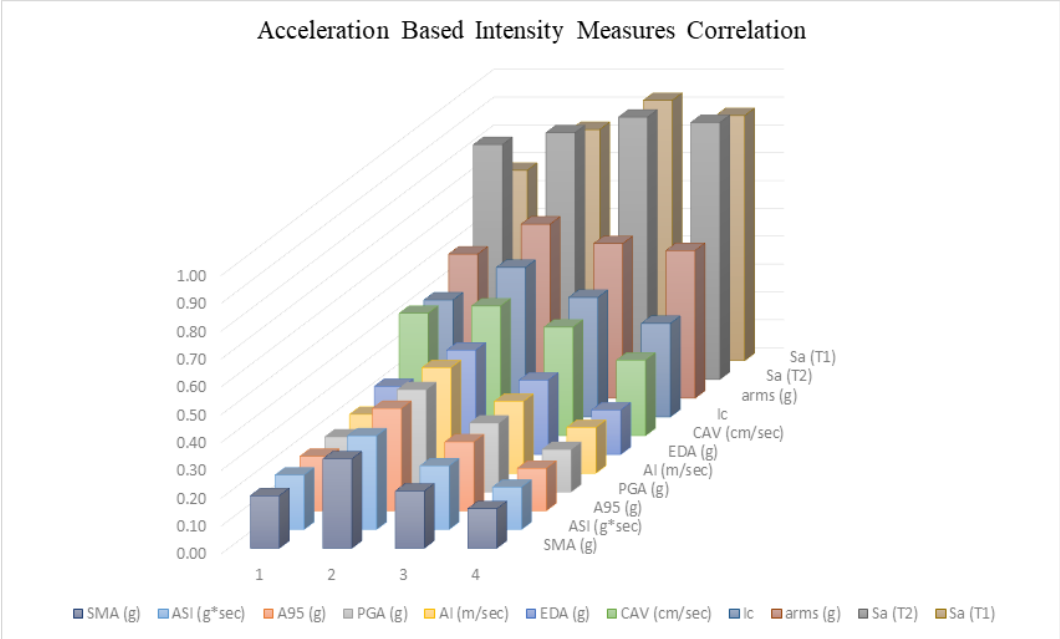


Figure B- 1 : r between acceleration based GMIM and P(tonf)

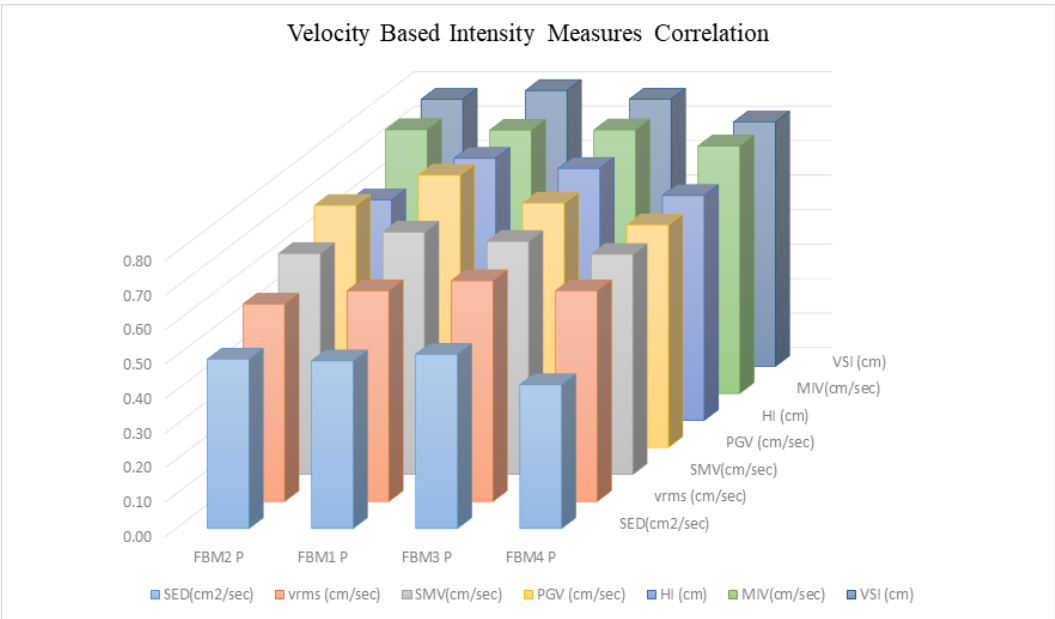


Figure B- 2 : r between velocity based GMIM and P(tonf)

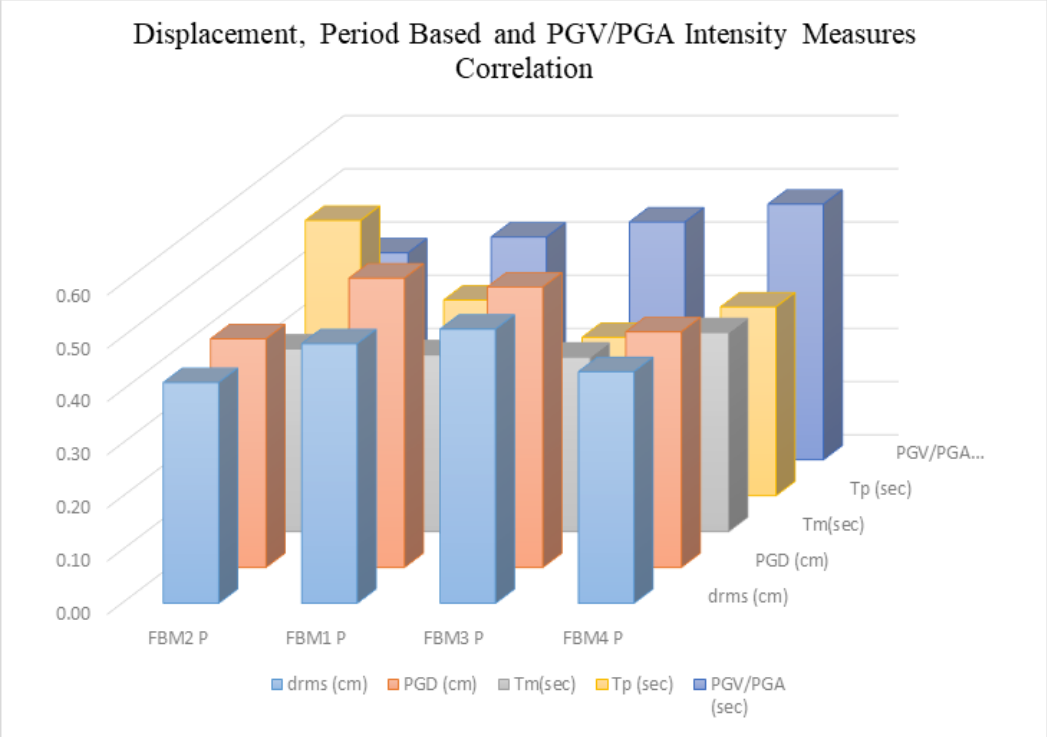


Figure B- 3 : r between displacement based and other GMIM and P(tonf)

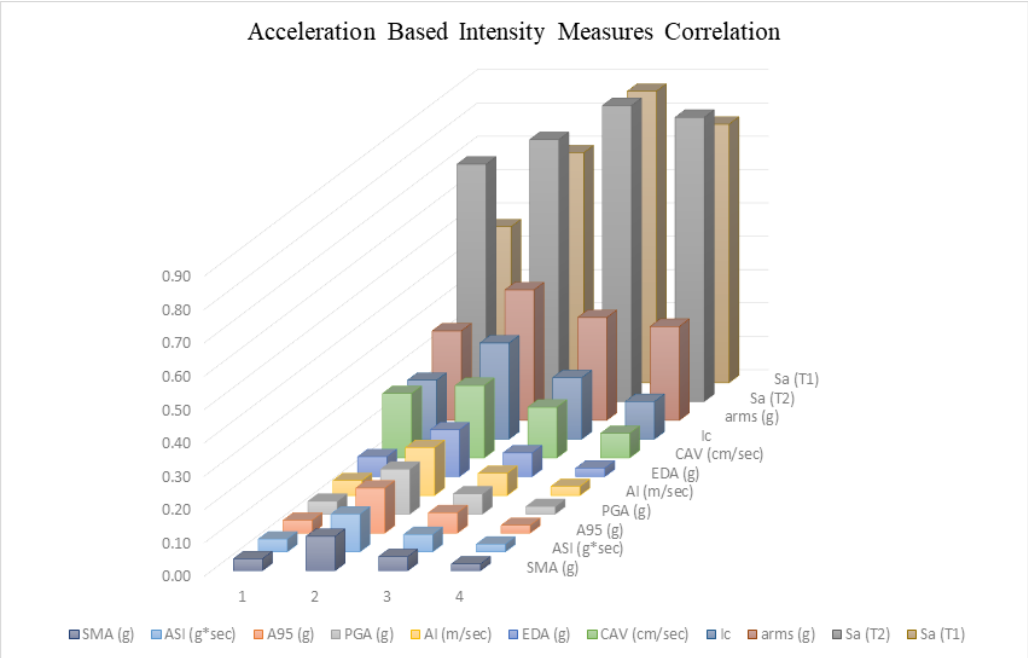


Figure B- 4 : R^2 values between acceleration based GMIM and P(tonf)

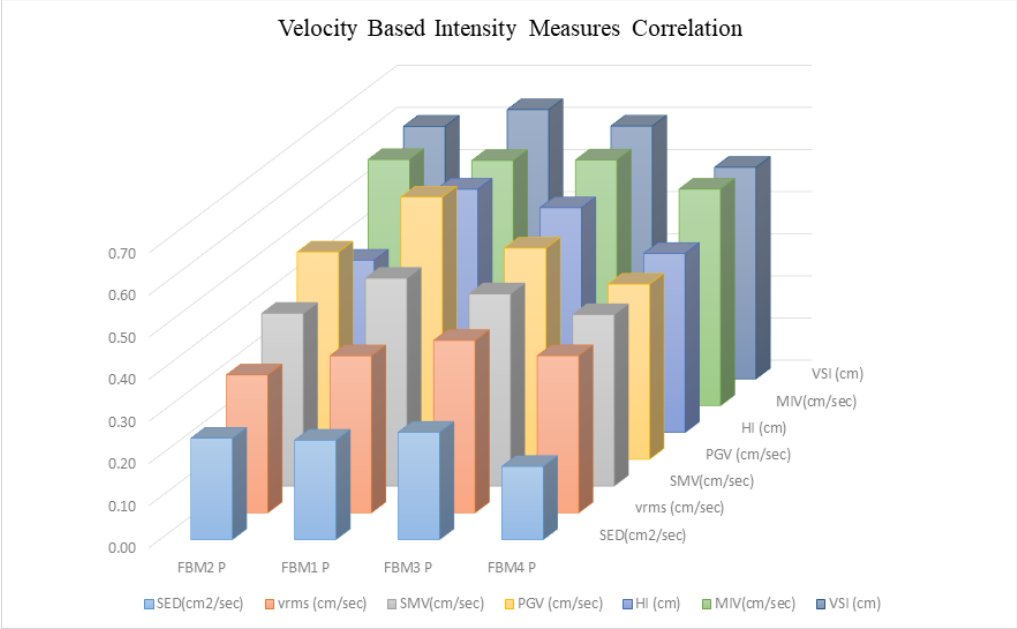


Figure B- 5 : R^2 values between velocity based GMIM and P(tonf)

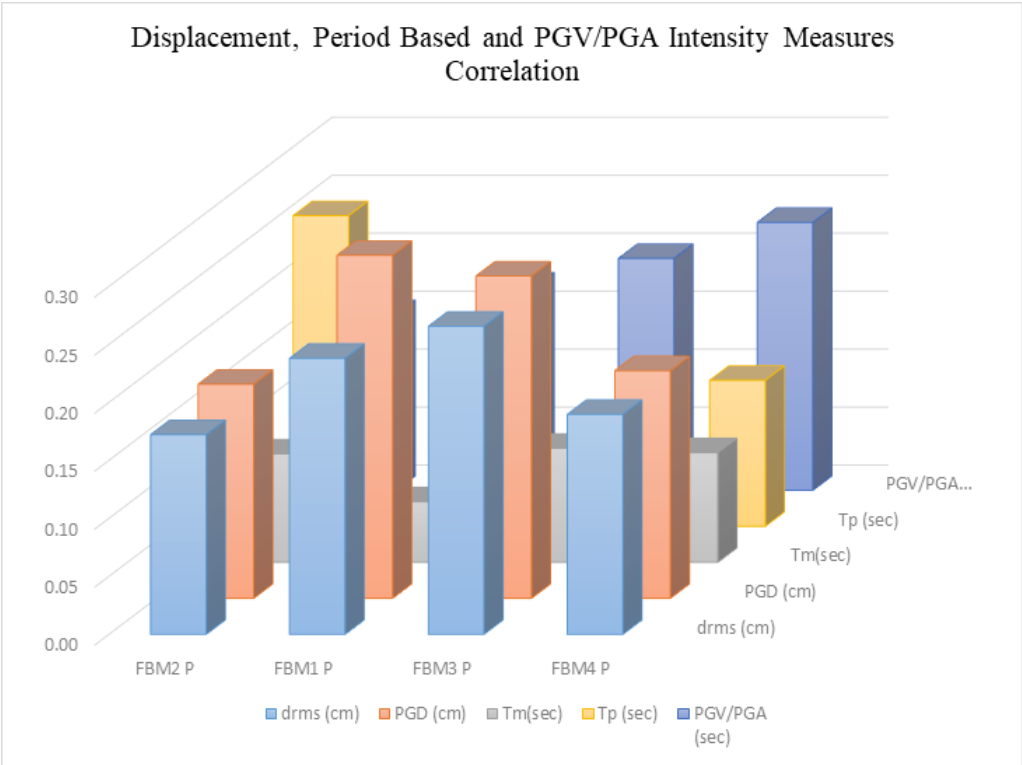


Figure B- 6 : R^2 values between displacement based and other GMIM and P(tonf)

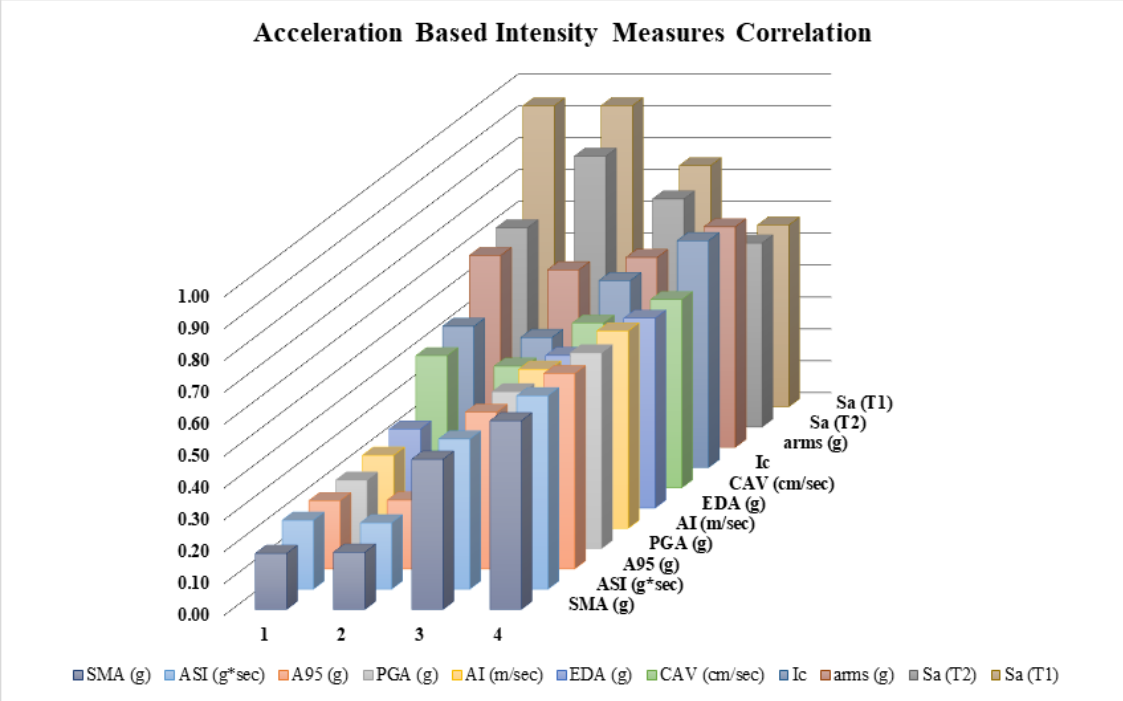


Figure B- 7 : r between acceleration based GMIM and V2(tonf)

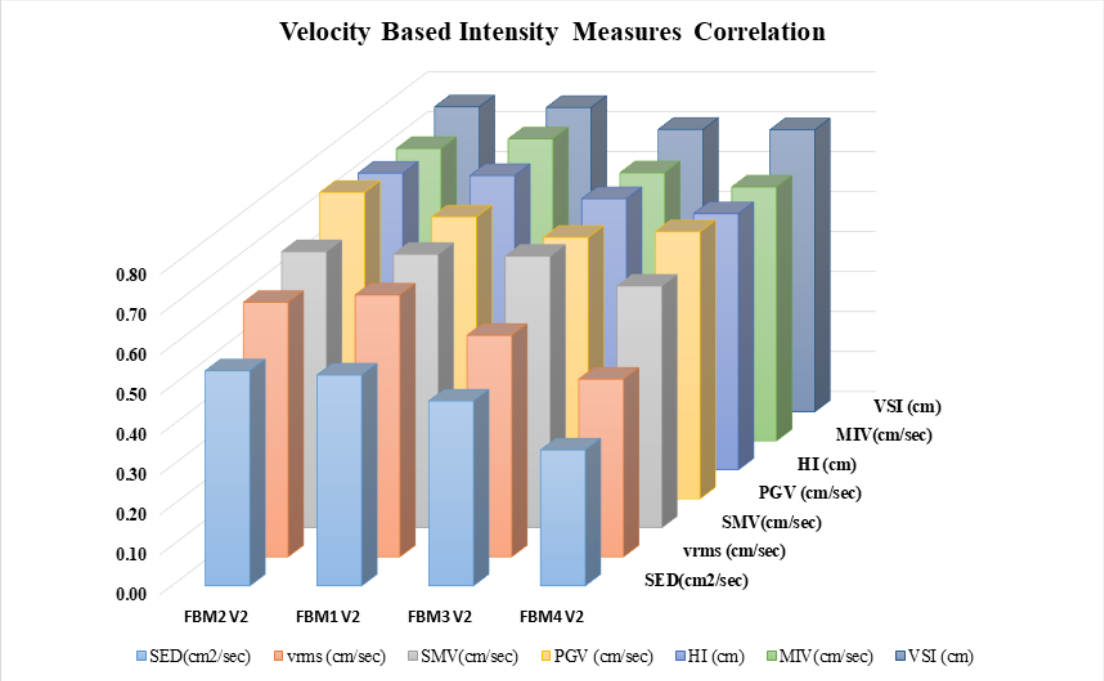


Figure B- 8 : r between velocity based GMIM and V2(tonf)

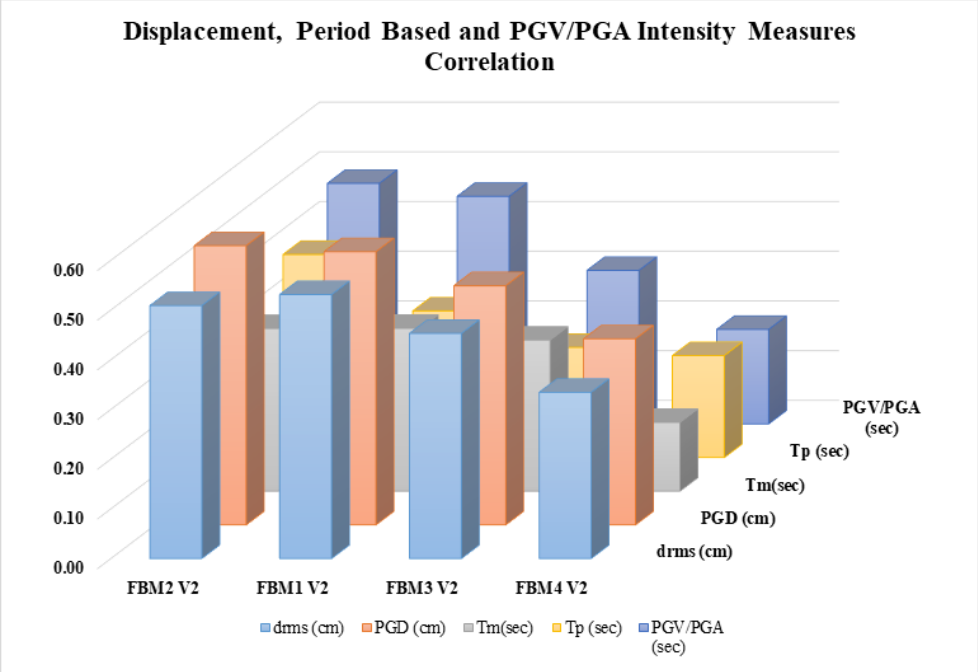


Figure B- 9 : r between displacement based and other GMIM and V2(tonf)

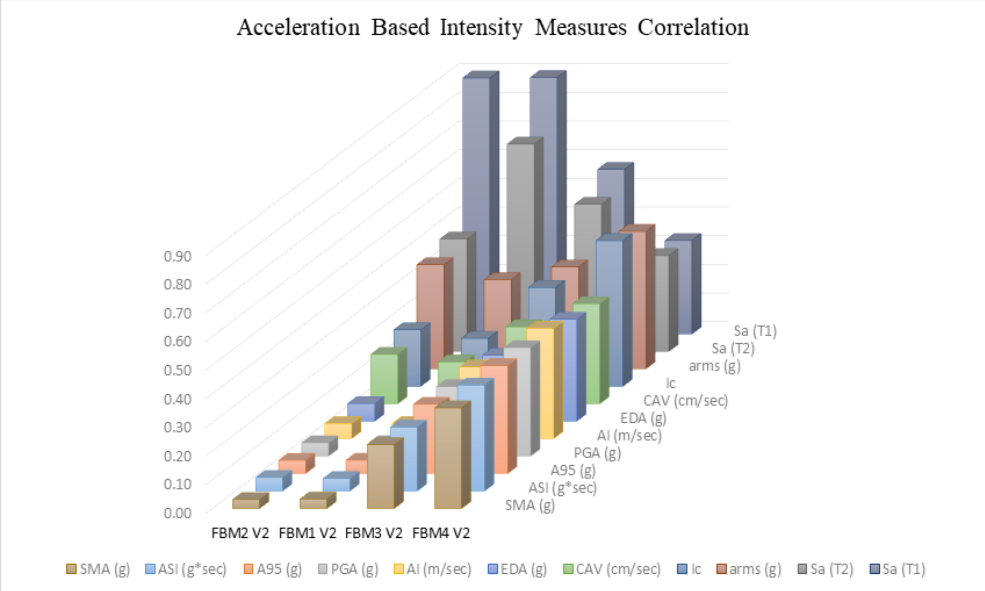


Figure B- 10 : R^2 values between acceleration based GMIM and V2(tonf)

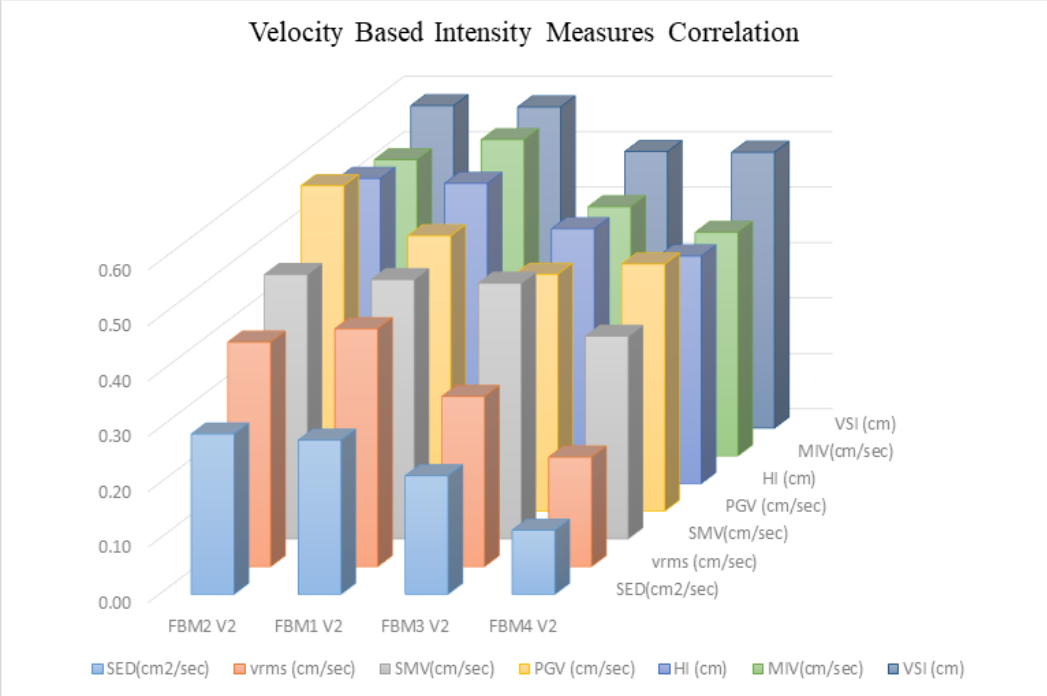


Figure B- 11 : R^2 values between velocity based GMIM and V2(tonf)

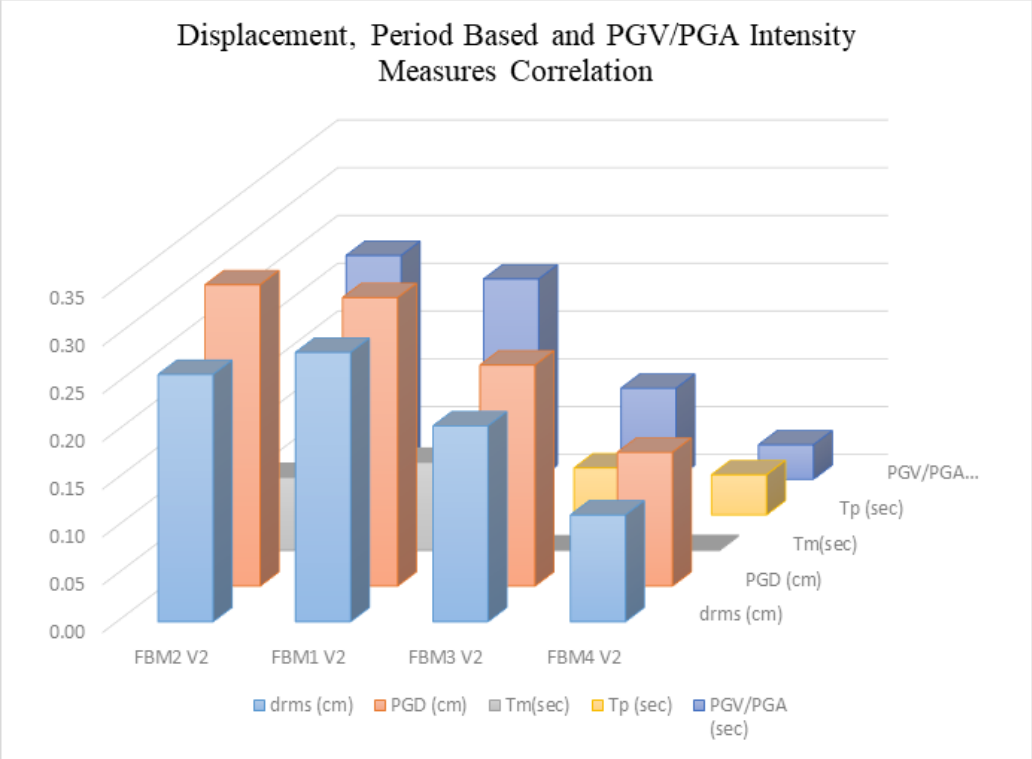


Figure B- 12 : R^2 values between displacement based and other GMIM and V2(tonf)

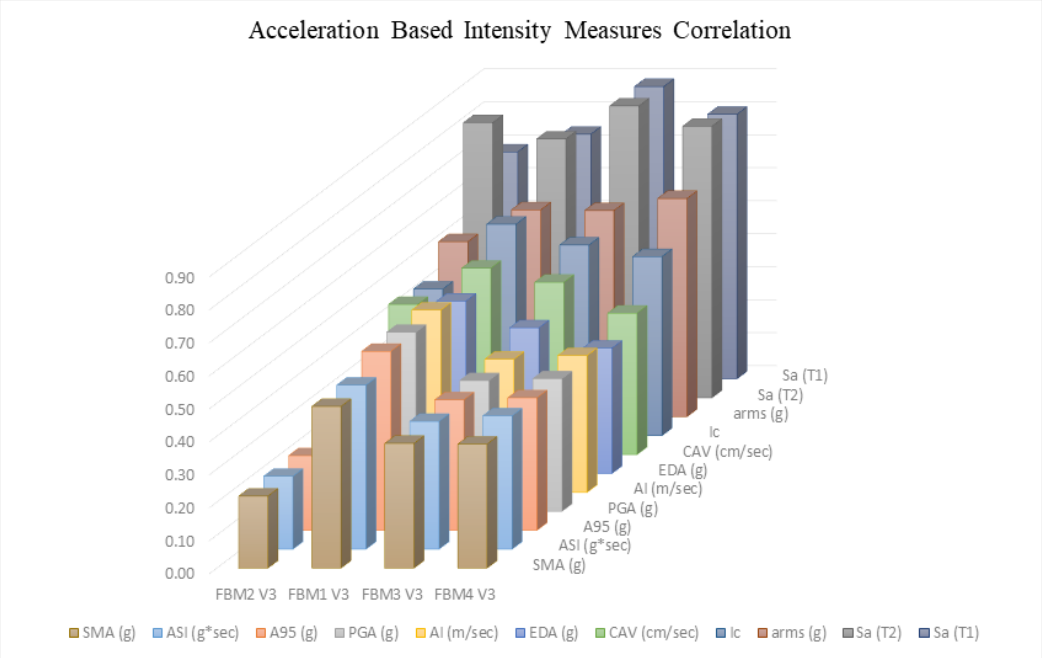


Figure B- 13 : r between acceleration based GMIM and V3(tonf)

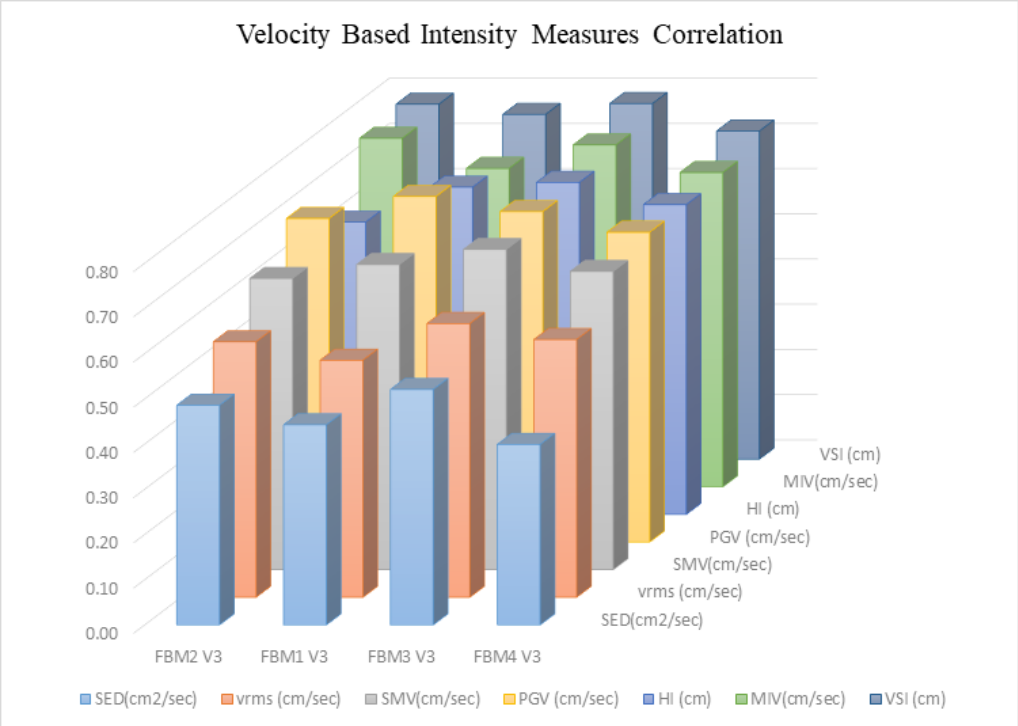


Figure B- 14 : r between velocity based GMIM and V3(tonf)

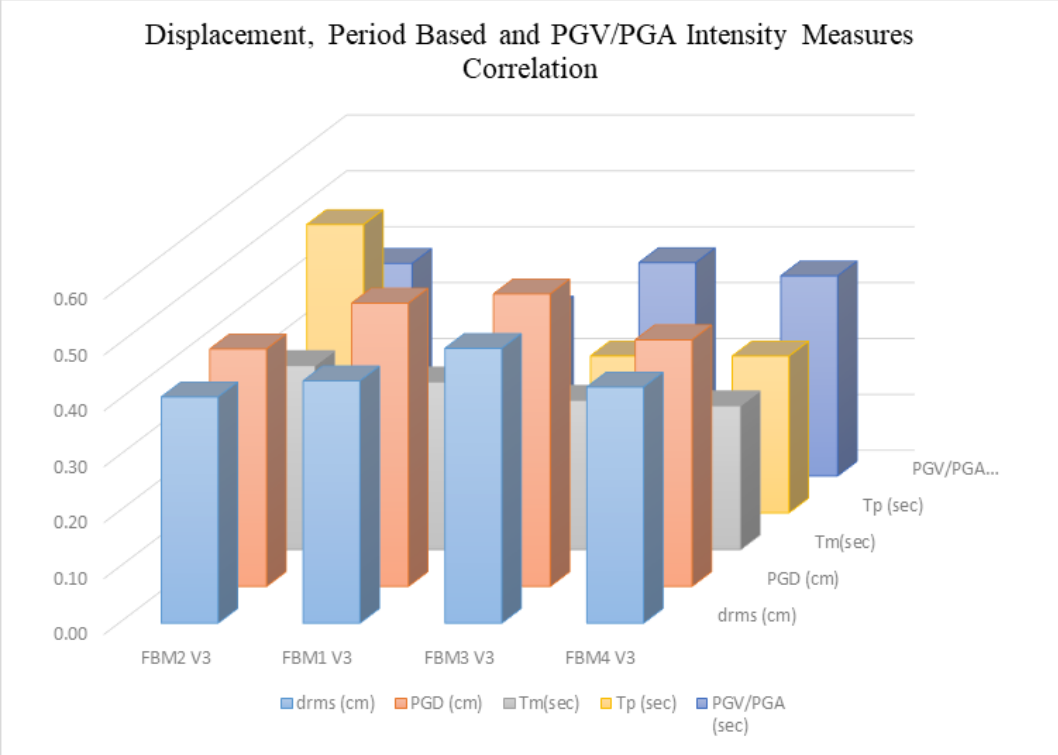


Figure B- 15 : r between displacement based and other GMIM and V3(tonf)

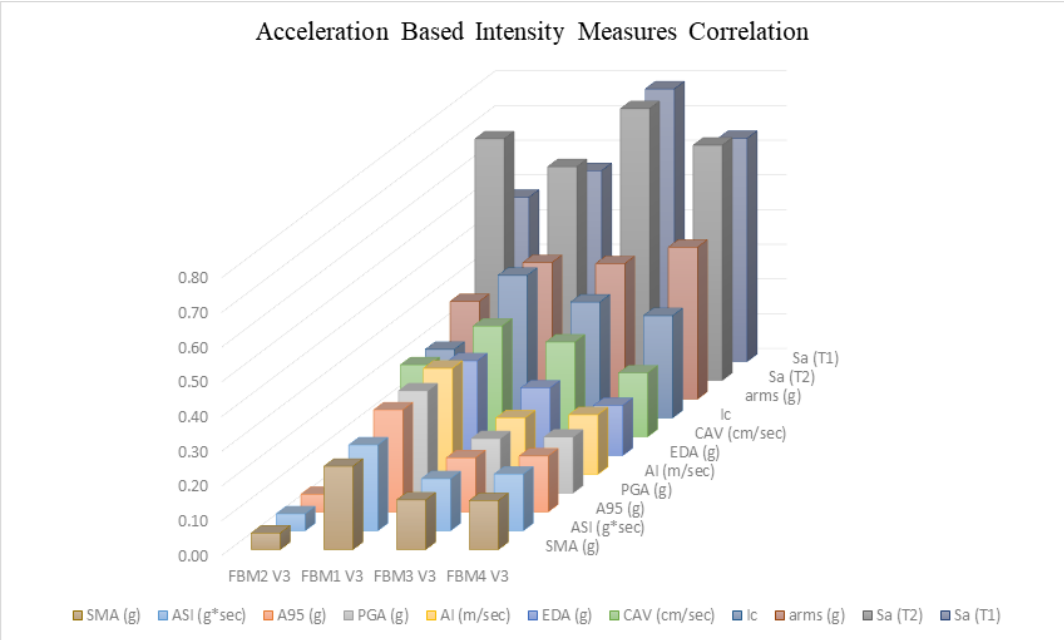


Figure B- 16 : R^2 values between acceleration based GMIM and V3(tonf)

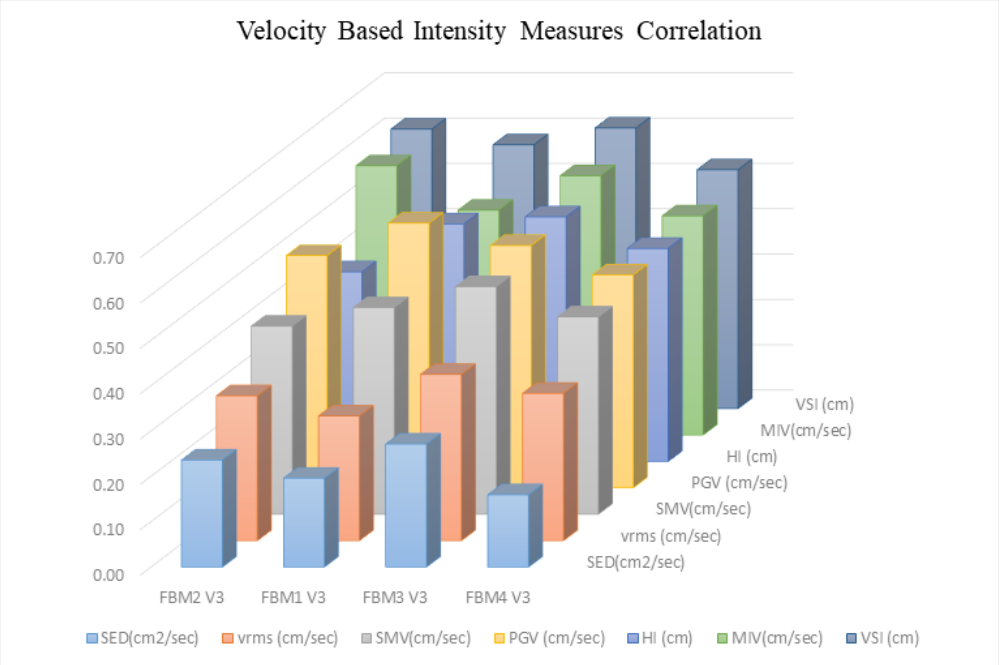


Figure B- 17 : R^2 values between velocity based GMIM and V3(tonf)

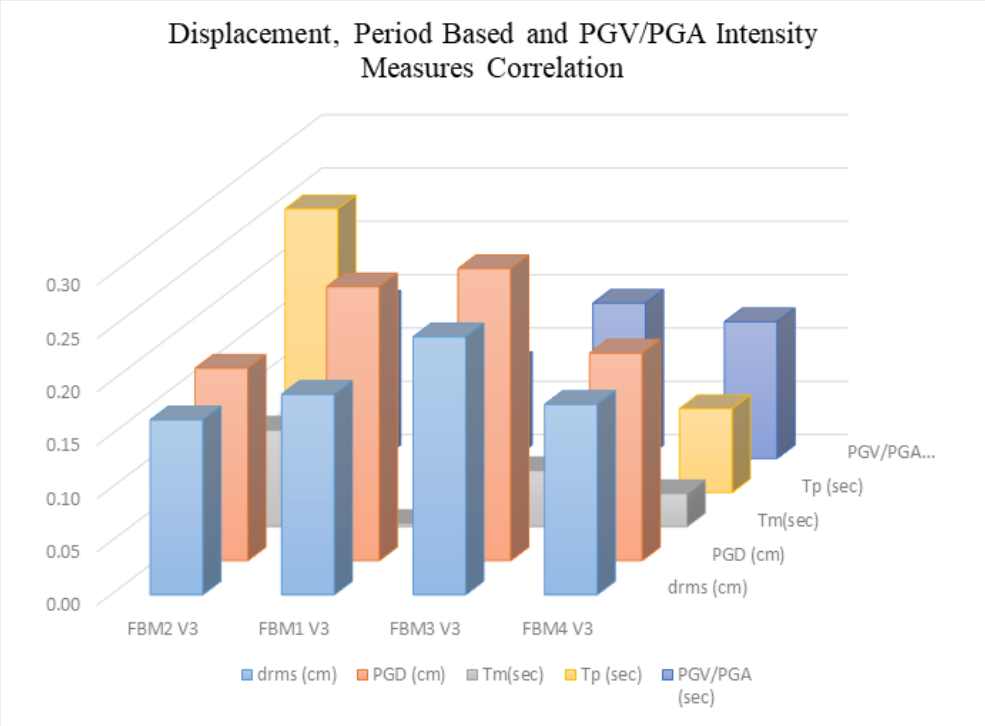


Figure B- 18 : R^2 values between displacement based and other GMIM and V3(tonf)

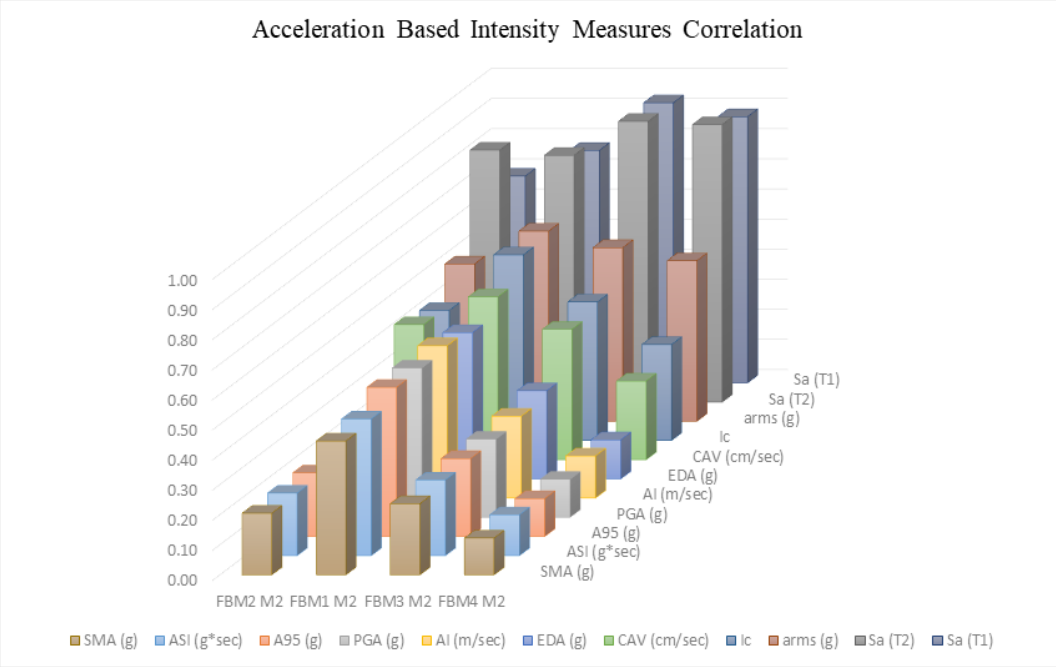


Figure B- 19 : r between acceleration based GMIM and M2(tonf.m)

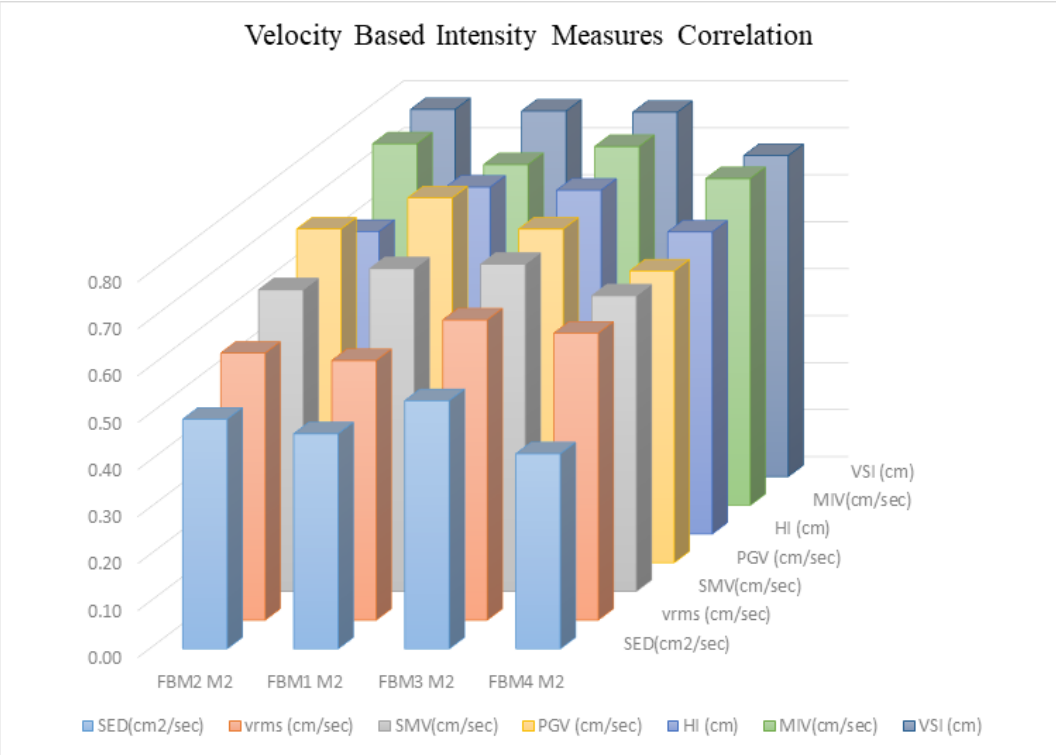


Figure B- 20 : r between velocity based GMIM and M2(tonf.m)

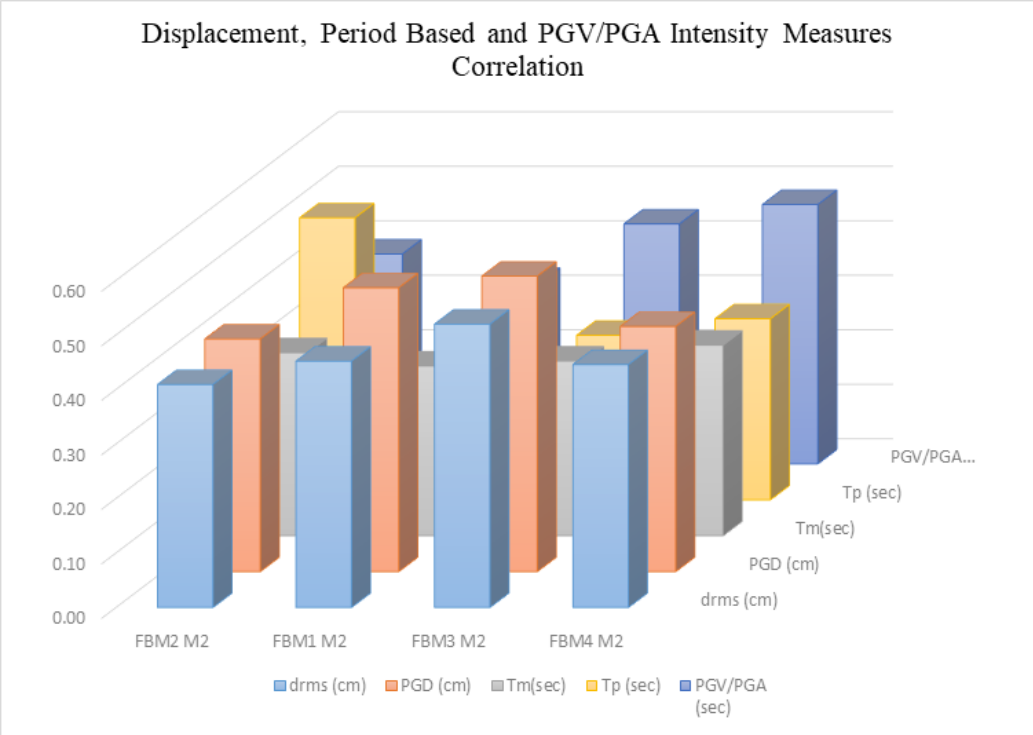


Figure B- 21 : r between displacement based and other GMIM and M2(tonf.m)

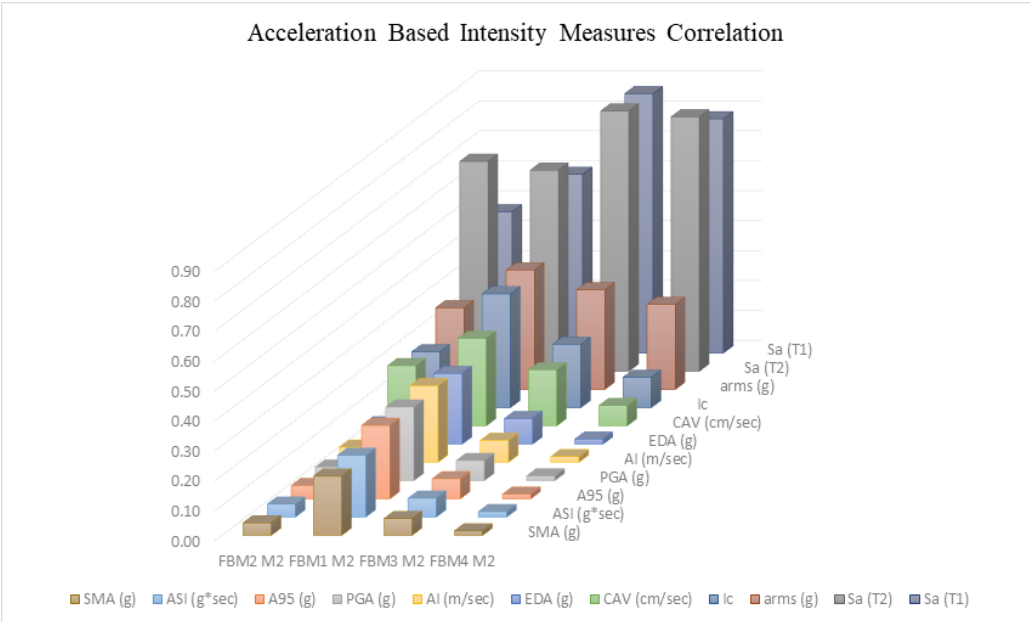


Figure B- 22 : R^2 values between acceleration based GMIM and M2(tonf.m)

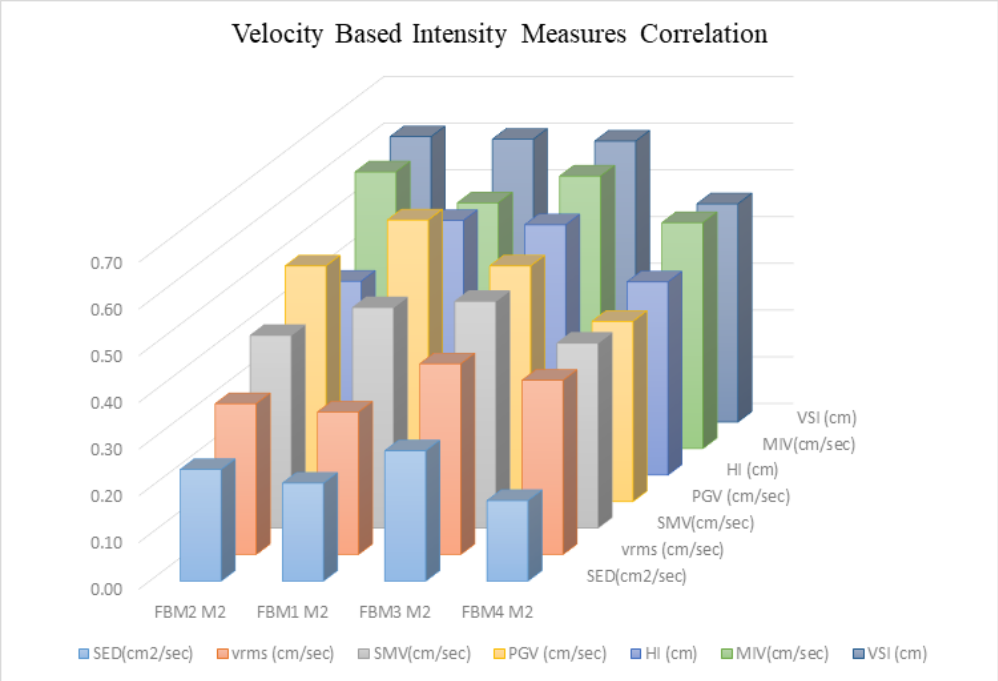


Figure B- 23 : R^2 values between velocity based GMIM and M2(tonf.m)

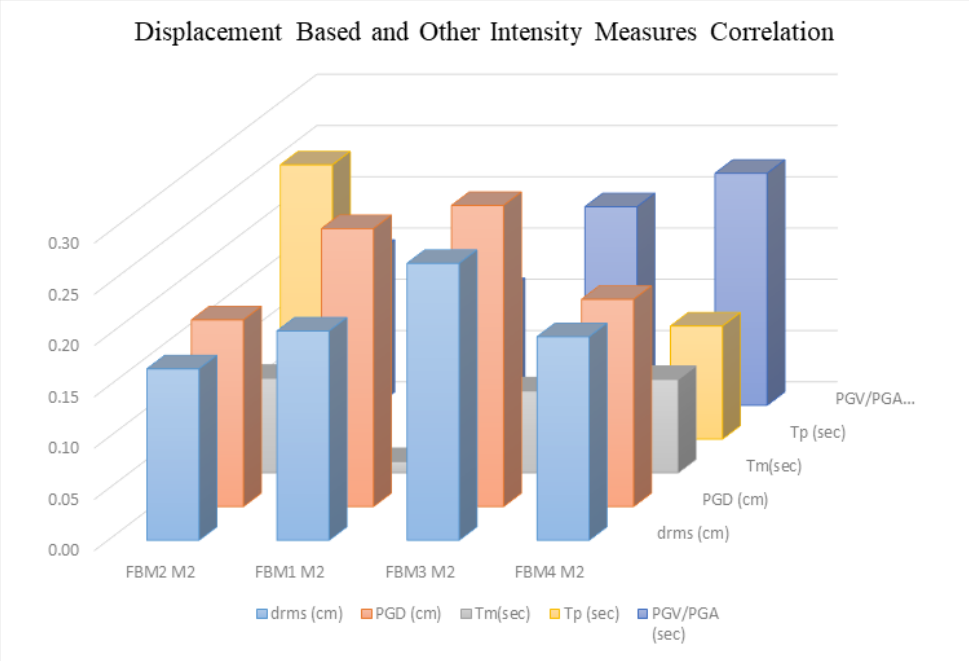


Figure B- 24 : R^2 values between displacement based and other GMIM and M2(tonf.m)

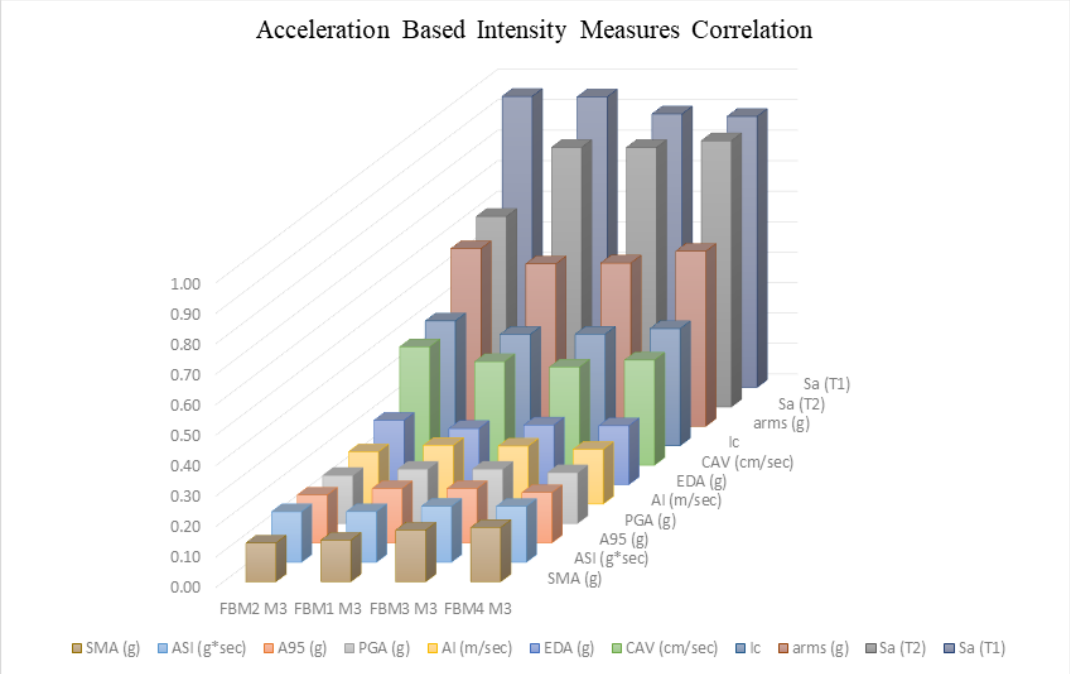


Figure B- 25 : r between acceleration based GMIM and M3(tonf.m)

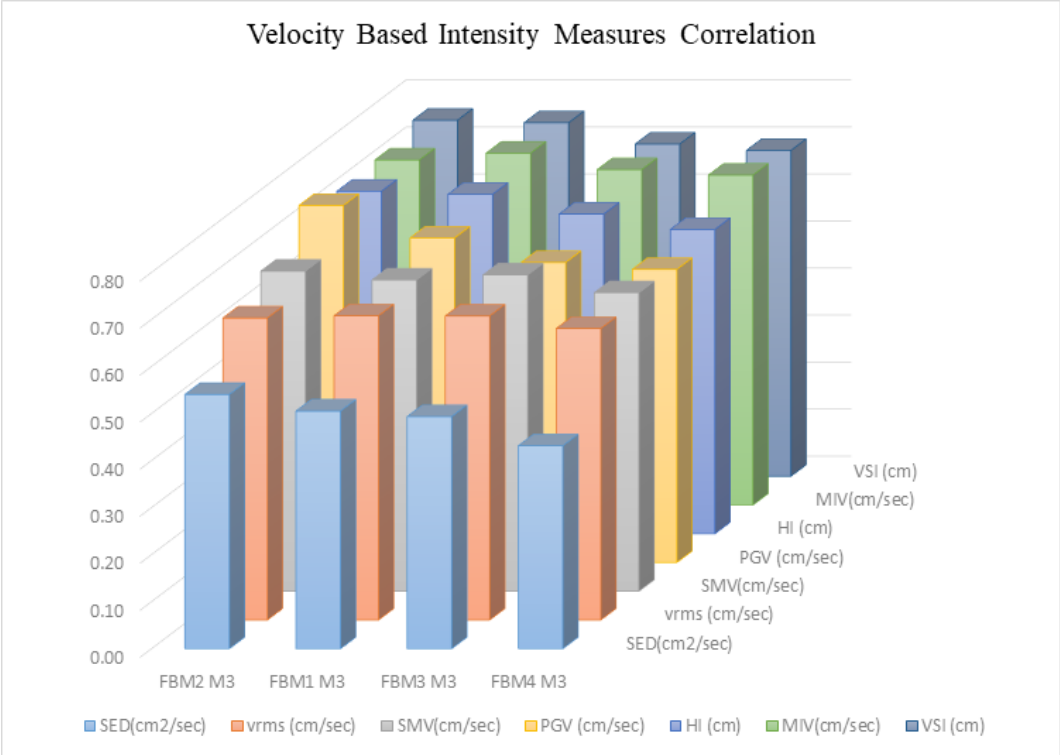


Figure B- 26 : r between velocity based GMIM and M3(tonf.m)

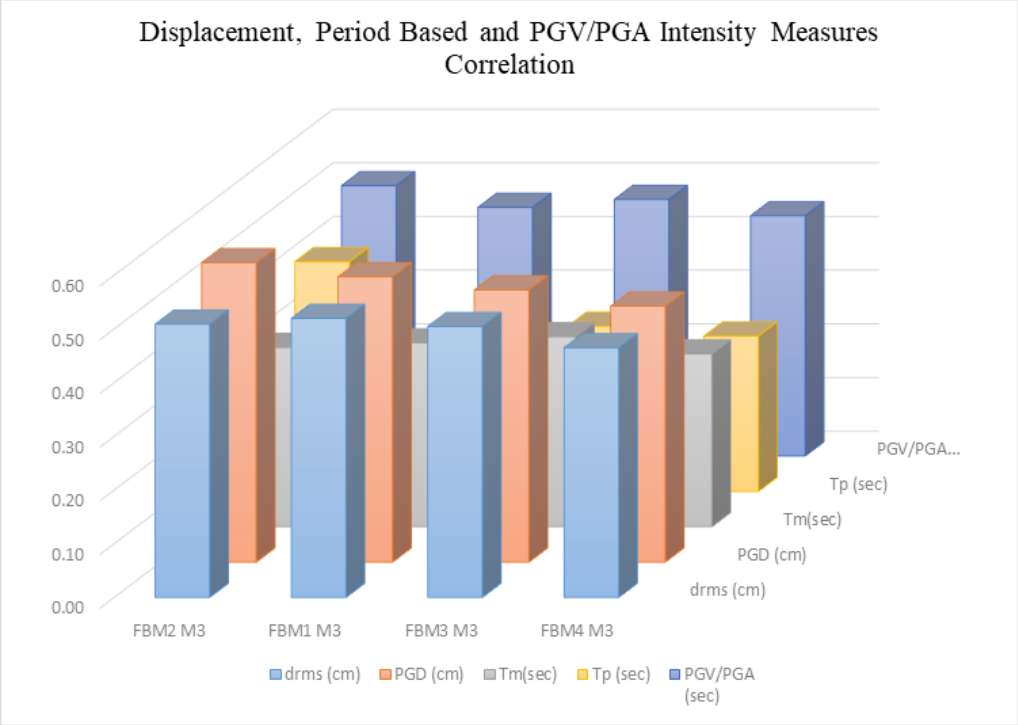


Figure B- 27 : r between displacement based and other GMIM and M3(tonf.m)

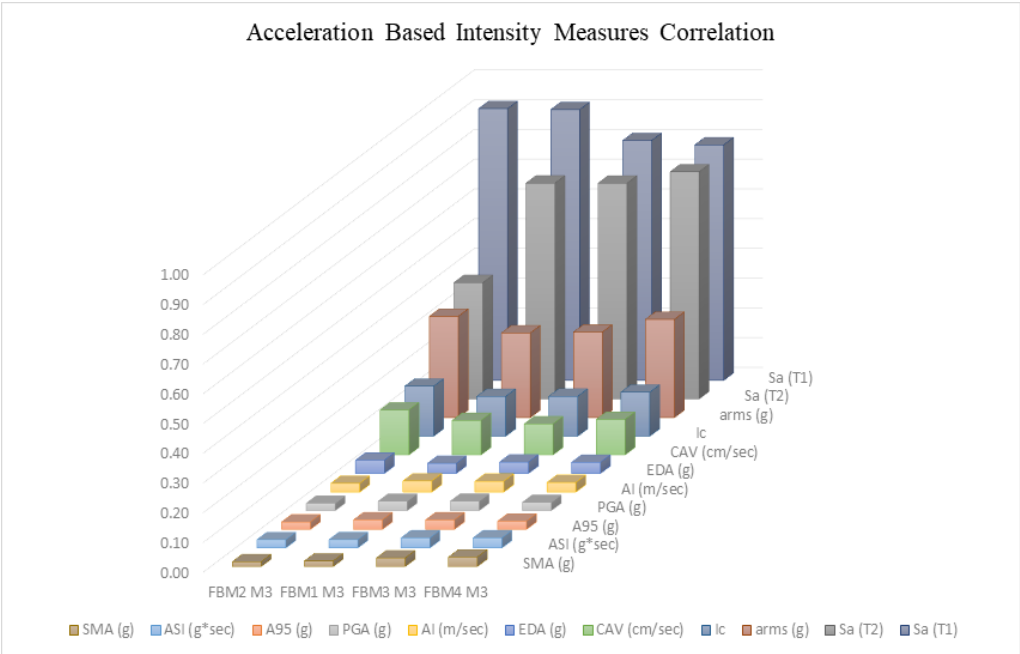


Figure B- 28 : R^2 values between acceleration based GMIM and M3(tonf.m)

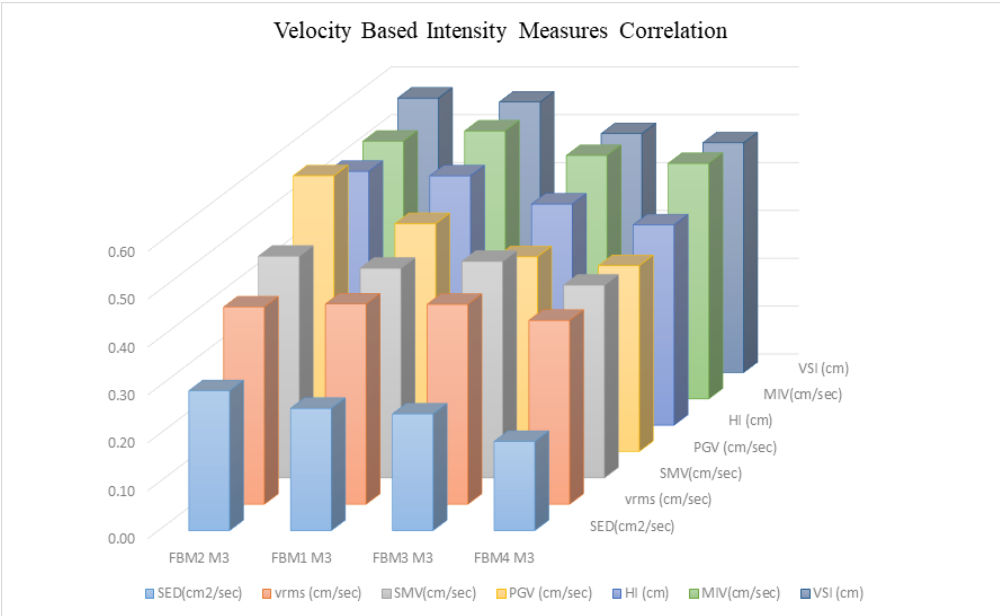


Figure B- 29 : R^2 values between velocity based GMIM and M3(tonf.m)

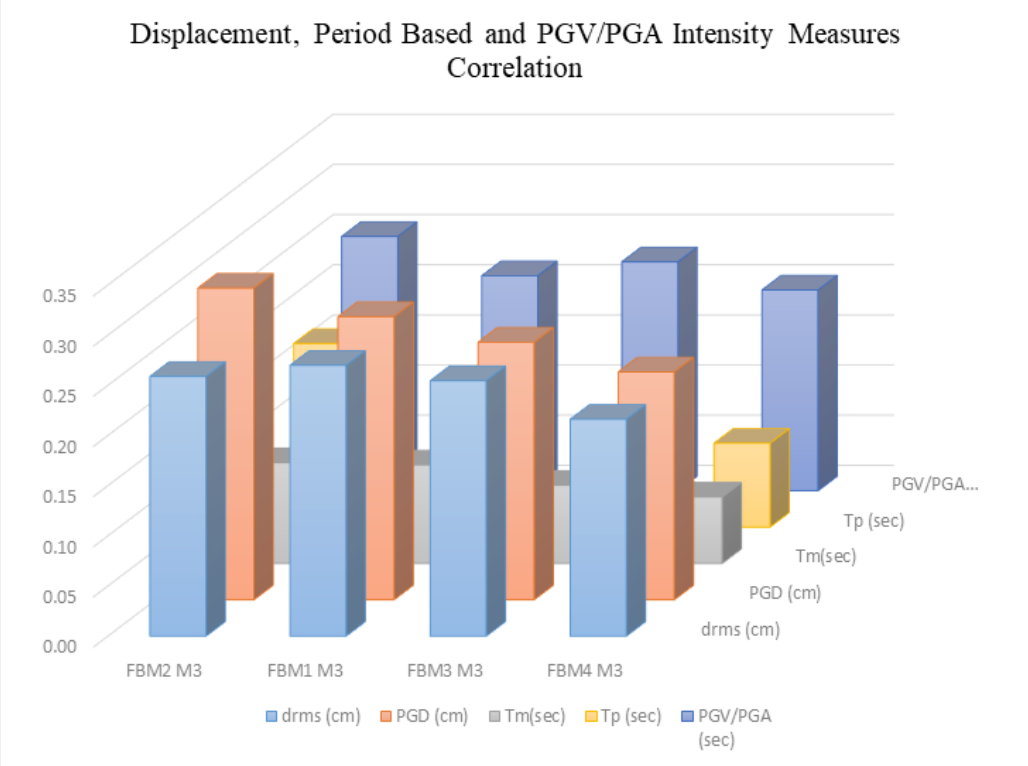


Figure B- 30 : R^2 values between displacement based and other GMIM and M3(tonf.m)

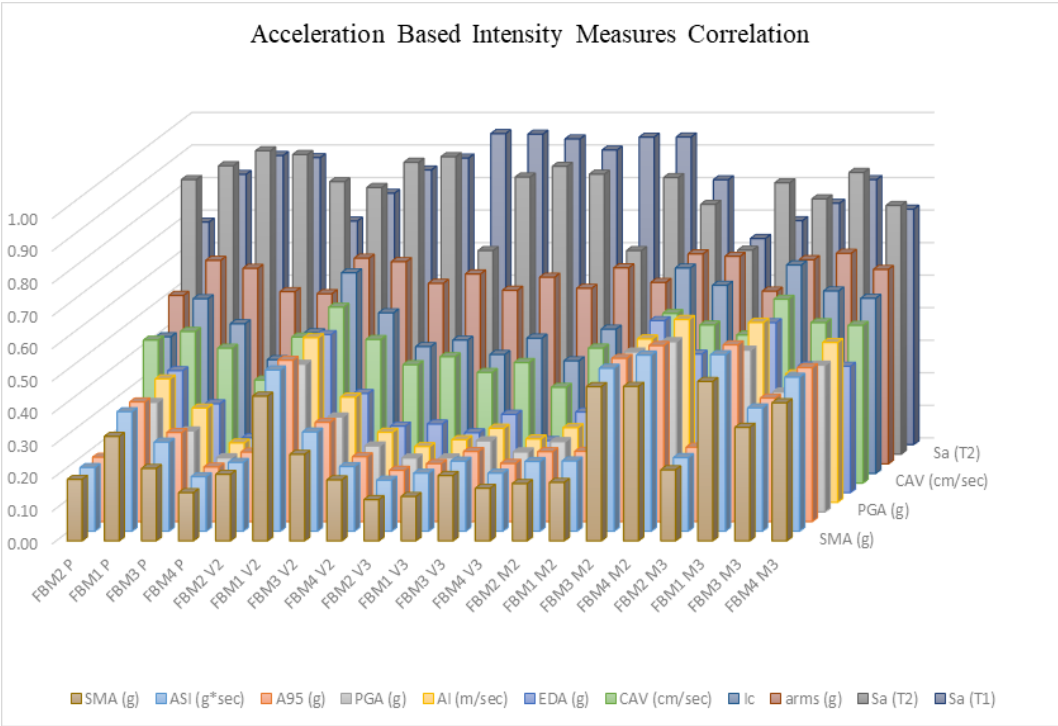


Figure B- 31 : r between acceleration based GMIM and P(tonf)

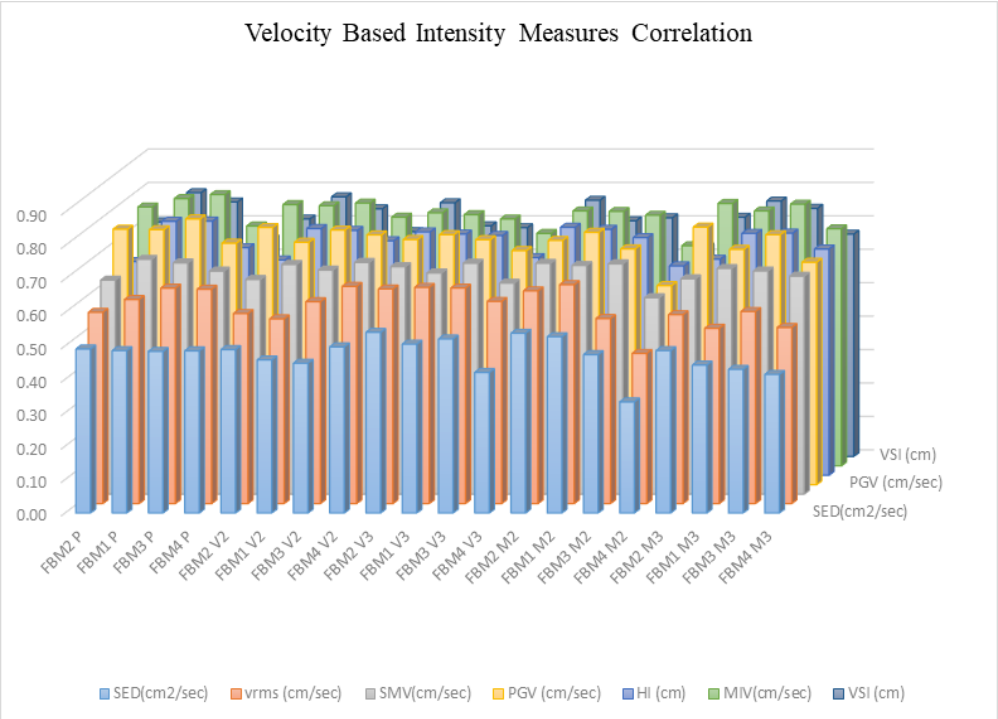


Figure B- 32 : r between velocity based GMIM and P(tonf)

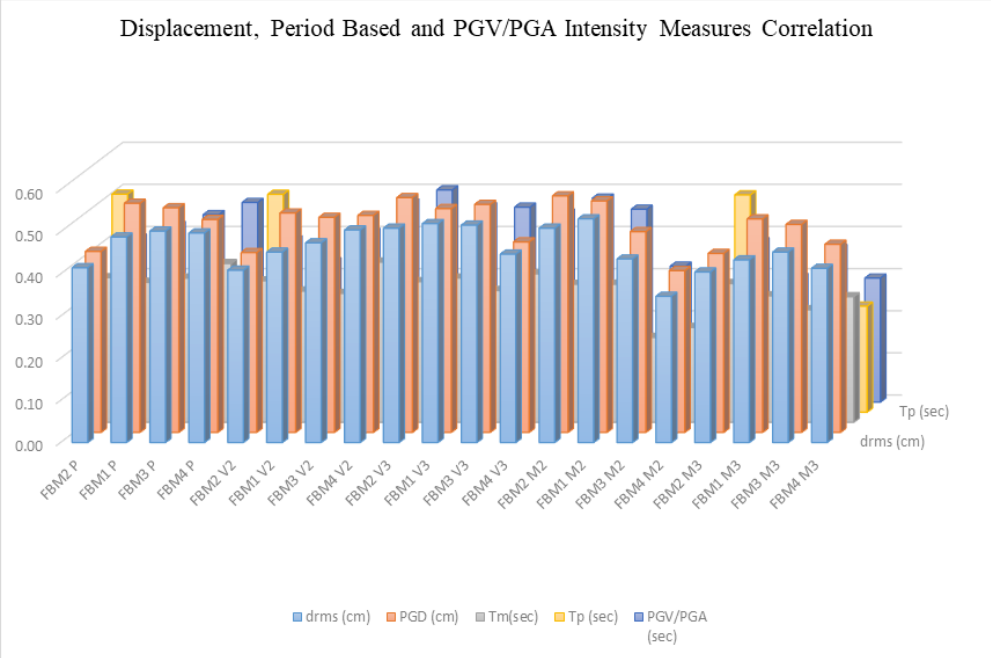


Figure B- 33 : r between displacement based and other GMIM and P(tonf)

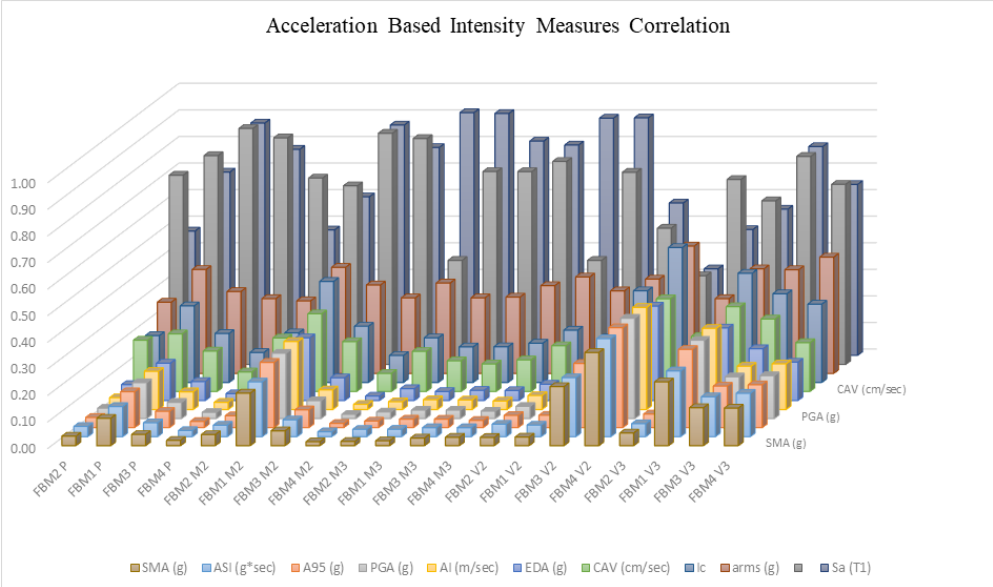


Figure B- 34 : R^2 values between acceleration based GMIM

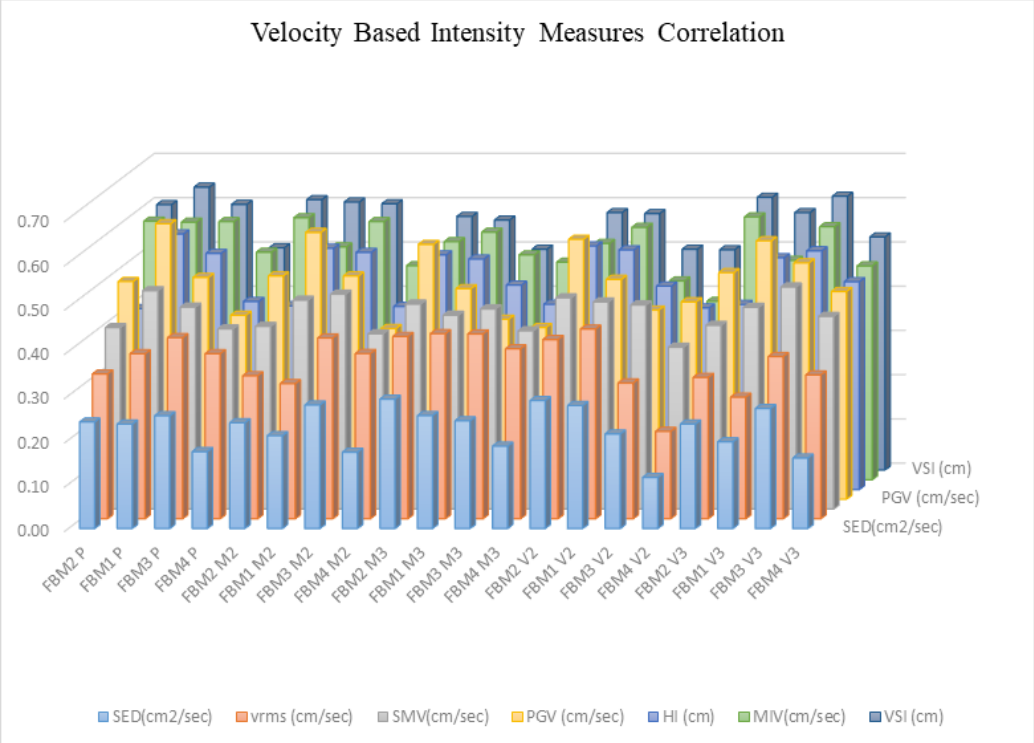


Figure B- 35 : R^2 values between velocity based GMIM

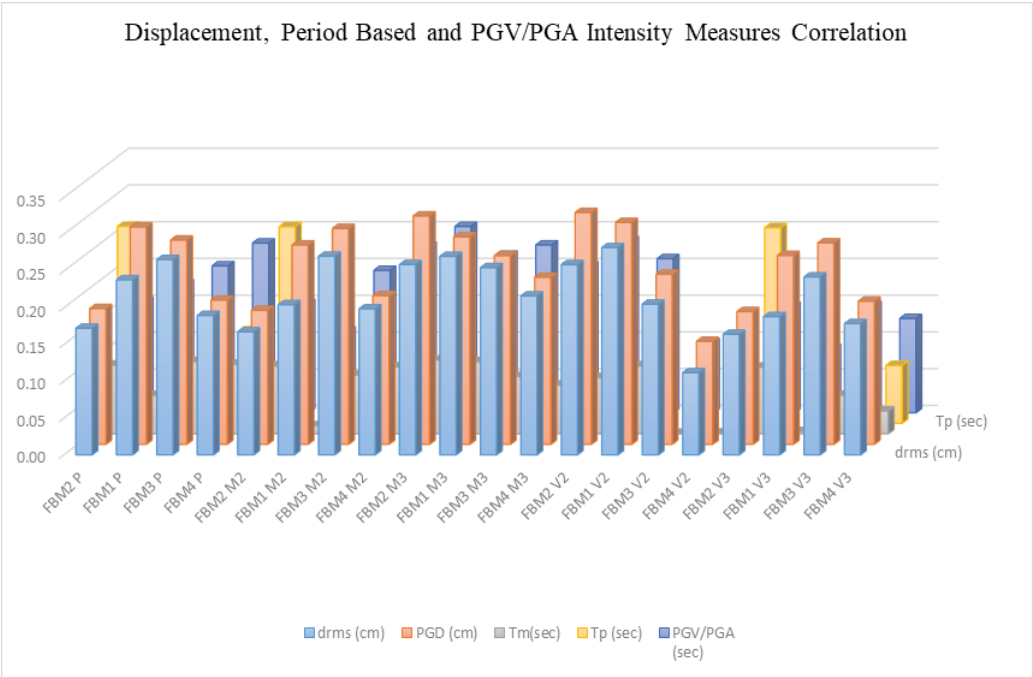


Figure B- 36 : R^2 values between displacement based and other GMIM and P(tonf)

C. Pearson's Correlation Coefficients and R^2 Values Between Ground motion intensity measures and Seismic Demand Parameters

Table C- 1:r between Acceleration based ground motion intensity measures and Seismic Demand Parameters (1/2)

	Acceleration Parameters					
Name	Sustained Maximum Acceleration (g)	Acceleration Spectrum Intensity (g*sec)	A95 parameter (g)	Max. Acceleration (g)	Effective Design Acceleration (g)	Arias Intensity: (m/sec)
FBM2 P	**0.19**	**0.20**	**0.20**	**0.20**	**0.21**	**0.24**
FBM1 P	**0.32**	**0.34**	**0.37**	**0.37**	**0.38**	**0.37**
FBM3 P	**0.21**	**0.23**	**0.25**	**0.25**	**0.26**	**0.27**
FBM4 P	**0.14**	**0.15**	**0.15**	**0.15**	**0.16**	**0.16**
FBM2 M2	**0.20**	**0.21**	**0.21**	**0.21**	**0.23**	**0.26**
FBM1 M2	**0.44**	**0.45**	**0.50**	**0.50**	**0.51**	**0.49**
FBM3 M2	**0.24**	**0.25**	**0.26**	**0.26**	**0.27**	**0.29**
FBM4 M2	**0.12**	**0.14**	**0.13**	**0.13**	**0.14**	**0.13**
FBM2 M3	**0.13**	**0.17**	**0.16**	**0.16**	**0.17**	**0.21**
FBM1 M3	**0.14**	**0.17**	**0.18**	**0.18**	**0.19**	**0.18**
FBM3 M3	**0.17**	**0.18**	**0.18**	**0.18**	**0.19**	**0.20**
FBM4 M3	**0.18**	**0.18**	**0.17**	**0.17**	**0.18**	**0.19**
FBM2 V2	**0.18**	**0.22**	**0.21**	**0.21**	**0.23**	**0.25**
FBM1 V2	**0.18**	**0.21**	**0.22**	**0.22**	**0.23**	**0.23**
FBM3 V2	**0.47**	**0.47**	**0.49**	**0.49**	**0.50**	**0.48**
FBM4 V2	**0.59**	**0.61**	**0.61**	**0.61**	**0.62**	**0.60**
FBM2 V3	**0.22**	**0.22**	**0.23**	**0.23**	**0.24**	**0.28**
FBM1 V3	**0.49**	**0.50**	**0.54**	**0.54**	**0.55**	**0.52**
FBM3 V3	**0.38**	**0.39**	**0.40**	**0.40**	**0.40**	**0.44**
FBM4 V3	**0.38**	**0.40**	**0.40**	**0.40**	**0.41**	**0.38**

Table C- 2:r between Acceleration based GMIM and Seismic Demand Parameters (2/2)

	Acceleration Parameters				
Name	Cumulative Absolute Velocity (cm/sec)	Characteristic Intensity (Ic)	Acceleration RMS: (g)	Sa (T2)	Sa (T1)
FBM2 P	**0.44**	**0.42**	**0.52**	**0.84**	**0.68**
FBM1 P	**0.47**	**0.54**	**0.63**	**0.89**	**0.83**
FBM3 P	**0.39**	**0.43**	**0.56**	**0.94**	**0.93**
FBM4 P	**0.27**	**0.34**	**0.53**	**0.92**	**0.88**
FBM2 M2	**0.45**	**0.43**	**0.52**	**0.84**	**0.69**
FBM1 M2	**0.54**	**0.62**	**0.63**	**0.82**	**0.77**
FBM3 M2	**0.43**	**0.46**	**0.58**	**0.93**	**0.93**
FBM4 M2	**0.26**	**0.32**	**0.53**	**0.92**	**0.88**
FBM2 M3	**0.39**	**0.41**	**0.58**	**0.63**	**0.96**
FBM1 M3	**0.34**	**0.37**	**0.53**	**0.85**	**0.95**
FBM3 M3	**0.32**	**0.37**	**0.54**	**0.85**	**0.90**
FBM4 M3	**0.34**	**0.38**	**0.57**	**0.87**	**0.89**
FBM2 V2	**0.41**	**0.44**	**0.60**	**0.63**	**0.94**
FBM1 V2	**0.38**	**0.41**	**0.56**	**0.85**	**0.95**
FBM3 V2	**0.52**	**0.59**	**0.60**	**0.72**	**0.76**
FBM4 V2	**0.59**	**0.71**	**0.69**	**0.58**	**0.57**
FBM2 V3	**0.46**	**0.44**	**0.53**	**0.83**	**0.69**
FBM1 V3	**0.56**	**0.64**	**0.63**	**0.78**	**0.74**
FBM3 V3	**0.52**	**0.58**	**0.62**	**0.88**	**0.89**
FBM4 V3	**0.43**	**0.54**	**0.66**	**0.82**	**0.80**

Table C- 3:r between Velocity based GMIM and Seismic Demand Parameters

	Velocity Parameters						
Name	Specific Energy Density (cm2/sec)	Velocity RMS (cm/sec)	Sustained Maximum Velocity (cm/sec)	Max Incremental Velocity (cm/sec)	Max. Velocity (cm/sec)	Housner Intensity (cm)	Velocity Spectrum Intensity (cm)
FBM2 P	**0.49**	**0.57**	**0.64**	**0.70**	**0.64**	**0.76**	**0.77**
FBM1 P	**0.49**	**0.61**	**0.70**	**0.79**	**0.76**	**0.76**	**0.80**
FBM3 P	**0.50**	**0.64**	**0.68**	**0.71**	**0.73**	**0.76**	**0.77**
FBM4 P	**0.42**	**0.61**	**0.64**	**0.64**	**0.65**	**0.72**	**0.71**
FBM2 M2	**0.49**	**0.57**	**0.64**	**0.71**	**0.64**	**0.77**	**0.78**
FBM1 M2	**0.46**	**0.55**	**0.69**	**0.78**	**0.74**	**0.73**	**0.78**
FBM3 M2	**0.53**	**0.64**	**0.70**	**0.71**	**0.73**	**0.76**	**0.78**
FBM4 M2	**0.42**	**0.61**	**0.63**	**0.62**	**0.64**	**0.70**	**0.68**
FBM2 M3	**0.54**	**0.64**	**0.68**	**0.76**	**0.73**	**0.73**	**0.76**
FBM1 M3	**0.51**	**0.65**	**0.66**	**0.69**	**0.72**	**0.75**	**0.75**
FBM3 M3	**0.49**	**0.65**	**0.67**	**0.64**	**0.68**	**0.71**	**0.71**
FBM4 M3	**0.43**	**0.62**	**0.63**	**0.62**	**0.65**	**0.70**	**0.69**
FBM2 V2	**0.54**	**0.64**	**0.69**	**0.77**	**0.74**	**0.73**	**0.76**
FBM1 V2	**0.53**	**0.65**	**0.68**	**0.70**	**0.74**	**0.76**	**0.76**
FBM3 V2	**0.46**	**0.55**	**0.68**	**0.65**	**0.68**	**0.67**	**0.71**
FBM4 V2	**0.34**	**0.44**	**0.60**	**0.67**	**0.64**	**0.63**	**0.71**
FBM2 V3	**0.49**	**0.57**	**0.64**	**0.72**	**0.65**	**0.77**	**0.79**
FBM1 V3	**0.44**	**0.52**	**0.67**	**0.76**	**0.72**	**0.70**	**0.76**
FBM3 V3	**0.52**	**0.61**	**0.71**	**0.73**	**0.73**	**0.76**	**0.79**
FBM4 V3	**0.40**	**0.57**	**0.66**	**0.69**	**0.69**	**0.70**	**0.73**

Table C- 4: r between Displacement based and other GMIM and Seismic Demand Parameters

	Displacement Parameters		Period Parameters		Other
Name	Displacement RMS: (cm)	Max. Displacement (cm)	Mean Period (sec)	Predominant Period (sec)	Vmax / Amax (sec)
FBM2 P	**0.41**	**0.43**	**0.34**	**0.52**	**0.39**
FBM1 P	**0.49**	**0.54**	**0.33**	**0.37**	**0.42**
FBM3 P	**0.52**	**0.53**	**0.33**	**0.30**	**0.45**
FBM4 P	**0.44**	**0.44**	**0.37**	**0.35**	**0.48**
FBM2 M2	**0.41**	**0.43**	**0.34**	**0.52**	**0.39**
FBM1 M2	**0.45**	**0.52**	**0.31**	**0.31**	**0.33**
FBM3 M2	**0.52**	**0.54**	**0.32**	**0.30**	**0.44**
FBM4 M2	**0.45**	**0.45**	**0.35**	**0.33**	**0.48**
FBM2 M3	**0.51**	**0.56**	**0.33**	**0.43**	**0.50**
FBM1 M3	**0.52**	**0.53**	**0.34**	**0.29**	**0.46**
FBM3 M3	**0.50**	**0.51**	**0.35**	**0.31**	**0.48**
FBM4 M3	**0.46**	**0.48**	**0.32**	**0.29**	**0.45**
FBM2 V2	**0.51**	**0.56**	**0.33**	**0.41**	**0.48**
FBM1 V2	**0.53**	**0.55**	**0.33**	**0.29**	**0.46**
FBM3 V2	**0.45**	**0.48**	**0.30**	**0.22**	**0.31**
FBM4 V2	**0.33**	**0.37**	**0.14**	**0.20**	**0.19**
FBM2 V3	**0.40**	**0.42**	**0.33**	**0.52**	**0.38**
FBM1 V3	**0.43**	**0.51**	**0.30**	**0.28**	**0.30**
FBM3 V3	**0.49**	**0.52**	**0.27**	**0.28**	**0.38**
FBM4 V3	**0.42**	**0.44**	**0.26**	**0.28**	**0.36**

Table C- 5: R^2 values between Acceleration based GMIM and Seismic Demand Parameters (1/2)

	Acceleration Parameters					
Name	Sustained Maximum Acceleration (g)	Acceleration Spectrum Intensity (g*sec)	A95 parameter (g)	Max. Acceleration (g)	Effective Design Acceleration (g)	Arias Intensity: (m/sec)
FBM2 P	**0.04**	**0.04**	**0.04**	**0.04**	**0.04**	**0.06**
FBM1 P	**0.10**	**0.11**	**0.13**	**0.14**	**0.14**	**0.14**
FBM3 P	**0.04**	**0.05**	**0.06**	**0.06**	**0.07**	**0.07**
FBM4 P	**0.02**	**0.02**	**0.02**	**0.02**	**0.03**	**0.03**
FBM2 M2	**0.04**	**0.04**	**0.04**	**0.05**	**0.05**	**0.07**
FBM1 M2	**0.20**	**0.21**	**0.25**	**0.25**	**0.26**	**0.24**
FBM3 M2	**0.06**	**0.06**	**0.07**	**0.07**	**0.07**	**0.09**
FBM4 M2	**0.01**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**
FBM2 M3	**0.02**	**0.03**	**0.02**	**0.02**	**0.03**	**0.04**
FBM1 M3	**0.02**	**0.03**	**0.03**	**0.03**	**0.04**	**0.03**
FBM3 M3	**0.03**	**0.03**	**0.03**	**0.03**	**0.04**	**0.04**
FBM4 M3	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.04**
FBM2 V2	**0.03**	**0.05**	**0.05**	**0.05**	**0.05**	**0.06**
FBM1 V2	**0.03**	**0.04**	**0.05**	**0.05**	**0.05**	**0.05**
FBM3 V2	**0.22**	**0.22**	**0.24**	**0.24**	**0.25**	**0.23**
FBM4 V2	**0.35**	**0.37**	**0.38**	**0.38**	**0.38**	**0.36**
FBM2 V3	**0.05**	**0.05**	**0.05**	**0.05**	**0.06**	**0.08**
FBM1 V3	**0.24**	**0.25**	**0.29**	**0.29**	**0.31**	**0.27**
FBM3 V3	**0.14**	**0.15**	**0.16**	**0.16**	**0.16**	**0.19**
FBM4 V3	**0.14**	**0.16**	**0.16**	**0.16**	**0.17**	**0.14**

Table C- 6: R^2 values between Acceleration based GMIM and Seismic Demand Parameters (2/2)

	Acceleration Parameters				
Name	Cumulative Absolute Velocity (cm/sec)	Characteristic Intensity (Ic)	Acceleration RMS: (g)	Sa (T2)	Sa (T1)
FBM2 P	**0.19**	**0.18**	**0.27**	**0.71**	**0.47**
FBM1 P	**0.22**	**0.29**	**0.39**	**0.79**	**0.69**
FBM3 P	**0.15**	**0.18**	**0.31**	**0.89**	**0.87**
FBM4 P	**0.07**	**0.11**	**0.28**	**0.85**	**0.78**
FBM2 M2	**0.20**	**0.19**	**0.27**	**0.70**	**0.47**
FBM1 M2	**0.29**	**0.38**	**0.40**	**0.67**	**0.60**
FBM3 M2	**0.19**	**0.21**	**0.33**	**0.87**	**0.87**
FBM4 M2	**0.07**	**0.10**	**0.28**	**0.85**	**0.78**
FBM2 M3	**0.15**	**0.17**	**0.34**	**0.39**	**0.91**
FBM1 M3	**0.12**	**0.13**	**0.28**	**0.73**	**0.91**
FBM3 M3	**0.10**	**0.13**	**0.29**	**0.73**	**0.81**
FBM4 M3	**0.12**	**0.15**	**0.33**	**0.76**	**0.79**
FBM2 V2	**0.17**	**0.20**	**0.36**	**0.39**	**0.89**
FBM1 V2	**0.15**	**0.17**	**0.31**	**0.72**	**0.89**
FBM3 V2	**0.27**	**0.34**	**0.35**	**0.51**	**0.57**
FBM4 V2	**0.35**	**0.51**	**0.48**	**0.33**	**0.33**
FBM2 V3	**0.21**	**0.20**	**0.28**	**0.70**	**0.47**
FBM1 V3	**0.32**	**0.41**	**0.39**	**0.62**	**0.55**
FBM3 V3	**0.27**	**0.33**	**0.39**	**0.78**	**0.79**
FBM4 V3	**0.18**	**0.29**	**0.44**	**0.68**	**0.64**

Table C- 7: R^2 values between Velocity based GMIM and Seismic Demand Parameters

	Velocity Parameters						
Name	Specific Energy Density (cm2/sec)	Velocity RMS (cm/sec)	Sustained Maximum Velocity (cm/sec)	Max Incremental Velocity (cm/sec)	Max. Velocity (cm/sec)	Housner Intensity (cm)	Velocity Spectrum Intensity (cm)
FBM2 P	**0.24**	**0.33**	**0.41**	**0.49**	**0.41**	**0.58**	**0.60**
FBM1 P	**0.24**	**0.37**	**0.49**	**0.62**	**0.58**	**0.58**	**0.64**
FBM3 P	**0.25**	**0.41**	**0.46**	**0.50**	**0.53**	**0.58**	**0.60**
FBM4 P	**0.17**	**0.37**	**0.41**	**0.42**	**0.42**	**0.51**	**0.50**
FBM2 M2	**0.24**	**0.32**	**0.41**	**0.50**	**0.41**	**0.59**	**0.61**
FBM1 M2	**0.21**	**0.31**	**0.47**	**0.60**	**0.55**	**0.53**	**0.61**
FBM3 M2	**0.28**	**0.41**	**0.49**	**0.50**	**0.54**	**0.58**	**0.60**
FBM4 M2	**0.17**	**0.37**	**0.40**	**0.39**	**0.41**	**0.48**	**0.47**
FBM2 M3	**0.29**	**0.41**	**0.46**	**0.58**	**0.53**	**0.54**	**0.57**
FBM1 M3	**0.26**	**0.42**	**0.44**	**0.48**	**0.52**	**0.56**	**0.56**
FBM3 M3	**0.24**	**0.42**	**0.45**	**0.41**	**0.46**	**0.51**	**0.50**
FBM4 M3	**0.19**	**0.38**	**0.40**	**0.39**	**0.42**	**0.49**	**0.48**
FBM2 V2	**0.29**	**0.40**	**0.48**	**0.59**	**0.55**	**0.53**	**0.58**
FBM1 V2	**0.28**	**0.43**	**0.47**	**0.50**	**0.54**	**0.57**	**0.58**
FBM3 V2	**0.21**	**0.31**	**0.46**	**0.43**	**0.46**	**0.45**	**0.50**
FBM4 V2	**0.12**	**0.20**	**0.37**	**0.45**	**0.41**	**0.40**	**0.50**
FBM2 V3	**0.24**	**0.32**	**0.41**	**0.51**	**0.42**	**0.59**	**0.62**
FBM1 V3	**0.20**	**0.27**	**0.46**	**0.58**	**0.52**	**0.50**	**0.58**
FBM3 V3	**0.27**	**0.37**	**0.50**	**0.53**	**0.54**	**0.57**	**0.62**
FBM4 V3	**0.16**	**0.32**	**0.44**	**0.47**	**0.47**	**0.48**	**0.53**

Table C- 8: R^2 values between Displacement based and other GMIM and Seismic Demand Parameters

	Displacement Parameters		**Period Parameters**		**Other**
Name	Displacement RMS: (cm)	Max. Displacement (cm)	Mean Period (sec)	Predominant Period (sec)	Vmax / Amax (sec)
FBM2 P	**0.17**	**0.18**	**0.09**	**0.27**	**0.15**
FBM1 P	**0.24**	**0.30**	**0.05**	**0.14**	**0.18**
FBM3 P	**0.27**	**0.28**	**0.10**	**0.09**	**0.20**
FBM4 P	**0.19**	**0.20**	**0.09**	**0.13**	**0.23**
FBM2 M2	**0.17**	**0.18**	**0.09**	**0.27**	**0.15**
FBM1 M2	**0.20**	**0.27**	**0.01**	**0.10**	**0.11**
FBM3 M2	**0.27**	**0.29**	**0.08**	**0.09**	**0.19**
FBM4 M2	**0.20**	**0.20**	**0.09**	**0.11**	**0.23**
FBM2 M3	**0.26**	**0.31**	**0.10**	**0.18**	**0.25**
FBM1 M3	**0.27**	**0.28**	**0.10**	**0.09**	**0.21**
FBM3 M3	**0.25**	**0.26**	**0.08**	**0.09**	**0.23**
FBM4 M3	**0.22**	**0.23**	**0.07**	**0.08**	**0.20**
FBM2 V2	**0.26**	**0.32**	**0.08**	**0.17**	**0.23**
FBM1 V2	**0.28**	**0.30**	**0.09**	**0.09**	**0.21**
FBM3 V2	**0.20**	**0.23**	**0.00**	**0.05**	**0.10**
FBM4 V2	**0.11**	**0.14**	**0.00**	**0.04**	**0.04**
FBM2 V3	**0.16**	**0.18**	**0.09**	**0.27**	**0.14**
FBM1 V3	**0.19**	**0.26**	**0.00**	**0.08**	**0.09**
FBM3 V3	**0.24**	**0.27**	**0.05**	**0.08**	**0.15**
FBM4 V3	**0.18**	**0.19**	**0.03**	**0.08**	**0.13**

D. Compressive Stress, Rotation, and Stability Check of Elastomeric Bearings

Since elastomeric bearings are more critical in FBM1, FBM3 and FBM4, checks are conducted only for these elastomeric bearings because same superstructure is carried by 12 elastomeric bearings in FBM2 while by 4 elastomeric bearings in FBM1, FBM3 and FBM4.

- Geometric and Material Properties

Table D- 1:Geometric and Material Properties of Elastomeric Bearings

Elastomeric bearing shear modulus, G=1.00Mpa
Elastomeric bearing length, L_{bp}=500mm
Elastomeric bearing width, W_{bp}=500mm
Area of elastomeric bearing, A_{bp}=250,000mm2
Steel plate yield strength, F_y=235Mpa
Layer thickness of elastomeric bearing, h_{ri}=10mm
Number of layer, nlayer=8
Total layer height, hbp=80mm
Steel plate thickness, hs=2mm
Number of steel plate=7
Height, h=94mm
Elastic modulus of the system, E=750.0Mpa
Number of Elastomeric Bearing, n_{bp}=4

- Loads from Superstructure

Load per bearing under all loads = P_S =316.00/4=79.00t = 774,990N

Load per bearing under live loads = P_L=218.00/4=54.50t = 534,645N

Shape Factor :S = (L. W) / (2. hri . (L + W)) >> S=12.5 *(11)*

- Compressive Stress Check:

σ_S<Min. (1.66 GS, 11Mpa) (σ_S=Comp. stress under all loads (MPa))

σ_L<0.66 GS (σ_L=Comp. stress under live loads (MPa))

1.66 GS=1.66x1.00x12.50=20.75MPa>11.00MPa

$\sigma_S = P_s / A$ *(12)*

=774,990/250,000=3.10MPa<11.00MPa

0.66 GS=0.66x1.00x12.50=8.25MPa

$\sigma_L = P_L / A$ *(13)*

=534,645/250,000=2.14MPa<8.25MPa

- Rotation Check

σ_S<1.875 GS [1- 0.20 (θS / n) (B / hri)²] (θS= Rotation under all loads (rad) = 0.0053 rad) >> σ_S=3.10MPa < 14.209MPa

- Stability Check:

A = 1.92(h_{rt} / L) / (1+ (2L / W))1/2 *(14)*

B = 2.67/(S + 2) (1+ (L / 4 W)) *(15)*

2A=0.355>B=0.147

Since requirement above did not met, compressive stress check should be done according to clause LRFD- 14.7.5.3.6.

σ_S<GS / (2A - B) *(16)*

σ_S=3.10MPa<60.27MPa

E. Ground Motion Intensity Measures

Table E- 1: Acceleration based GMIM 1/5

	Acceleration Parameters					
Name	Max. Acceleration (g)	Acceleration RMS: (g)	Arias Intensity: (m/sec)	Characteristic Intensity (Ic)	Cumulative Absolute Velocity (cm/sec)	Acceleration Spectrum Intensity (g*sec)
60CI1_H1	0.21	0.03	0.34	0.02	400.07	0.18
60CI1_H2	0.19	0.03	0.43	0.03	473.50	0.18
60CI2_H1	0.16	0.01	0.13	0.01	265.43	0.12
60CI2_H2	0.09	0.01	0.09	0.01	246.90	0.10
60CI3_H1	0.08	0.01	0.06	0.01	197.00	0.09
60CI3_H2	0.11	0.01	0.09	0.01	215.56	0.10
60CI4_H1	0.12	0.01	0.12	0.01	313.57	0.08
60CI4_H2	0.09	0.01	0.08	0.01	269.70	0.06
60CI5_H1	0.36	0.03	0.45	0.03	358.92	0.30
60CI5_H2	0.27	0.03	0.31	0.02	321.67	0.26
60CI6_H1	0.09	0.01	0.08	0.01	207.58	0.04
60CI6_H2	0.11	0.02	0.10	0.01	211.68	0.05
60CI7_H1	0.15	0.02	0.26	0.02	383.66	0.14
60CI7_H2	0.13	0.02	0.19	0.02	332.23	0.11
60DI1_H1	0.10	0.01	0.12	0.01	303.91	0.09
60DI1_H2	0.18	0.02	0.17	0.01	342.74	0.11
60DI2_H1	0.08	0.02	0.14	0.01	395.65	0.07
60DI2_H2	0.08	0.01	0.14	0.01	395.18	0.09
60DI3_H1	0.10	0.02	0.10	0.01	244.41	0.09
60DI3_H2	0.10	0.02	0.08	0.01	218.84	0.06
60DI4_H1	0.03	0.01	0.05	0.00	295.08	0.04
60DI4_H2	0.03	0.01	0.06	0.01	353.81	0.03
60DI5_H1	0.18	0.02	0.39	0.02	635.69	0.19
60DI5_H2	0.15	0.02	0.33	0.02	605.10	0.14
60DI6_H1	0.41	0.05	1.28	0.07	730.11	0.25
60DI6_H2	0.21	0.03	0.35	0.03	476.52	0.16
60DI7_H1	0.13	0.01	0.12	0.01	339.28	0.09
60DI7_H2	0.10	0.01	0.09	0.01	305.33	0.09
65CI1_H1	0.11	0.01	0.09	0.01	234.97	0.08
65CI1_H2	0.20	0.02	0.21	0.02	301.35	0.15
65CI2_H1	0.16	0.03	0.32	0.02	472.13	0.13
65CI2_H2	0.11	0.02	0.20	0.02	406.89	0.10
65CI3_H1	0.15	0.04	0.54	0.04	610.19	0.17
65CI3_H2	0.12	0.03	0.31	0.02	479.53	0.12
65CI4_H1	0.17	0.04	1.22	0.05	1416.29	0.20
65CI4_H2	0.16	0.04	1.34	0.06	1589.70	0.17
65CI5_H1	0.54	0.03	3.21	0.07	1992.53	0.38
65CI5_H2	0.82	0.04	7.19	0.14	2510.24	0.66
65CI6_H1	0.58	0.02	2.65	0.06	1910.35	0.41
65CI6_H2	0.32	0.02	1.10	0.03	1291.64	0.26
65CI7_H1	0.18	0.02	1.08	0.03	1481.17	0.14
65CI7_H2	0.29	0.02	1.33	0.04	1557.02	0.17

Table E- 2: Acceleration based GMIM 2/5

	Acceleration Parameters					
Name	Max. Acceleration (g)	Acceleration RMS: (g)	Arias Intensity: (m/sec)	Characteristic Intensity (Ic)	Cumulative Absolute Velocity (cm/sec)	Acceleration Spectrum Intensity (g*sec)
65DI1_H1	0.36	0.03	1.10	0.05	1126.22	0.27
65DI1_H2	0.26	0.03	0.74	0.04	1037.35	0.20
65DI2_H1	0.14	0.03	0.40	0.03	647.61	0.13
65DI2_H2	0.12	0.02	0.34	0.02	586.79	0.11
65DI3_H1	0.13	0.02	0.15	0.01	397.69	0.10
65DI3_H2	0.08	0.01	0.10	0.01	339.05	0.08
65DI4_H1	0.16	0.03	0.55	0.03	691.70	0.14
65DI4_H2	0.20	0.02	0.38	0.02	553.55	0.12
65DI5_H1	0.14	0.02	0.29	0.02	492.91	0.11
65DI5_H2	0.14	0.02	0.22	0.02	455.57	0.09
65DI6_H1	0.15	0.03	0.36	0.03	500.82	0.13
65DI6_H2	0.10	0.03	0.29	0.02	510.68	0.09
65DI7_H1	0.29	0.01	0.84	0.03	1183.42	0.26
65DI7_H2	0.34	0.01	0.75	0.03	1051.72	0.23
70CI1_H1	0.22	0.04	1.21	0.05	1371.47	0.21
70CI1_H2	0.21	0.04	1.22	0.05	1350.83	0.23
70CI2_H1	0.16	0.02	0.93	0.04	1261.06	0.16
70CI2_H2	0.16	0.02	1.01	0.04	1315.28	0.17
70CI3_H1	0.22	0.04	1.20	0.05	1309.10	0.19
70CI3_H2	0.16	0.03	0.71	0.04	1109.03	0.12
70CI4_H1	0.58	0.04	3.83	0.10	2023.46	0.53
70CI4_H2	0.63	0.04	4.12	0.11	2211.20	0.50
70CI5_H1	0.12	0.03	0.61	0.03	1026.20	0.12
70CI5_H2	0.12	0.03	0.55	0.03	982.32	0.10
70CI6_H1	0.14	0.03	0.69	0.04	1120.00	0.11
70CI6_H2	0.14	0.03	0.58	0.03	1014.77	0.13
70CI7_H1	0.36	0.03	0.69	0.04	709.66	0.19
70CI7_H2	0.24	0.03	0.68	0.04	740.48	0.23
70DI1_H1	0.25	0.03	2.07	0.07	2388.49	0.21
70DI1_H2	0.20	0.03	2.30	0.07	2531.18	0.21
70DI2_H1	0.21	0.03	2.14	0.07	2430.47	0.21
70DI2_H2	0.23	0.03	1.85	0.06	2286.51	0.22
70DI3_H1	0.17	0.03	0.94	0.04	1296.36	0.14
70DI3_H2	0.18	0.02	0.67	0.03	1042.38	0.18
70DI4_H1	0.11	0.01	0.27	0.01	734.52	0.13
70DI4_H2	0.08	0.01	0.22	0.01	706.88	0.08
70DI5_H1	0.22	0.02	0.58	0.02	1139.12	0.17
70DI5_H2	0.23	0.02	0.58	0.02	1210.52	0.14
70DI6_H1	0.18	0.03	1.42	0.06	1532.16	0.14
70DI6_H2	0.22	0.03	0.90	0.04	1301.92	0.15
70DI7_H1	0.21	0.02	1.25	0.04	1671.35	0.14
70DI7_H2	0.13	0.01	0.56	0.02	1312.02	0.10

Table E- 3: Acceleration based GMIM 3/5

Name	Sustained Maximum Acceleration (g)	Effective Design Acceleration (g)	A95 parameter (g)	Sa (T1)-FBM1	Sa (T1)-FBM2	Sa (T1)-FBM3	Sa (T1)-FBM4
60CI1_H1	0.13	0.21	0.21	0.07	0.18	0.03	0.02
60CI1_H2	0.19	0.19	0.19	0.03	0.07	0.01	0.01
60CI2_H1	0.09	0.16	0.16	0.03	0.05	0.02	0.02
60CI2_H2	0.08	0.09	0.09	0.04	0.04	0.02	0.02
60CI3_H1	0.05	0.08	0.08	0.07	0.11	0.05	0.02
60CI3_H2	0.07	0.11	0.11	0.10	0.19	0.04	0.03
60CI4_H1	0.06	0.12	0.12	0.19	0.18	0.08	0.05
60CI4_H2	0.06	0.09	0.09	0.07	0.15	0.04	0.04
60CI5_H1	0.09	0.36	0.35	0.13	0.15	0.05	0.04
60CI5_H2	0.11	0.28	0.27	0.04	0.07	0.02	0.02
60CI6_H1	0.07	0.08	0.09	0.04	0.07	0.02	0.03
60CI6_H2	0.09	0.11	0.11	0.03	0.03	0.03	0.03
60CI7_H1	0.13	0.15	0.15	0.19	0.23	0.12	0.10
60CI7_H2	0.10	0.13	0.13	0.19	0.16	0.09	0.05
60DI1_H1	0.10	0.10	0.10	0.02	0.06	0.02	0.03
60DI1_H2	0.12	0.17	0.17	0.03	0.07	0.02	0.02
60DI2_H1	0.06	0.08	0.08	0.18	0.17	0.09	0.05
60DI2_H2	0.07	0.08	0.08	0.09	0.13	0.05	0.04
60DI3_H1	0.09	0.10	0.10	0.03	0.04	0.02	0.01
60DI3_H2	0.08	0.09	0.10	0.02	0.04	0.02	0.01
60DI4_H1	0.03	0.03	0.03	0.06	0.08	0.04	0.04
60DI4_H2	0.03	0.03	0.03	0.09	0.11	0.05	0.06
60DI5_H1	0.13	0.17	0.17	0.10	0.18	0.14	0.10
60DI5_H2	0.12	0.15	0.15	0.10	0.18	0.14	0.10
60DI6_H1	0.19	0.41	0.40	0.47	0.72	0.28	0.18
60DI6_H2	0.13	0.20	0.21	0.15	0.16	0.13	0.07
60DI7_H1	0.08	0.13	0.12	0.13	0.18	0.07	0.04
60DI7_H2	0.06	0.10	0.10	0.11	0.11	0.06	0.05
65CI1_H1	0.06	0.11	0.11	0.02	0.04	0.03	0.02
65CI1_H2	0.14	0.19	0.20	0.04	0.05	0.04	0.03
65CI2_H1	0.13	0.16	0.16	0.09	0.07	0.05	0.03
65CI2_H2	0.09	0.11	0.11	0.08	0.15	0.05	0.05
65CI3_H1	0.14	0.15	0.14	0.24	0.17	0.13	0.14
65CI3_H2	0.11	0.12	0.12	0.14	0.35	0.16	0.09
65CI4_H1	0.16	0.16	0.16	0.04	0.08	0.03	0.04
65CI4_H2	0.15	0.15	0.15	0.05	0.11	0.07	0.04
65CI5_H1	0.43	0.51	0.53	0.01	0.04	0.01	0.01
65CI5_H2	0.56	0.75	0.81	0.04	0.09	0.03	0.02
65CI6_H1	0.37	0.58	0.57	0.13	0.15	0.06	0.03
65CI6_H2	0.26	0.32	0.32	0.03	0.07	0.03	0.02
65CI7_H1	0.17	0.18	0.18	0.05	0.10	0.04	0.05
65CI7_H2	0.22	0.29	0.28	0.05	0.05	0.05	0.03

Table E- 4: Acceleration based GMIM 4/5

	Acceleration Parameters						
Name	Sustained Maximum Acceleration (g)	Effective Design Acceleration (g)	A95 parameter (g)	Sa (T1)-FBM1	Sa (T1)-FBM2	Sa (T1)-FBM3	Sa (T1)-FBM4
65DI1_H1	0.15	0.35	0.35	0.45	0.50	0.22	0.20
65DI1_H2	0.14	0.26	0.26	0.31	0.17	0.30	0.34
65DI2_H1	0.11	0.14	0.14	0.18	0.18	0.12	0.13
65DI2_H2	0.10	0.12	0.12	0.14	0.14	0.13	0.09
65DI3_H1	0.07	0.13	0.13	0.08	0.10	0.07	0.06
65DI3_H2	0.06	0.08	0.08	0.09	0.11	0.07	0.05
65DI4_H1	0.14	0.16	0.16	0.37	0.33	0.39	0.33
65DI4_H2	0.11	0.20	0.20	0.33	0.44	0.24	0.16
65DI5_H1	0.13	0.14	0.14	0.07	0.10	0.09	0.09
65DI5_H2	0.09	0.14	0.13	0.05	0.07	0.06	0.07
65DI6_H1	0.12	0.15	0.15	0.09	0.21	0.04	0.05
65DI6_H2	0.08	0.10	0.09	0.12	0.15	0.11	0.10
65DI7_H1	0.21	0.27	0.28	0.04	0.07	0.02	0.01
65DI7_H2	0.15	0.31	0.33	0.04	0.07	0.02	0.01
70CI1_H1	0.15	0.21	0.21	0.12	0.45	0.07	0.05
70CI1_H2	0.18	0.20	0.20	0.13	0.34	0.13	0.08
70CI2_H1	0.14	0.16	0.16	0.22	0.46	0.14	0.10
70CI2_H2	0.16	0.16	0.16	0.24	0.43	0.21	0.13
70CI3_H1	0.18	0.22	0.22	0.26	0.33	0.28	0.20
70CI3_H2	0.11	0.16	0.16	0.18	0.23	0.30	0.30
70CI4_H1	0.45	0.57	0.57	0.12	0.26	0.07	0.09
70CI4_H2	0.46	0.63	0.62	0.10	0.16	0.05	0.04
70CI5_H1	0.11	0.12	0.12	0.06	0.24	0.05	0.04
70CI5_H2	0.11	0.12	0.12	0.07	0.08	0.05	0.05
70CI6_H1	0.10	0.14	0.14	0.22	0.15	0.15	0.20
70CI6_H2	0.10	0.14	0.13	0.11	0.21	0.09	0.10
70CI7_H1	0.23	0.35	0.35	0.14	0.17	0.07	0.08
70CI7_H2	0.21	0.24	0.24	0.12	0.23	0.05	0.04
70DI1_H1	0.21	0.25	0.24	0.38	0.52	0.15	0.12
70DI1_H2	0.19	0.19	0.19	0.28	0.40	0.15	0.13
70DI2_H1	0.19	0.20	0.20	0.27	0.50	0.18	0.20
70DI2_H2	0.18	0.23	0.22	0.18	0.40	0.16	0.22
70DI3_H1	0.16	0.17	0.17	0.22	0.35	0.27	0.23
70DI3_H2	0.15	0.17	0.17	0.19	0.28	0.11	0.09
70DI4_H1	0.09	0.11	0.11	0.09	0.12	0.08	0.04
70DI4_H2	0.07	0.08	0.08	0.07	0.06	0.08	0.05
70DI5_H1	0.16	0.22	0.22	0.06	0.09	0.07	0.09
70DI5_H2	0.14	0.22	0.23	0.11	0.12	0.08	0.07
70DI6_H1	0.16	0.18	0.18	0.11	0.31	0.13	0.12
70DI6_H2	0.13	0.21	0.21	0.14	0.31	0.07	0.08
70DI7_H1	0.18	0.21	0.21	0.14	0.18	0.09	0.08
70DI7_H2	0.12	0.13	0.12	0.07	0.12	0.05	0.05

Table E- 5: Acceleration based GMIM 5/5

Name	Sa (T2)-FBM1	Sa (T2)-FBM2	Sa (T2)-FBM3	Sa (T2)-FBM4
60CI1_H1	0.08	0.33	0.07	0.03
60CI1_H2	0.03	0.21	0.03	0.02
60CI2_H1	0.04	0.16	0.03	0.02
60CI2_H2	0.04	0.26	0.04	0.03
60CI3_H1	0.11	0.26	0.07	0.05
60CI3_H2	0.18	0.27	0.11	0.04
60CI4_H1	0.16	0.16	0.20	0.08
60CI4_H2	0.14	0.11	0.08	0.04
60CI5_H1	0.22	0.49	0.14	0.05
60CI5_H2	0.06	0.11	0.04	0.02
60CI6_H1	0.05	0.06	0.05	0.02
60CI6_H2	0.02	0.06	0.02	0.03
60CI7_H1	0.20	0.52	0.17	0.12
60CI7_H2	0.12	0.34	0.17	0.10
60DI1_H1	0.03	0.12	0.02	0.02
60DI1_H2	0.05	0.21	0.03	0.02
60DI2_H1	0.18	0.17	0.18	0.10
60DI2_H2	0.13	0.19	0.10	0.05
60DI3_H1	0.03	0.08	0.03	0.02
60DI3_H2	0.03	0.08	0.02	0.02
60DI4_H1	0.07	0.11	0.06	0.03
60DI4_H2	0.12	0.07	0.09	0.05
60DI5_H1	0.16	0.23	0.10	0.13
60DI5_H2	0.16	0.23	0.10	0.13
60DI6_H1	0.71	0.63	0.49	0.29
60DI6_H2	0.13	0.32	0.14	0.14
60DI7_H1	0.16	0.18	0.14	0.08
60DI7_H2	0.10	0.17	0.11	0.06
65CI1_H1	0.03	0.09	0.02	0.03
65CI1_H2	0.05	0.13	0.04	0.04
65CI2_H1	0.07	0.12	0.08	0.05
65CI2_H2	0.08	0.16	0.07	0.05
65CI3_H1	0.23	0.36	0.26	0.14
65CI3_H2	0.15	0.20	0.14	0.16
65CI4_H1	0.06	0.10	0.04	0.03
65CI4_H2	0.09	0.30	0.05	0.07
65CI5_H1	0.03	0.08	0.02	0.01
65CI5_H2	0.07	0.18	0.05	0.03
65CI6_H1	0.12	0.35	0.12	0.07
65CI6_H2	0.04	0.20	0.03	0.03
65CI7_H1	0.09	0.14	0.05	0.04
65CI7_H2	0.04	0.13	0.05	0.05

Name	Sa (T2)-FBM1	Sa (T2)-FBM2	Sa (T2)-FBM3	Sa (T2)-FBM4
65DI1_H1	0.33	0.63	0.47	0.23
65DI1_H2	0.25	0.58	0.31	0.30
65DI2_H1	0.20	0.22	0.18	0.12
65DI2_H2	0.15	0.20	0.13	0.13
65DI3_H1	0.10	0.12	0.08	0.07
65DI3_H2	0.11	0.11	0.09	0.07
65DI4_H1	0.27	0.32	0.35	0.39
65DI4_H2	0.38	0.34	0.34	0.25
65DI5_H1	0.11	0.21	0.07	0.09
65DI5_H2	0.07	0.15	0.06	0.06
65DI6_H1	0.16	0.22	0.10	0.05
65DI6_H2	0.16	0.15	0.14	0.11
65DI7_H1	0.05	0.11	0.04	0.02
65DI7_H2	0.06	0.14	0.04	0.02
70CI1_H1	0.22	0.48	0.13	0.07
70CI1_H2	0.22	0.36	0.12	0.12
70CI2_H1	0.38	0.43	0.23	0.14
70CI2_H2	0.33	0.49	0.25	0.22
70CI3_H1	0.25	0.78	0.25	0.29
70CI3_H2	0.17	0.38	0.19	0.31
70CI4_H1	0.23	0.87	0.12	0.07
70CI4_H2	0.16	0.39	0.10	0.05
70CI5_H1	0.14	0.19	0.06	0.05
70CI5_H2	0.11	0.19	0.07	0.05
70CI6_H1	0.26	0.25	0.22	0.15
70CI6_H2	0.14	0.21	0.11	0.10
70CI7_H1	0.17	0.27	0.16	0.07
70CI7_H2	0.16	0.57	0.11	0.06
70DI1_H1	0.42	0.63	0.34	0.16
70DI1_H2	0.22	0.56	0.29	0.15
70DI2_H1	0.42	0.32	0.32	0.17
70DI2_H2	0.27	0.28	0.18	0.16
70DI3_H1	0.29	0.45	0.21	0.27
70DI3_H2	0.23	0.37	0.18	0.12
70DI4_H1	0.11	0.25	0.09	0.08
70DI4_H2	0.07	0.12	0.08	0.08
70DI5_H1	0.09	0.36	0.05	0.07
70DI5_H2	0.09	0.18	0.13	0.08
70DI6_H1	0.17	0.89	0.12	0.12
70DI6_H2	0.26	0.53	0.15	0.08
70DI7_H1	0.18	0.64	0.17	0.09
70DI7_H2	0.10	0.32	0.08	0.05

Table E- 6: Velocity based GMIM 1/2

Name	Max. Velocity (cm/sec)	Velocity RMS (cm/sec)	Specific Energy Density (cm2/sec)	Velocity Spectrum Intensity (cm)	Housner Intensity (cm)	Sustained Maximum Velocity (cm/sec)	Max Incremental Velocity (cm/sec)
60CI1_H1	11.70	1.83	94.95	46.53	33.76	10.24	21.96
60CI1_H2	8.09	1.22	42.42	26.85	17.35	6.03	12.66
60CI2_H1	7.18	0.87	30.28	22.09	17.51	4.24	11.63
60CI2_H2	5.58	0.94	35.27	21.06	17.32	4.44	8.48
60CI3_H1	6.61	1.26	44.89	28.70	26.45	4.52	11.13
60CI3_H2	10.70	1.67	79.40	43.70	34.09	7.09	18.68
60CI4_H1	14.51	2.30	374.55	48.16	47.91	9.62	20.36
60CI4_H2	9.39	1.93	265.12	33.97	32.93	8.06	14.32
60CI5_H1	22.17	2.58	202.84	72.28	52.11	10.14	33.22
60CI5_H2	15.40	2.23	150.65	55.55	48.30	9.97	25.66
60CI6_H1	5.85	1.30	43.72	20.75	21.10	4.66	4.11
60CI6_H2	5.47	1.09	30.83	16.85	16.36	4.21	4.04
60CI7_H1	8.20	1.29	48.38	32.02	23.52	5.70	13.14
60CI7_H2	6.66	1.07	33.39	24.37	18.25	5.31	8.69
60DI1_H1	4.33	0.94	35.02	21.79	17.32	4.10	7.13
60DI1_H2	7.57	0.98	38.21	22.17	18.13	4.35	10.36
60DI2_H1	9.49	2.51	252.96	48.03	42.84	7.84	17.99
60DI2_H2	7.06	1.66	110.16	33.76	30.64	5.69	11.20
60DI3_H1	4.60	1.03	22.61	17.57	13.49	3.32	7.72
60DI3_H2	4.94	1.18	29.68	14.69	11.16	3.79	5.88
60DI4_H1	5.24	1.49	133.13	25.59	26.45	4.81	9.30
60DI4_H2	5.63	1.86	206.96	33.53	33.34	5.29	9.00
60DI5_H1	18.13	3.03	828.23	79.89	81.82	14.04	31.91
60DI5_H2	18.85	3.38	1027.64	61.02	59.93	14.60	33.45
60DI6_H1	53.07	6.49	1195.16	192.55	162.13	26.94	85.01
60DI6_H2	12.83	2.70	207.77	63.32	55.32	10.58	16.40
60DI7_H1	9.96	2.40	230.55	46.16	44.49	7.31	13.55
60DI7_H2	6.47	2.12	178.68	34.44	33.41	5.29	10.13
65CI1_H1	5.06	1.36	52.44	15.46	14.35	4.15	5.01
65CI1_H2	8.92	1.54	67.61	27.18	21.35	6.24	9.90
65CI2_H1	7.11	1.68	80.22	33.30	28.25	6.11	9.73
65CI2_H2	8.08	1.73	84.92	36.74	31.49	5.82	11.66
65CI3_H1	15.97	4.16	492.77	84.99	78.75	14.23	30.19
65CI3_H2	12.52	3.22	294.30	69.78	62.40	10.92	20.60
65CI4_H1	11.55	3.16	638.23	59.97	51.85	10.72	20.94
65CI4_H2	19.28	4.75	1442.44	87.75	79.22	15.64	28.33
65CI5_H1	13.62	0.82	199.42	53.77	34.87	11.24	25.90
65CI5_H2	23.57	1.38	568.24	105.98	74.20	18.32	45.39
65CI6_H1	21.17	1.19	423.28	72.53	48.23	17.57	32.10
65CI6_H2	10.46	0.52	79.98	38.55	25.24	8.52	16.21
65CI7_H1	7.60	0.55	90.11	35.95	27.94	6.25	10.34
65CI7_H2	8.45	0.62	116.42	34.10	26.73	7.62	12.06

Table E- 7: Velocity based GMIM 2/2

	Velocity Parameters						
Name	Max. Velocity (cm/sec)	Velocity RMS (cm/sec)	Specific Energy Density (cm2/sec)	Velocity Spectrum Intensity (cm)	Housner Intensity (cm)	Sustained Maximum Velocity (cm/sec)	Max Incremental Velocity (cm/sec)
65DI1_H1	48.07	8.31	4141.71	162.08	138.77	20.99	58.98
65DI1_H2	41.79	9.43	5332.32	142.66	147.15	29.97	40.58
65DI2_H1	21.49	6.17	1489.52	75.13	73.09	16.63	19.22
65DI2_H2	23.00	5.92	1366.46	59.30	55.93	17.89	21.30
65DI3_H1	15.60	4.45	785.30	35.01	37.26	12.22	11.00
65DI3_H2	13.68	3.53	494.33	35.48	35.53	10.21	15.35
65DI4_H1	36.07	7.09	2009.31	151.76	145.09	31.53	52.52
65DI4_H2	26.21	4.97	987.58	105.87	105.59	18.94	47.27
65DI5_H1	16.06	3.99	621.43	49.70	45.02	9.49	13.67
65DI5_H2	10.98	2.70	284.95	34.62	33.37	9.18	9.54
65DI6_H1	26.01	6.95	1305.40	106.18	95.67	15.16	40.49
65DI6_H2	18.49	7.95	1705.94	76.12	75.13	17.52	32.44
65DI7_H1	12.42	0.76	175.36	58.31	45.98	8.47	23.84
65DI7_H2	19.79	0.69	143.54	63.68	49.31	8.35	17.18
70CI1_H1	24.16	3.69	766.98	88.60	67.24	15.58	39.75
70CI1_H2	17.40	3.46	677.47	74.76	63.40	13.50	23.61
70CI2_H1	21.57	2.55	911.55	89.51	82.19	14.49	31.38
70CI2_H2	20.49	2.69	1014.96	100.26	91.34	17.87	33.64
70CI3_H1	29.94	4.96	1380.81	130.89	119.03	22.99	49.48
70CI3_H2	22.22	5.20	1516.40	104.53	103.44	15.25	36.52
70CI4_H1	42.33	3.58	1772.60	110.80	87.71	31.49	43.45
70CI4_H2	22.72	2.37	779.87	78.93	55.54	21.64	34.42
70CI5_H1	9.78	1.90	203.85	45.26	38.35	8.10	18.50
70CI5_H2	6.82	2.21	275.46	35.10	30.73	6.54	11.33
70CI6_H1	14.61	4.89	1338.25	83.27	82.83	13.66	22.56
70CI6_H2	11.54	3.10	538.05	57.12	54.19	9.21	17.10
70CI7_H1	30.29	4.73	1200.84	68.41	59.21	21.54	17.93
70CI7_H2	17.70	2.10	236.39	60.32	50.16	9.83	24.21
70DI1_H1	38.35	10.60	14607.66	120.74	114.77	38.00	40.30
70DI1_H2	34.00	8.68	9789.00	106.58	101.68	32.81	34.53
70DI2_H1	34.96	6.93	6244.50	124.71	127.00	26.07	49.10
70DI2_H2	52.82	10.09	13230.43	116.20	114.74	41.39	69.02
70DI3_H1	60.16	14.47	14958.72	120.29	124.30	48.40	51.55
70DI3_H2	38.67	9.38	6281.25	78.81	77.79	28.62	33.53
70DI4_H1	11.08	2.21	730.29	42.54	39.56	9.24	16.77
70DI4_H2	8.80	1.77	470.67	32.12	32.46	7.68	10.75
70DI5_H1	21.25	3.39	1606.62	68.48	64.43	13.63	27.57
70DI5_H2	24.78	3.80	2025.79	72.16	72.37	11.77	22.00
70DI6_H1	31.40	7.93	5034.04	161.24	156.92	28.36	57.93
70DI6_H2	30.76	7.29	4249.06	147.84	149.54	25.48	56.26
70DI7_H1	27.05	4.16	3432.13	146.37	144.74	22.83	49.11
70DI7_H2	23.71	3.04	1833.68	83.58	80.20	13.71	33.44

Table E- 8: Displacement based and other GMIM 1/2

	Displacement Parameters		Other		
Name	Max. Displacement (cm)	Displacement RMS: (cm)	Predominant Period (sec)	Mean Period (sec)	Vmax / Amax (sec)
60CI1_H1	2.38	0.55	0.28	0.33	0.06
60CI1_H2	0.66	0.23	0.22	0.21	0.04
60CI2_H1	0.97	0.23	0.28	0.31	0.04
60CI2_H2	1.77	0.38	0.20	0.38	0.06
60CI3_H1	1.12	0.32	0.48	0.54	0.08
60CI3_H2	2.36	0.52	0.44	0.62	0.10
60CI4_H1	9.35	1.85	0.28	0.74	0.13
60CI4_H2	7.87	1.76	0.08	0.60	0.10
60CI5_H1	5.56	1.33	0.38	0.41	0.06
60CI5_H2	3.12	0.77	0.26	0.41	0.06
60CI6_H1	1.65	0.49	0.08	0.26	0.07
60CI6_H2	1.33	0.42	0.08	0.20	0.05
60CI7_H1	0.75	0.15	0.18	0.29	0.06
60CI7_H2	0.58	0.16	0.18	0.27	0.05
60DI1_H1	1.14	0.42	0.18	0.29	0.04
60DI1_H2	1.17	0.38	0.18	0.26	0.04
60DI2_H1	3.85	1.50	0.14	0.75	0.12
60DI2_H2	1.42	0.57	0.18	0.53	0.09
60DI3_H1	1.22	0.50	0.22	0.26	0.05
60DI3_H2	2.29	0.98	0.08	0.25	0.05
60DI4_H1	2.29	0.70	0.22	1.04	0.17
60DI4_H2	2.20	0.72	0.98	1.22	0.18
60DI5_H1	8.14	1.79	0.26	0.66	0.10
60DI5_H2	12.64	2.22	0.30	0.67	0.13
60DI6_H1	8.90	1.41	0.62	0.69	0.13
60DI6_H2	3.55	0.92	0.22	0.47	0.06
60DI7_H1	2.81	0.83	0.24	0.85	0.08
60DI7_H2	2.46	0.96	0.26	0.77	0.07
65CI1_H1	2.14	0.99	0.14	0.27	0.05
65CI1_H2	2.77	1.10	0.16	0.24	0.05
65CI2_H1	1.58	0.59	0.22	0.28	0.04
65CI2_H2	2.80	0.75	0.26	0.34	0.07
65CI3_H1	3.74	1.09	0.42	0.60	0.11
65CI3_H2	2.93	0.66	0.36	0.66	0.11
65CI4_H1	5.24	1.47	0.32	0.39	0.07
65CI4_H2	7.85	2.33	0.30	0.58	0.13
65CI5_H1	1.14	0.09	0.18	0.18	0.03
65CI5_H2	3.00	0.19	0.18	0.20	0.03
65CI6_H1	10.16	1.12	0.16	-1.00	0.04
65CI6_H2	0.84	0.08	0.20	-1.00	0.03
65CI7_H1	4.51	0.53	0.12	-1.00	0.04
65CI7_H2	9.40	1.02	0.12	-1.00	0.03

Table E- 9: Displacement based and other GMIM 2/2

	Displacement Parameters		Other		
Name	Max. Displacement (cm)	Displacement RMS: (cm)	Predominant Period (sec)	Mean Period (sec)	Vmax / Amax (sec)
65DI1_H1	19.28	7.56	0.22	0.66	0.14
65DI1_H2	21.86	8.04	0.46	0.97	0.16
65DI2_H1	17.33	5.57	0.20	0.66	0.15
65DI2_H2	13.35	5.82	0.28	0.59	0.20
65DI3_H1	13.26	4.68	0.28	0.66	0.12
65DI3_H2	6.85	3.02	0.20	0.74	0.18
65DI4_H1	14.63	3.10	0.38	1.24	0.23
65DI4_H2	9.85	2.54	0.80	1.07	0.13
65DI5_H1	9.82	4.06	0.10	0.36	0.12
65DI5_H2	7.10	2.28	0.10	0.34	0.08
65DI6_H1	13.53	5.83	0.62	0.84	0.18
65DI6_H2	18.42	7.71	0.30	1.10	0.19
65DI7_H1	4.35	0.45	0.30	0.27	0.04
65DI7_H2	6.42	0.61	0.18	0.23	0.06
70CI1_H1	5.71	2.49	0.30	0.49	0.11
70CI1_H2	6.97	2.95	0.30	0.44	0.09
70CI2_H1	15.38	2.33	0.34	0.60	0.14
70CI2_H2	12.33	2.01	0.24	0.65	0.13
70CI3_H1	5.01	1.35	0.60	0.70	0.14
70CI3_H2	10.29	3.47	0.52	0.88	0.14
70CI4_H1	19.06	3.64	0.36	0.28	0.07
70CI4_H2	12.87	2.11	0.20	0.23	0.04
70CI5_H1	1.58	0.42	0.26	0.35	0.08
70CI5_H2	4.75	1.82	0.22	0.28	0.06
70CI6_H1	7.15	2.51	0.18	0.72	0.11
70CI6_H2	4.79	1.59	0.24	0.50	0.08
70CI7_H1	21.27	6.34	0.20	0.32	0.09
70CI7_H2	3.82	1.06	0.16	0.32	0.08
70DI1_H1	48.23	13.92	0.48	0.65	0.16
70DI1_H2	30.72	9.33	0.30	0.55	0.18
70DI2_H1	19.63	6.98	0.14	0.66	0.17
70DI2_H2	52.20	10.51	0.30	0.62	0.24
70DI3_H1	47.71	16.19	0.72	1.03	0.36
70DI3_H2	26.66	9.66	0.12	0.74	0.22
70DI4_H1	7.42	2.07	0.30	0.50	0.10
70DI4_H2	5.39	1.36	0.18	0.48	0.12
70DI5_H1	7.98	2.13	0.38	0.70	0.10
70DI5_H2	9.87	2.84	0.14	0.75	0.11
70DI6_H1	14.86	4.32	0.92	1.17	0.17
70DI6_H2	14.57	4.73	0.86	1.18	0.15
70DI7_H1	10.76	2.13	0.58	0.98	0.13
70DI7_H2	9.84	1.90	0.62	0.87	0.19

F. Acceleration vs Time Graphs of Recorded Ground Motions

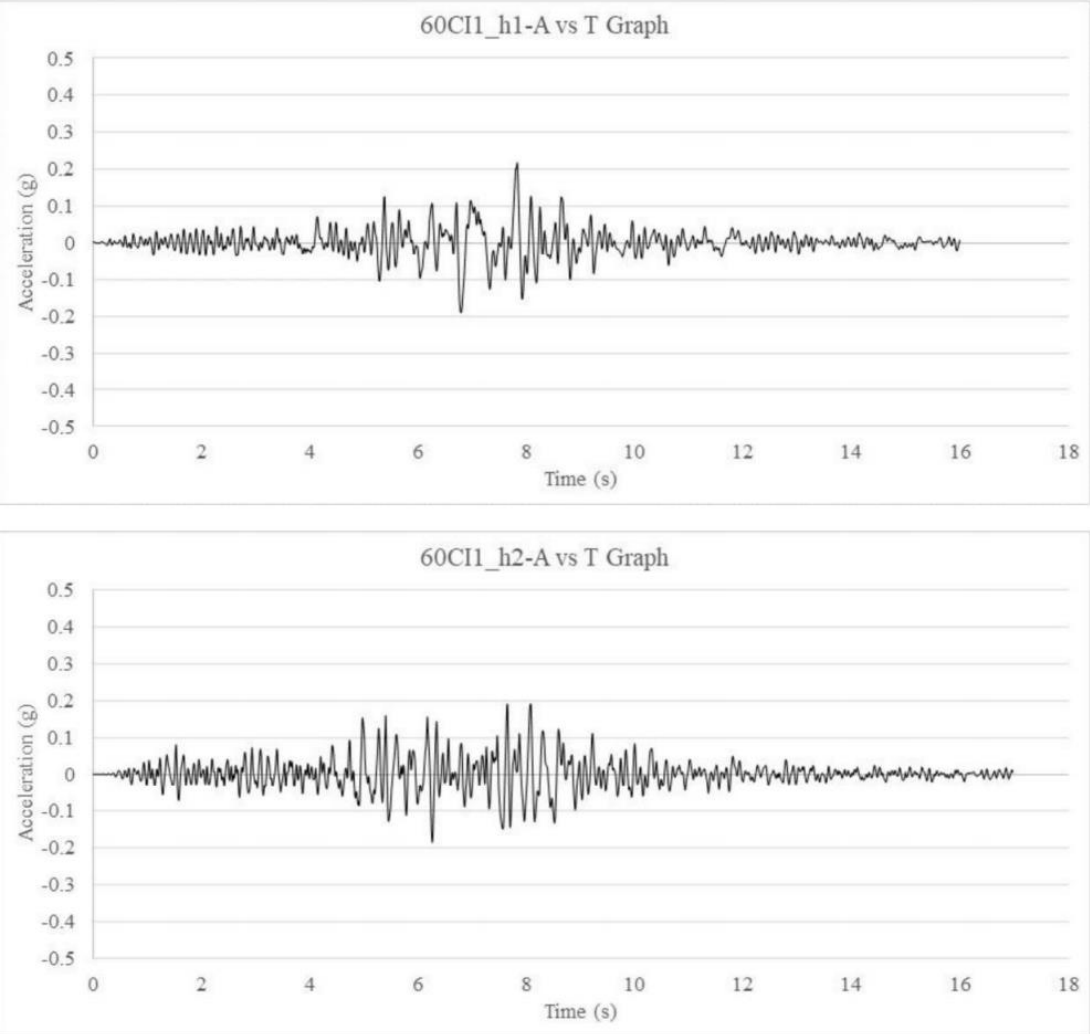
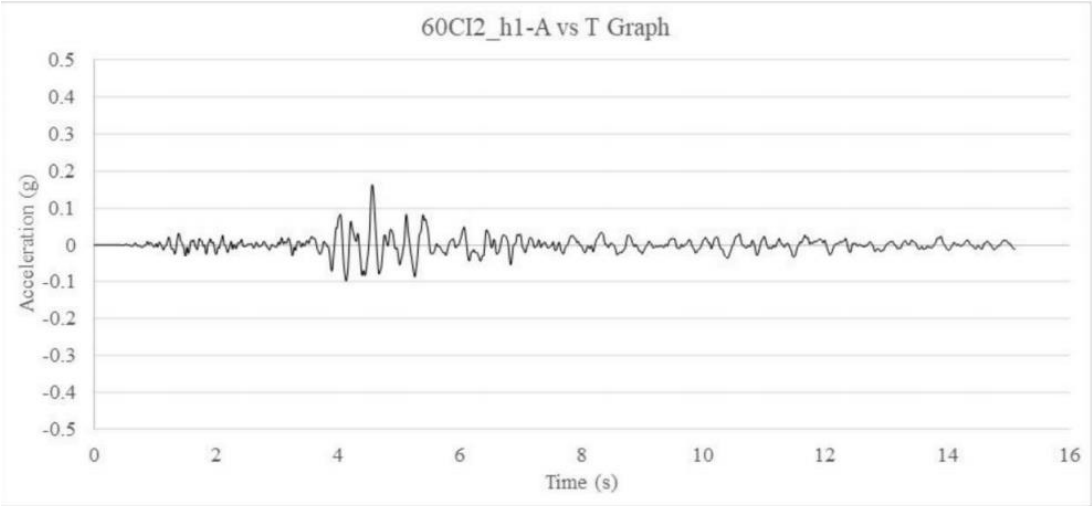


Figure F- 1: Acceleration vs Time Graphs of 60CI1



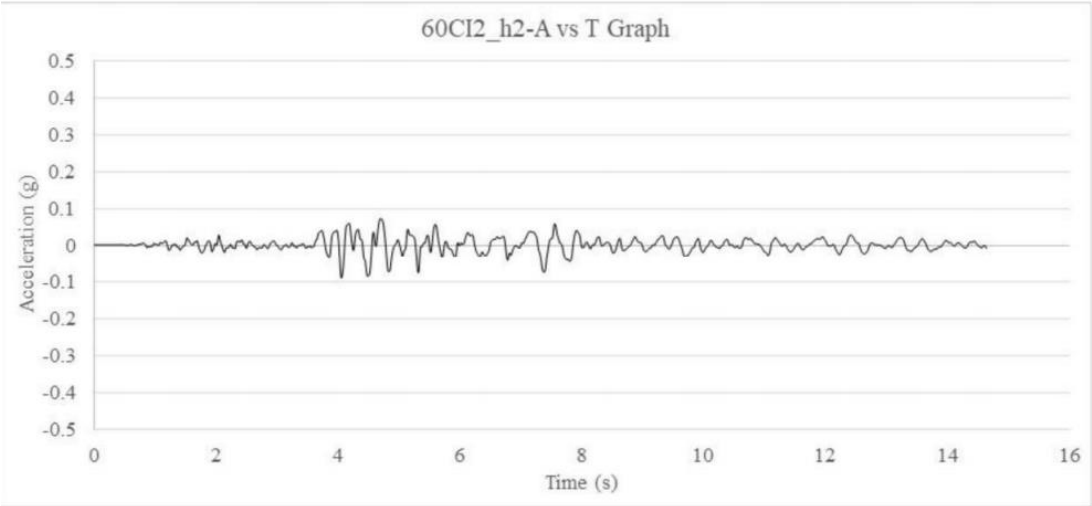
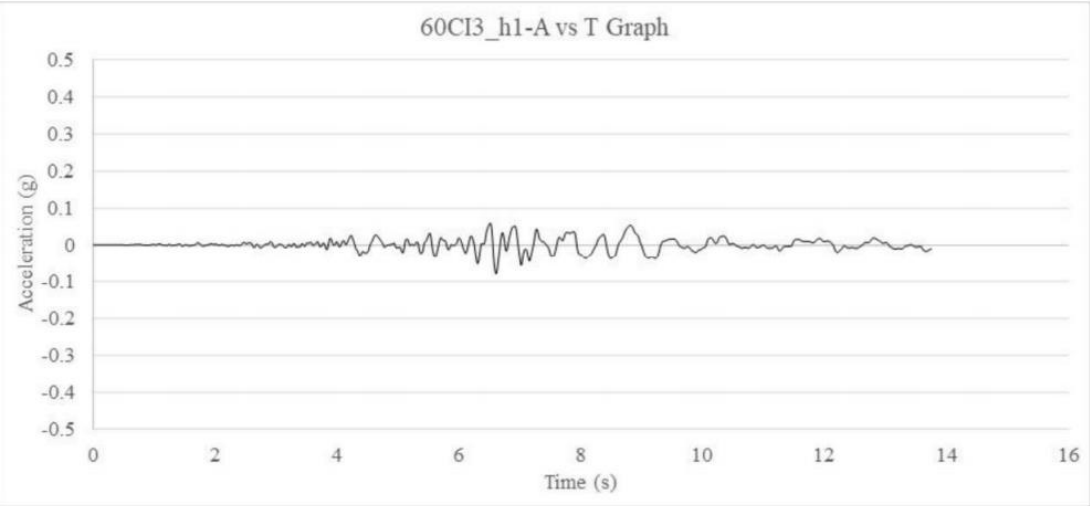


Figure F- 2: Acceleration vs Time Graphs of 60CI2



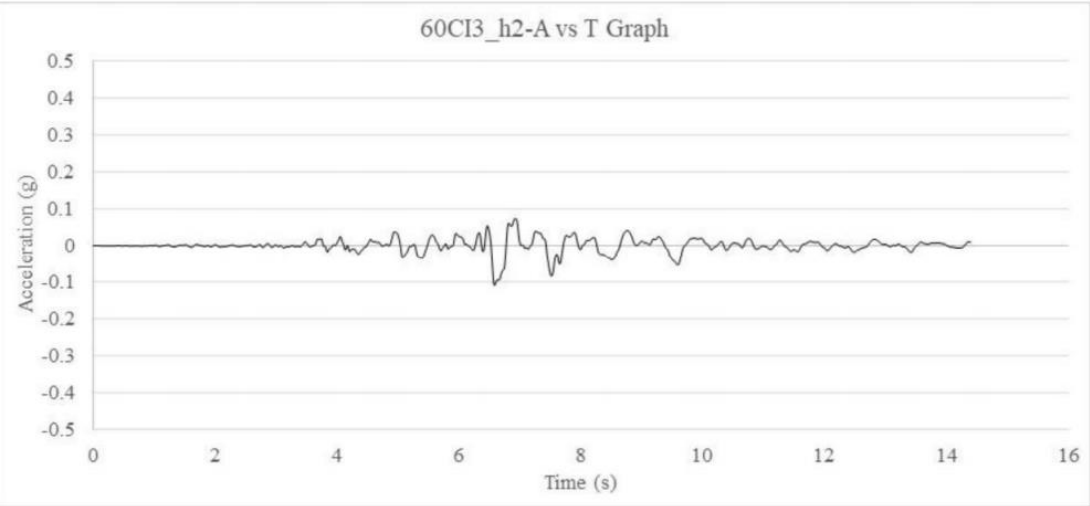
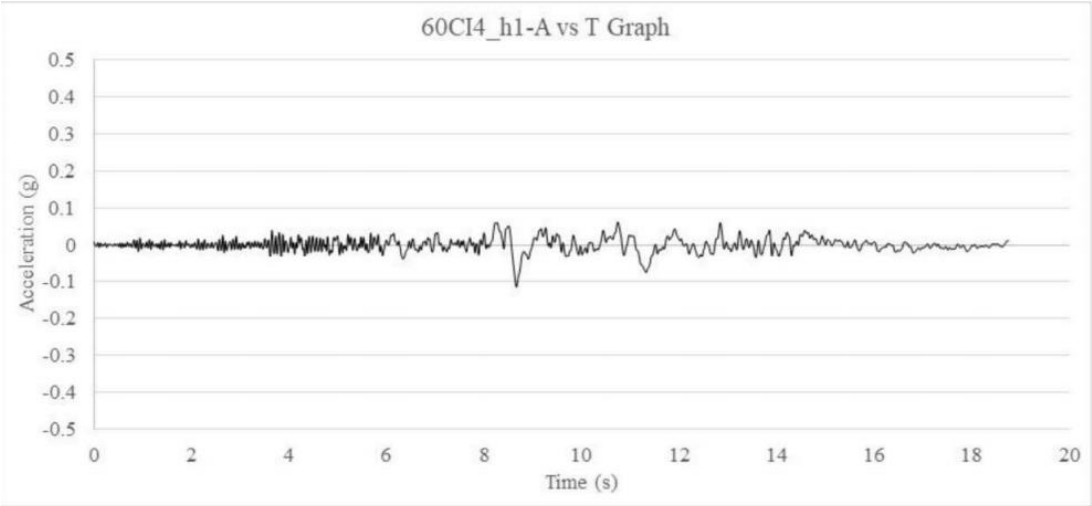


Figure F- 3: Acceleration vs Time Graphs of 60CI3



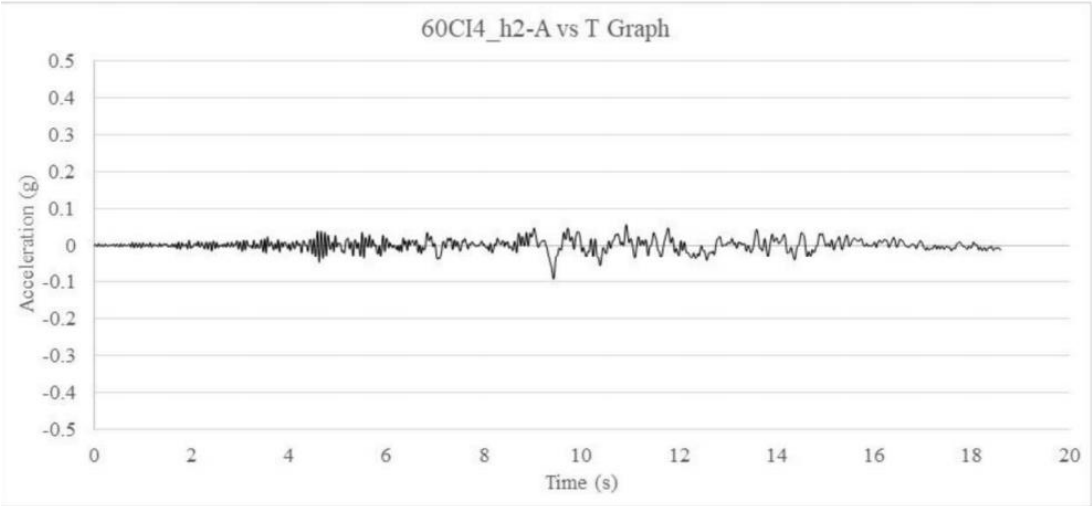
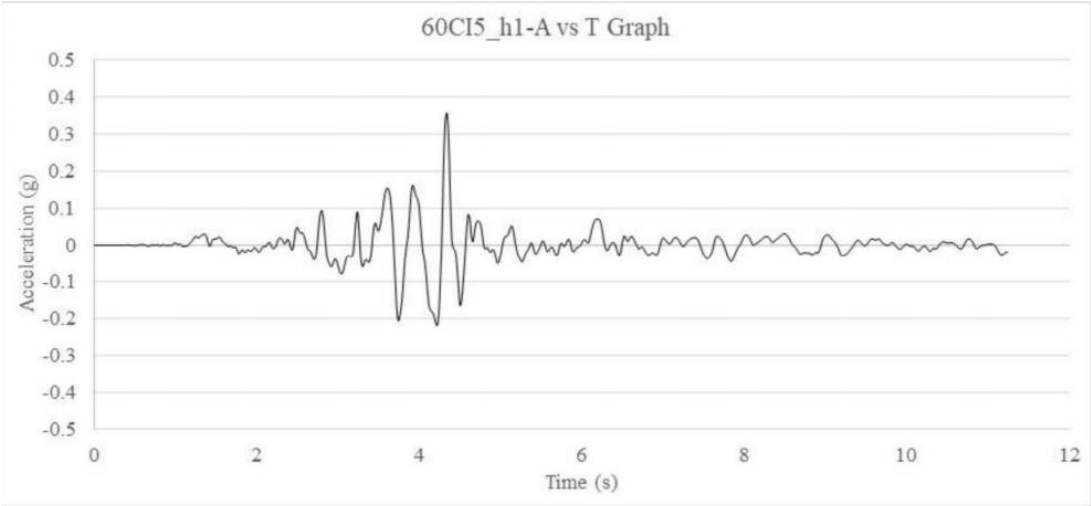


Figure F- 4: Acceleration vs Time Graphs of 60CI4



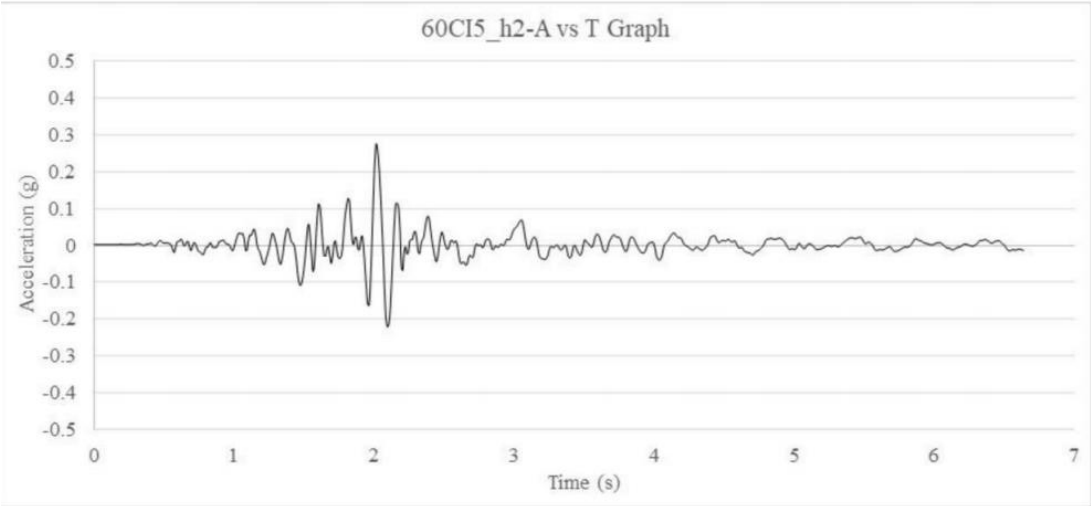
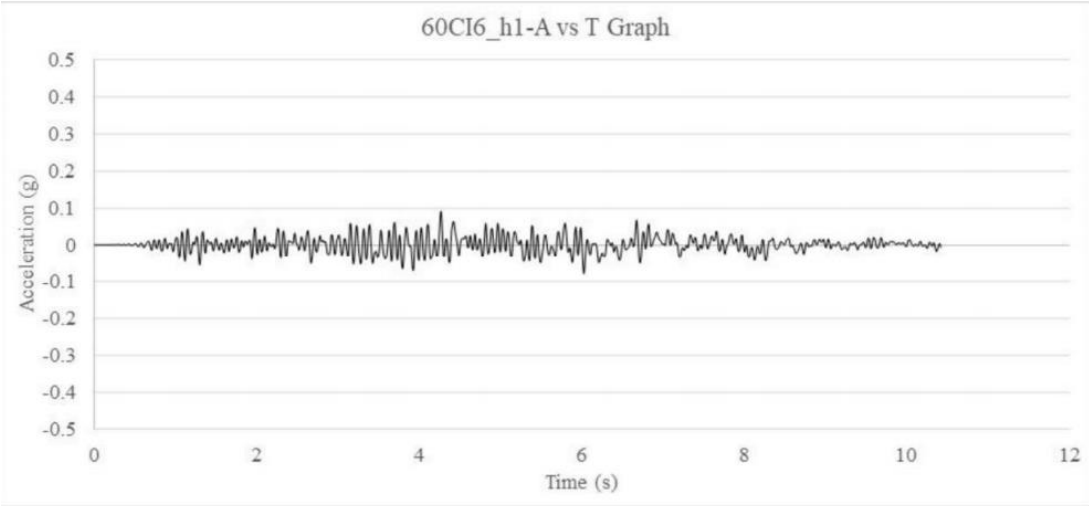


Figure F- 5: Acceleration vs Time Graphs of 60CI5



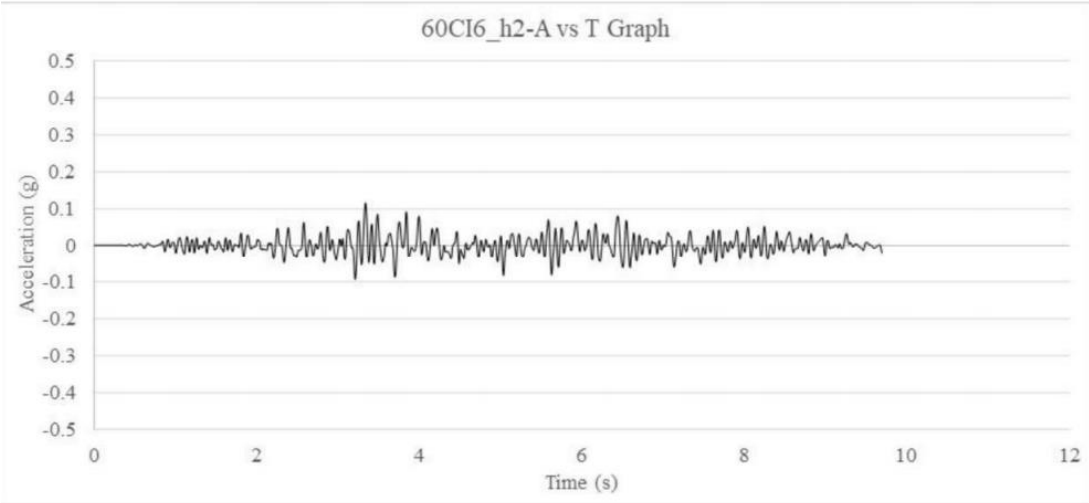
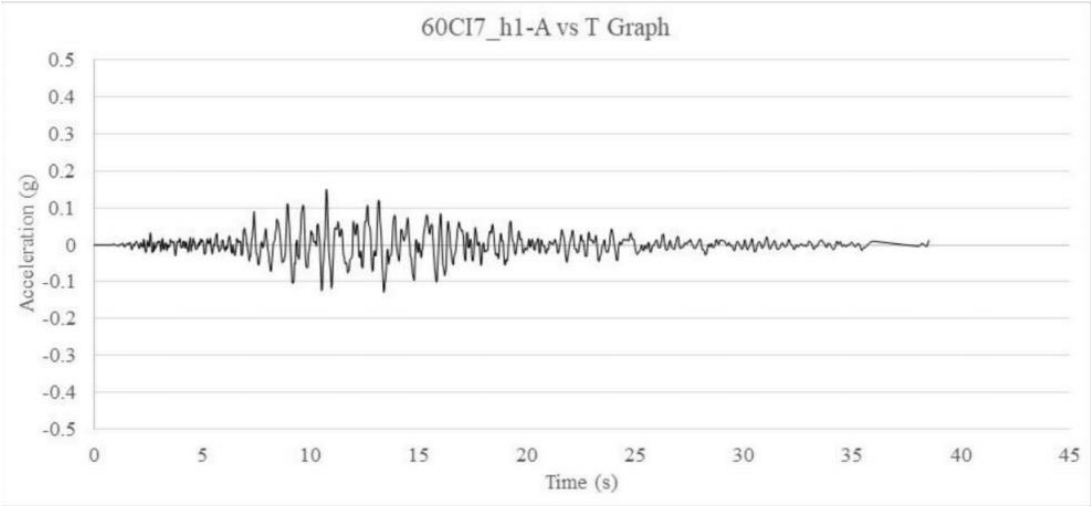


Figure F- 6: Acceleration vs Time Graphs of 60CI6



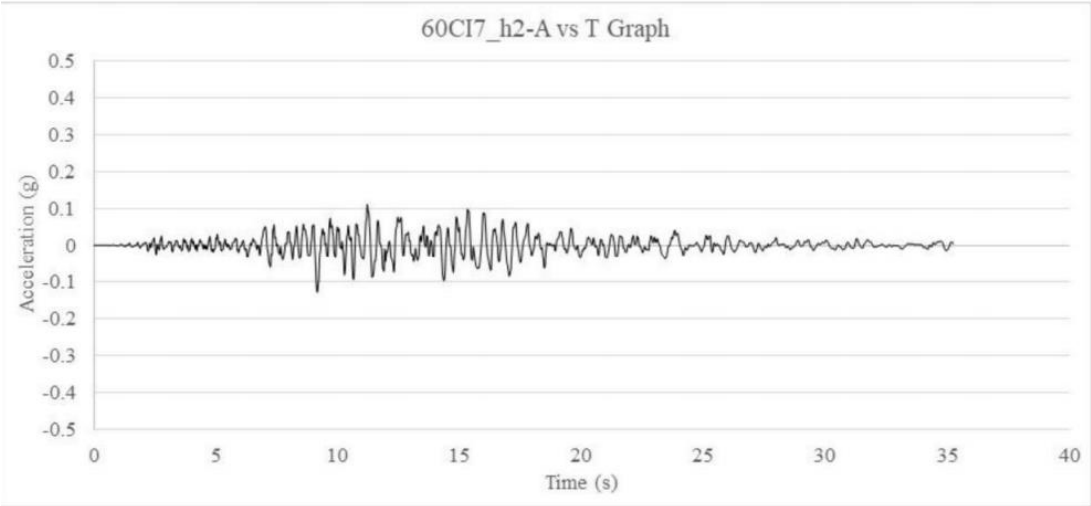
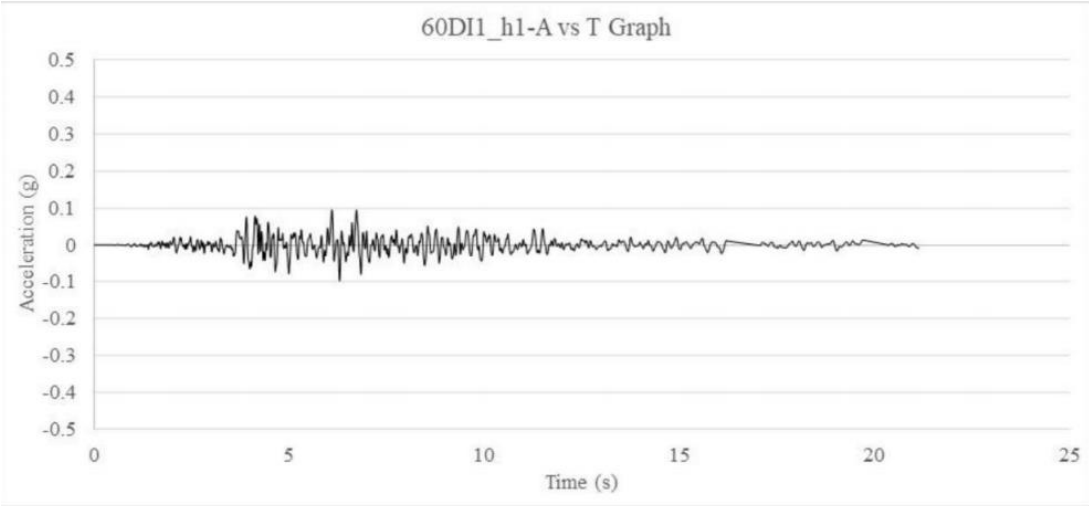


Figure F- 7: Acceleration vs Time Graphs of 60CI7



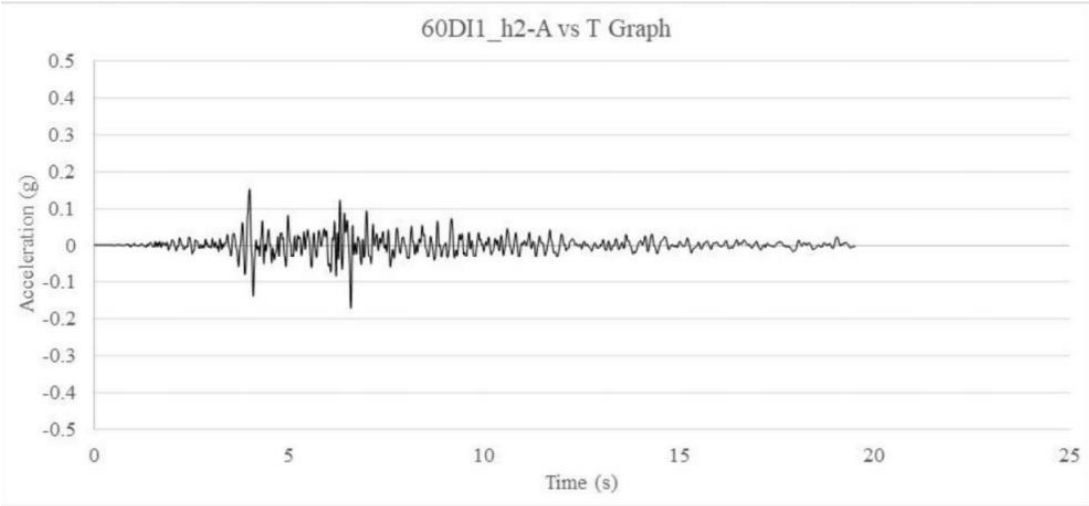
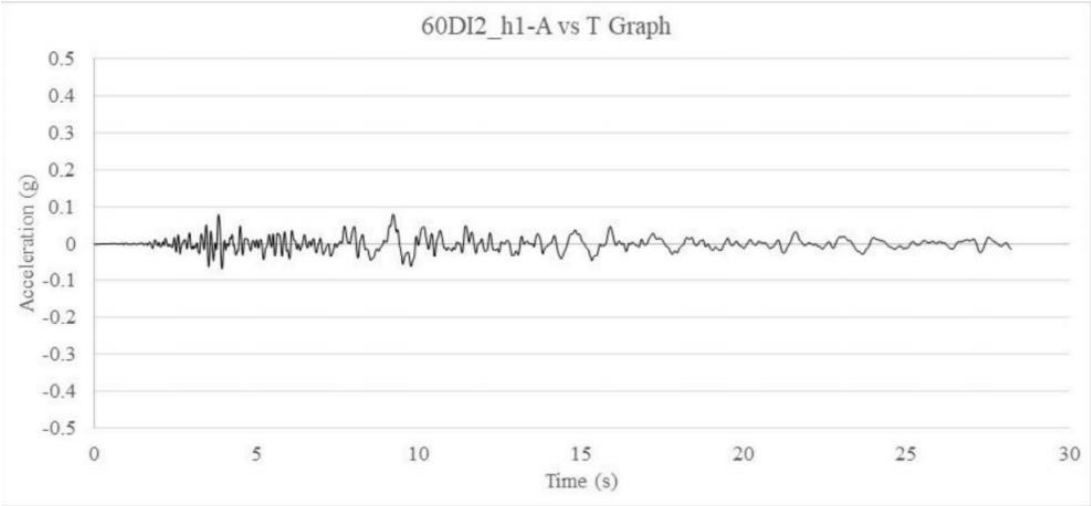


Figure F- 8: Acceleration vs Time Graphs of 60DI1



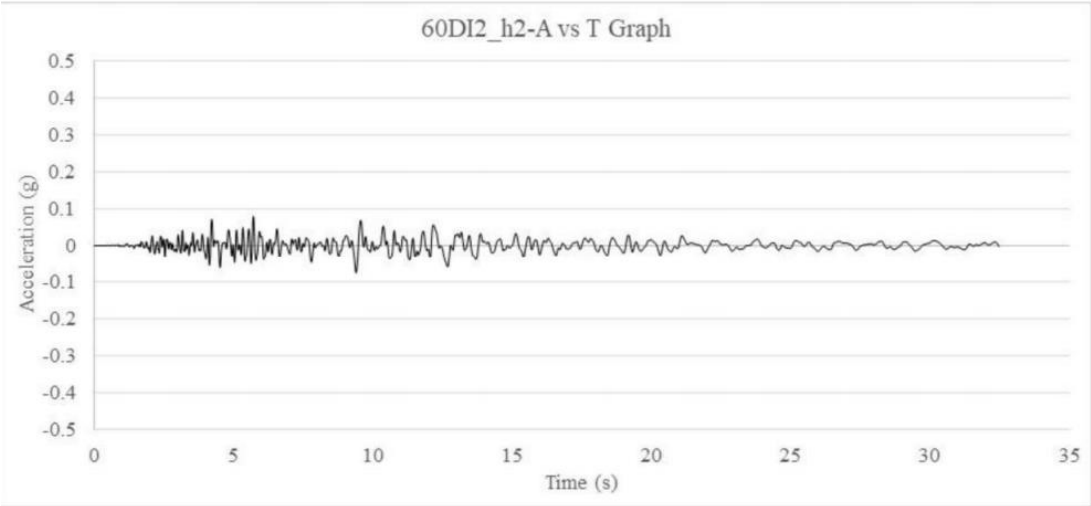
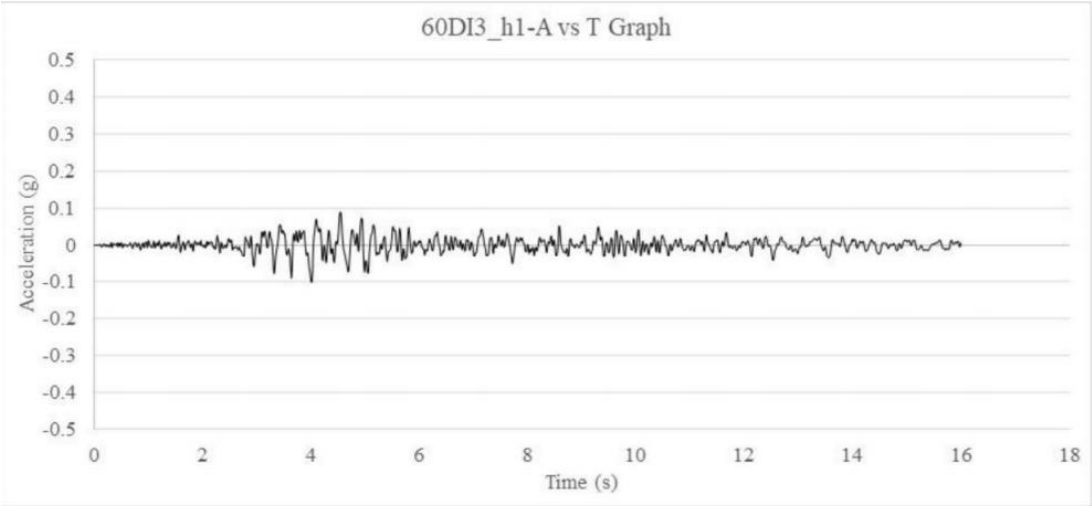


Figure F- 9: Acceleration vs Time Graphs of 60DI2



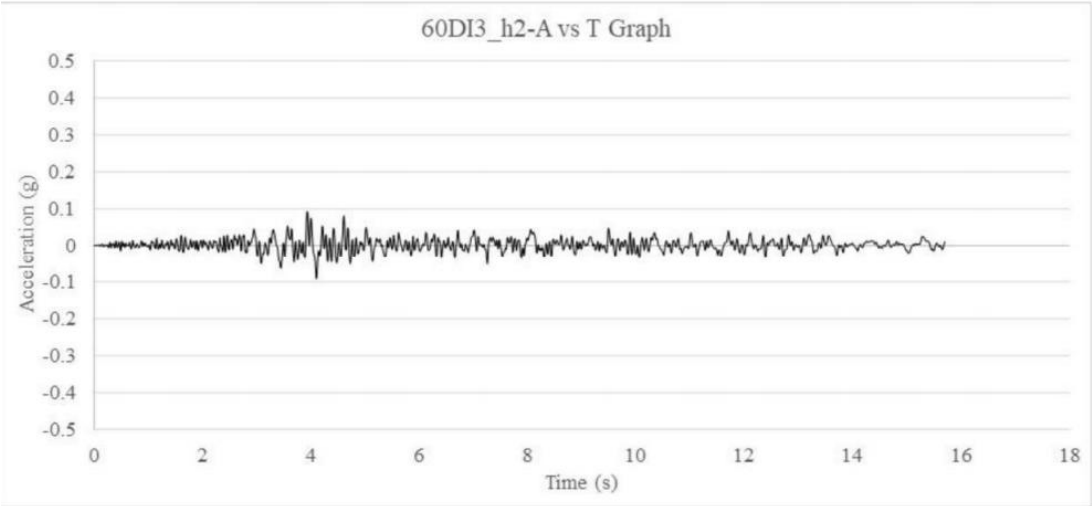
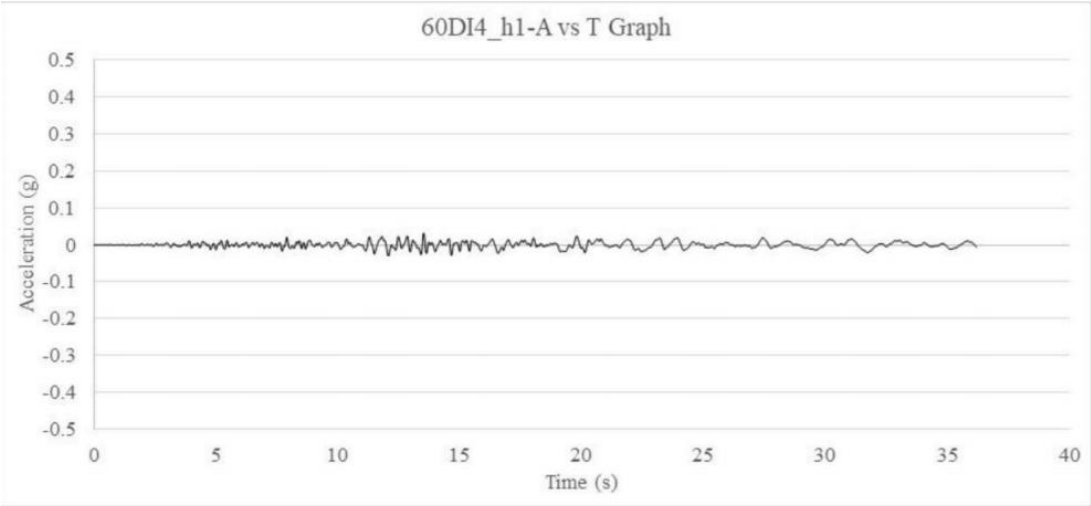


Figure F- 10: Acceleration vs Time Graphs of 60DI3



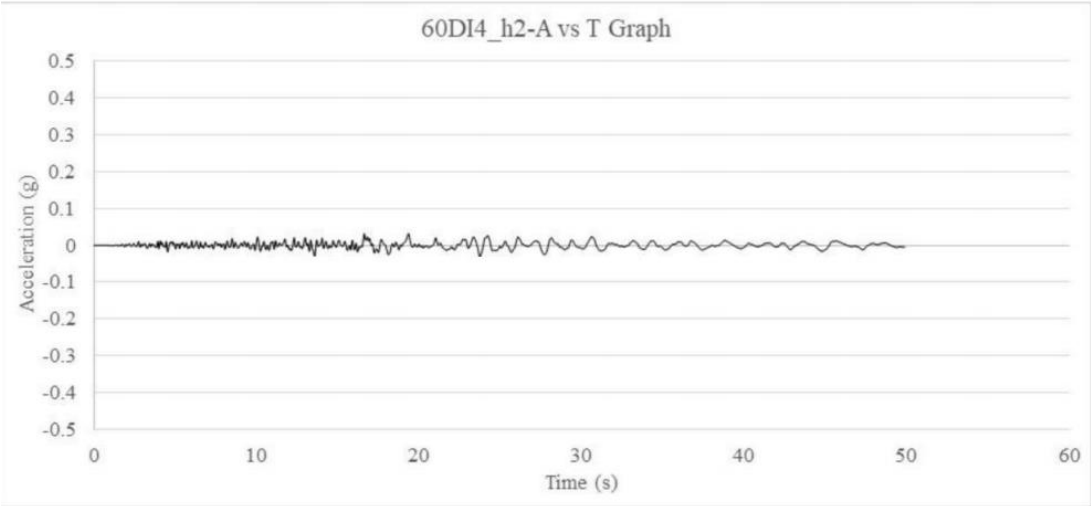
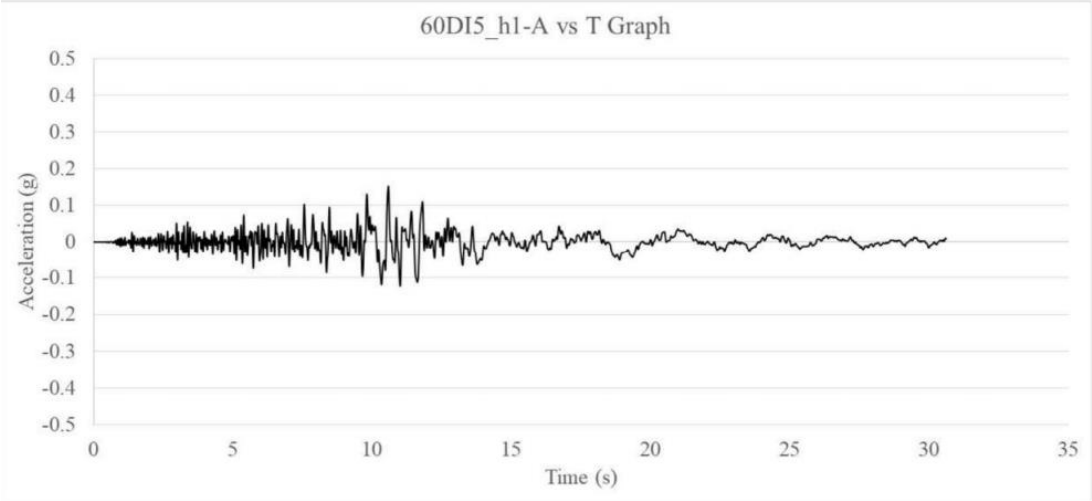


Figure F- 11: Acceleration vs Time Graphs of 60DI4



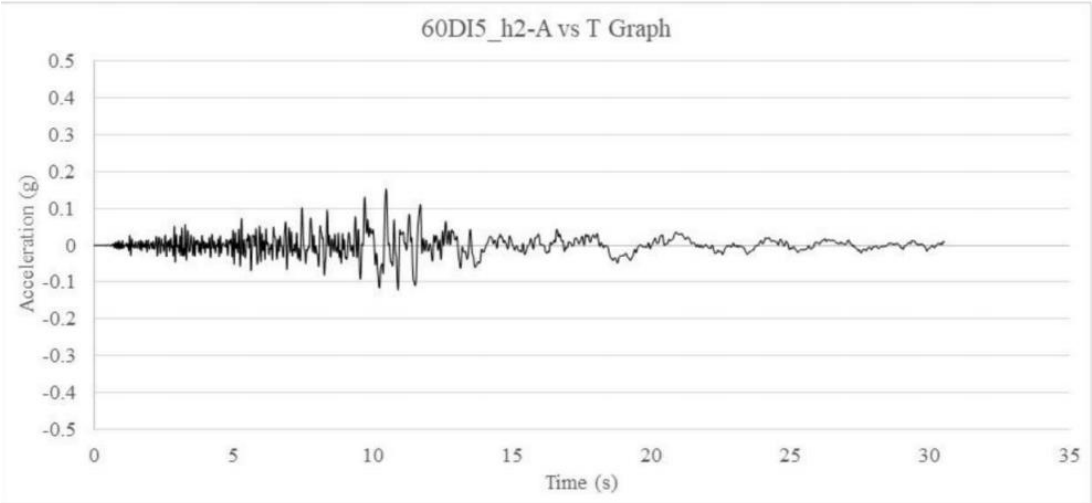
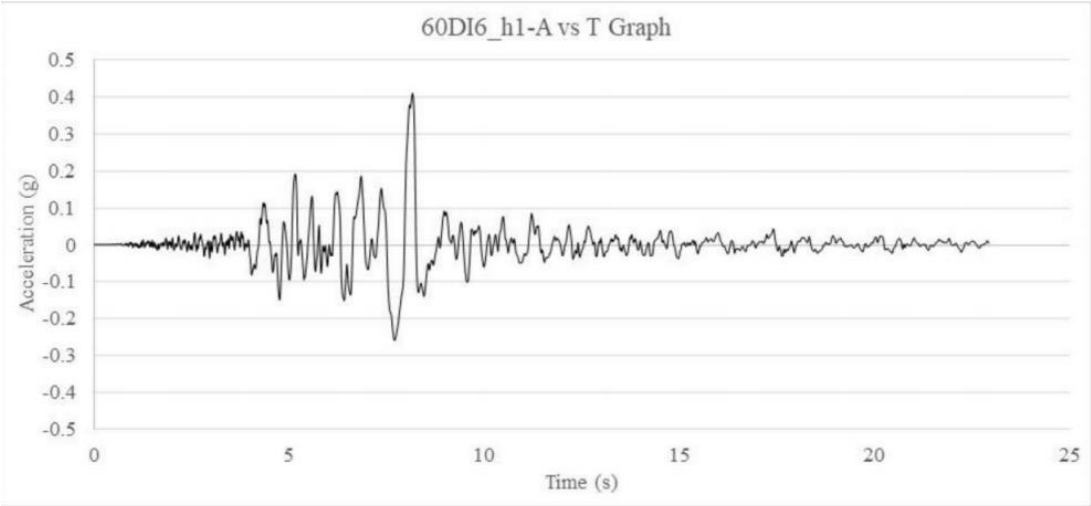


Figure F- 12: Acceleration vs Time Graphs of 60DI5



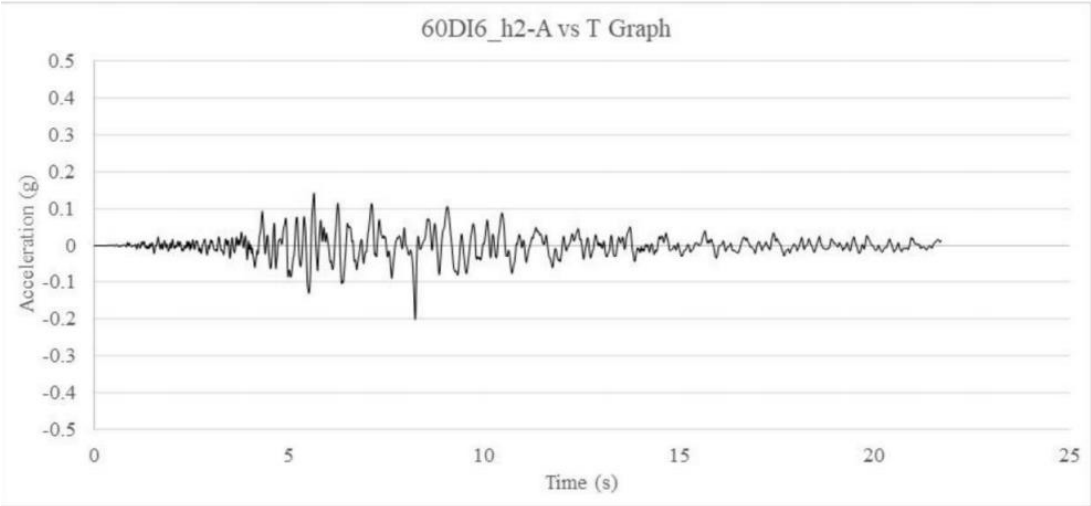
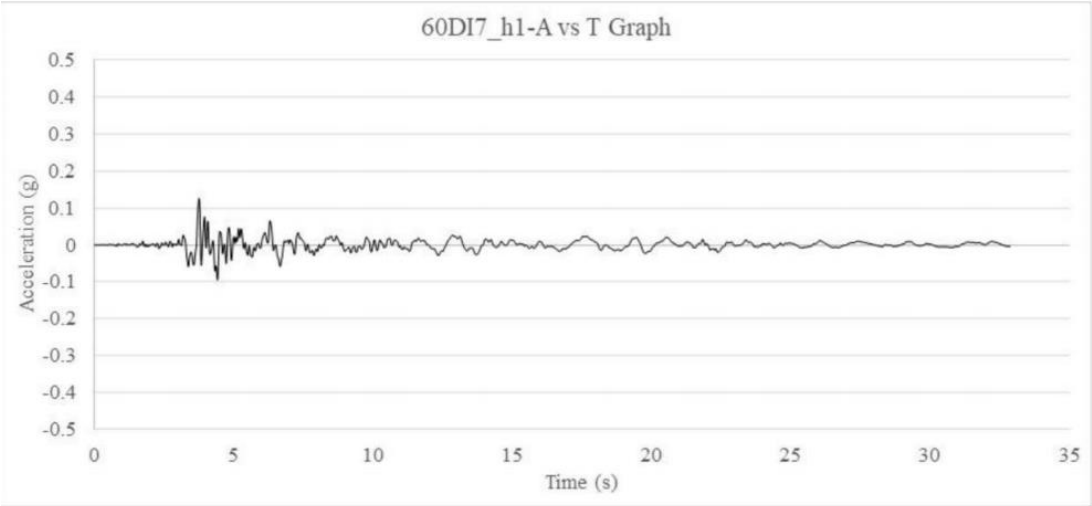


Figure F- 13: Acceleration vs Time Graphs of 60DI6



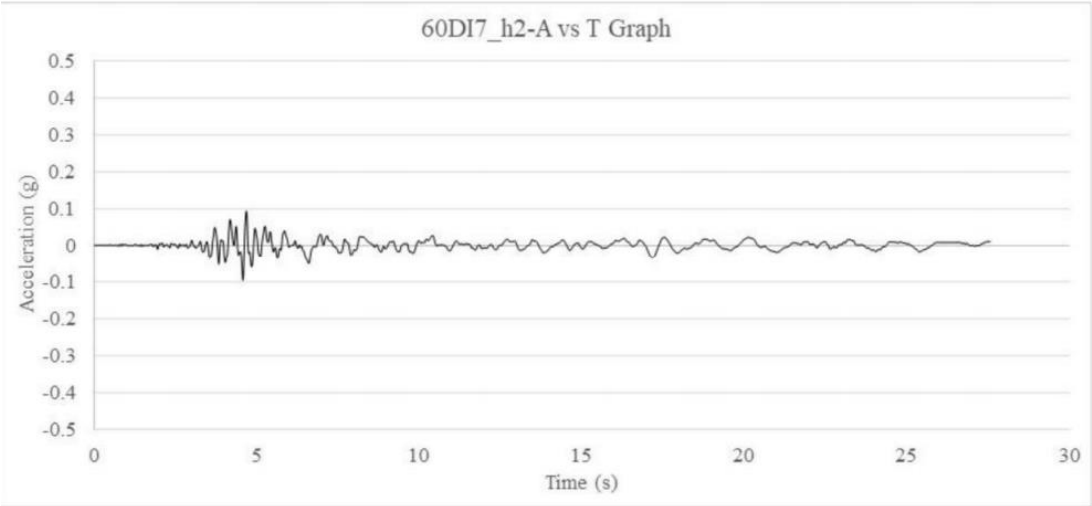
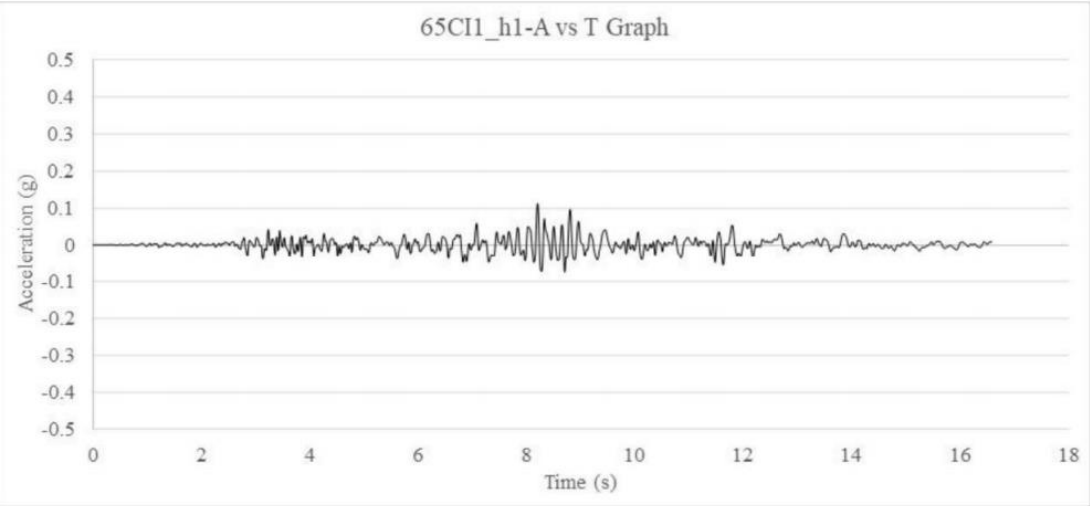


Figure F- 14: Acceleration vs Time Graphs of 60DI7



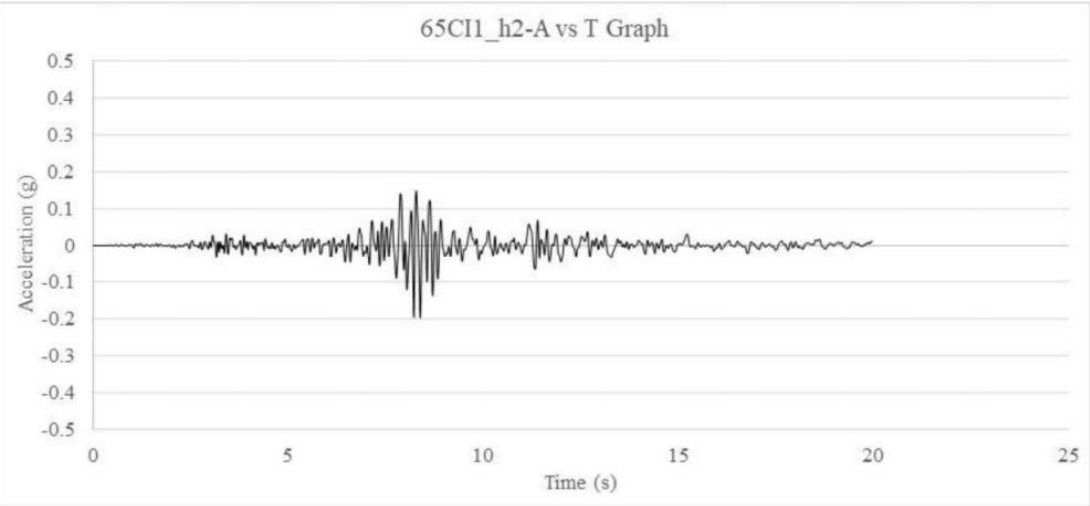
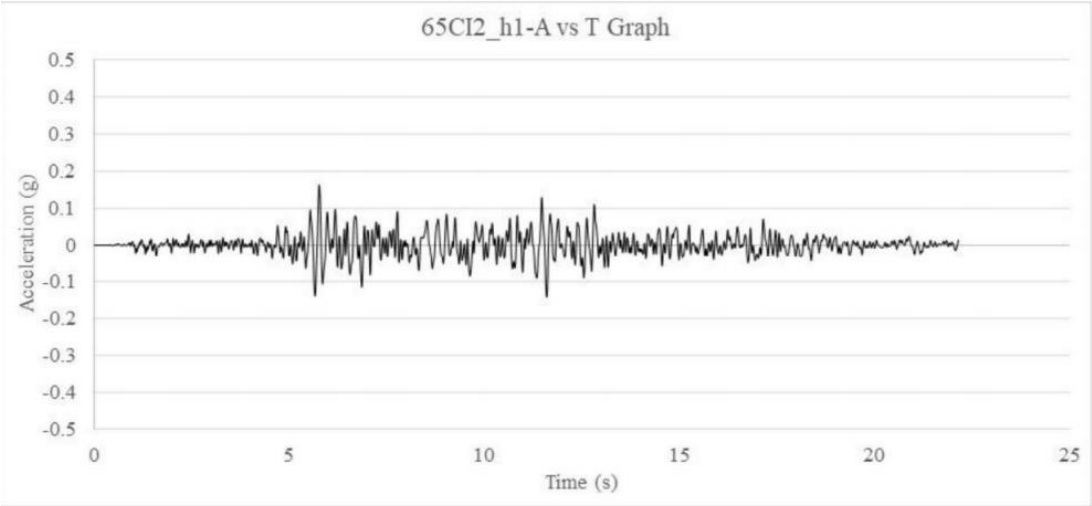


Figure F- 15: Acceleration vs Time Graphs of 65CI1



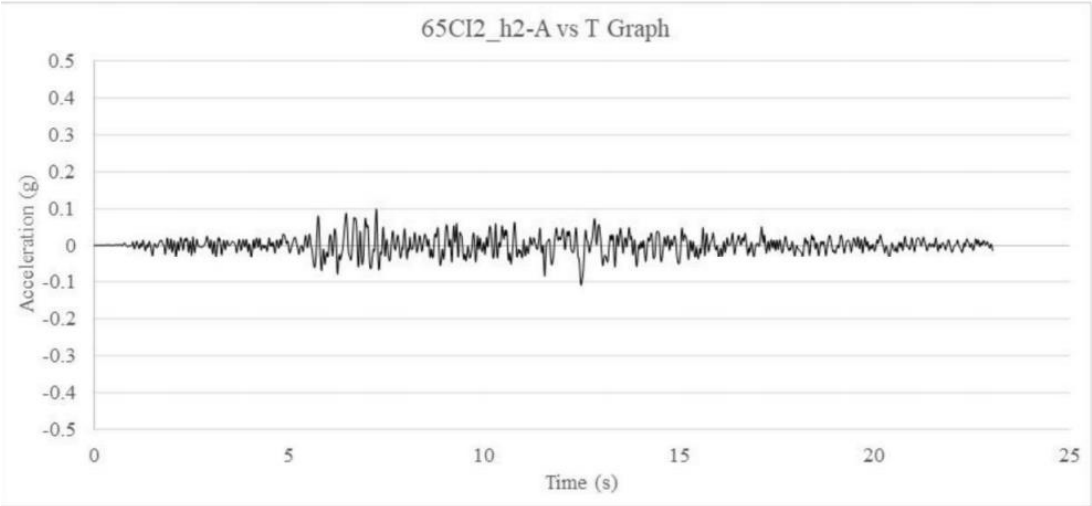
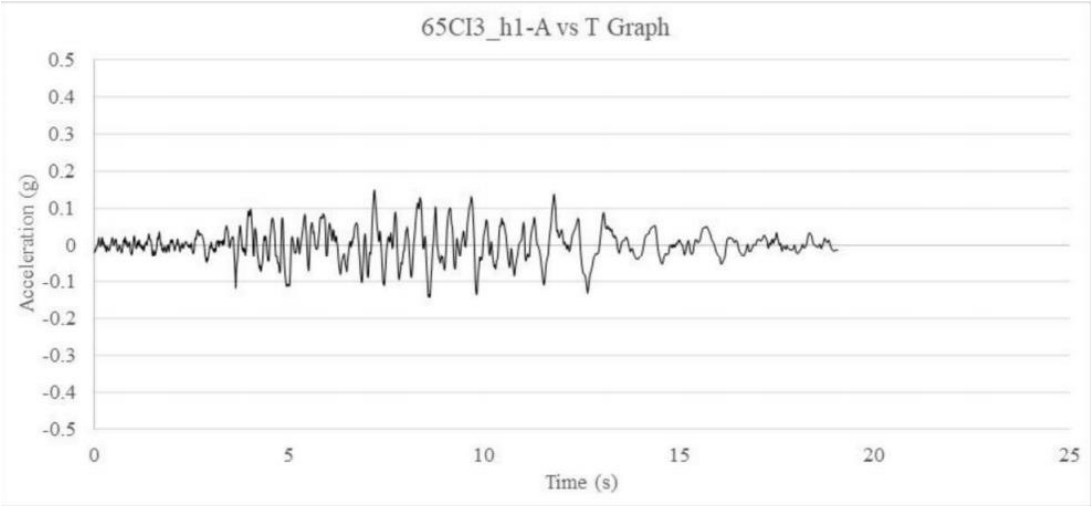


Figure F- 16: Acceleration vs Time Graphs of 65CI2



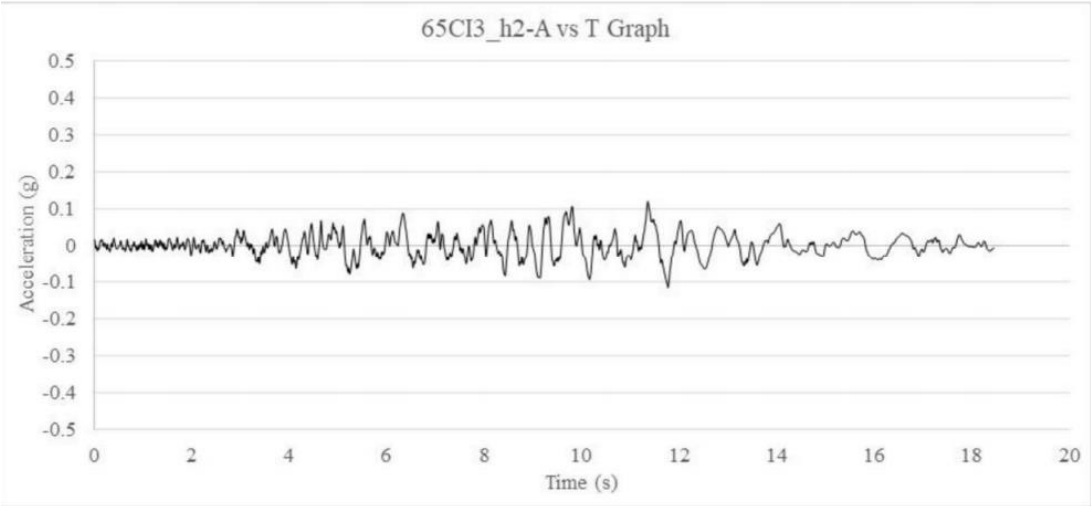
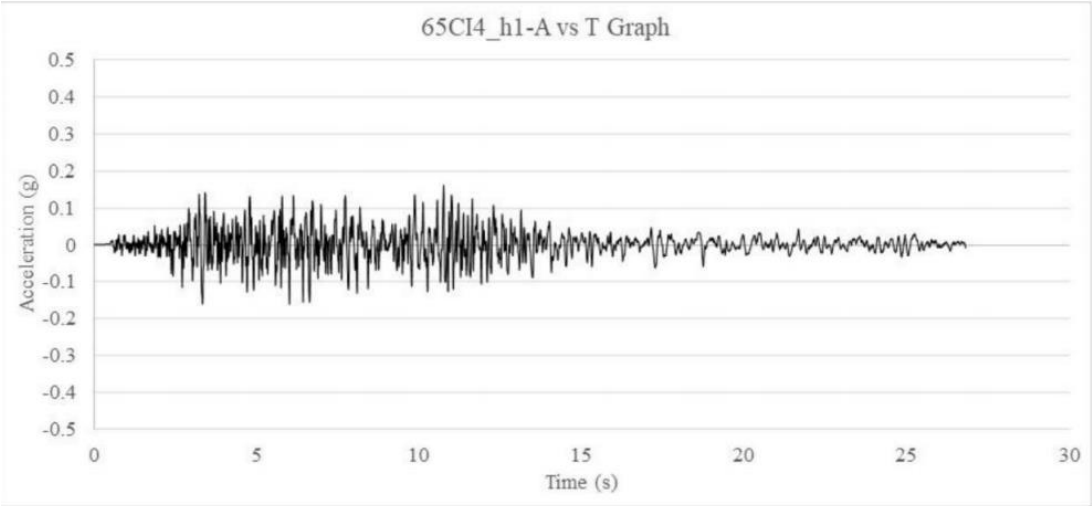


Figure F- 17: Acceleration vs Time Graphs of 65CI3



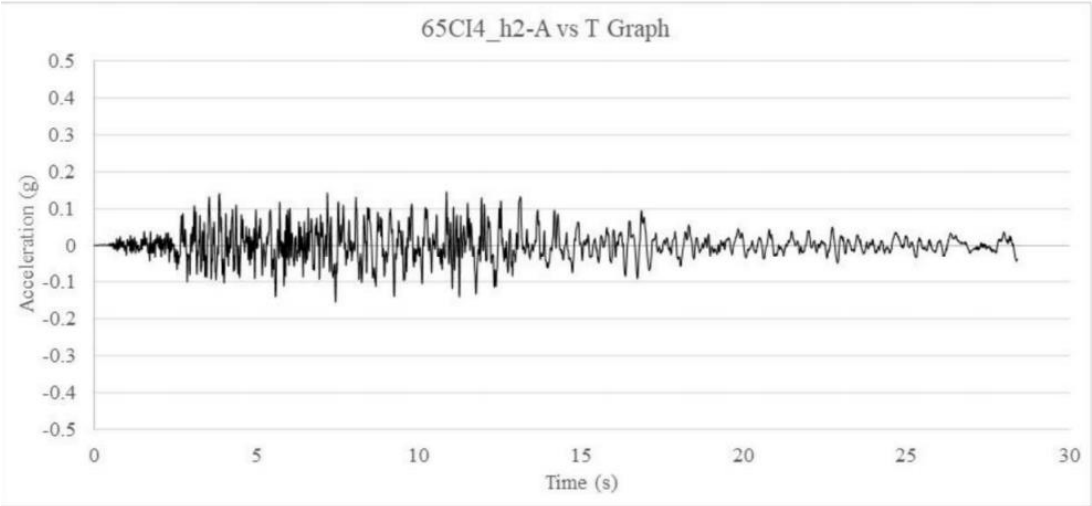
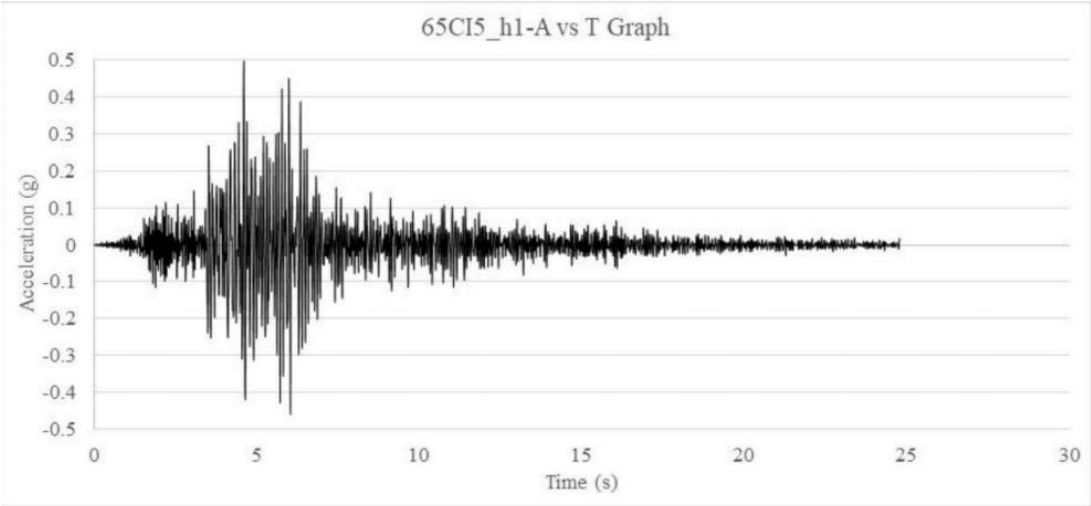


Figure F- 18: Acceleration vs Time Graphs of 65CI4



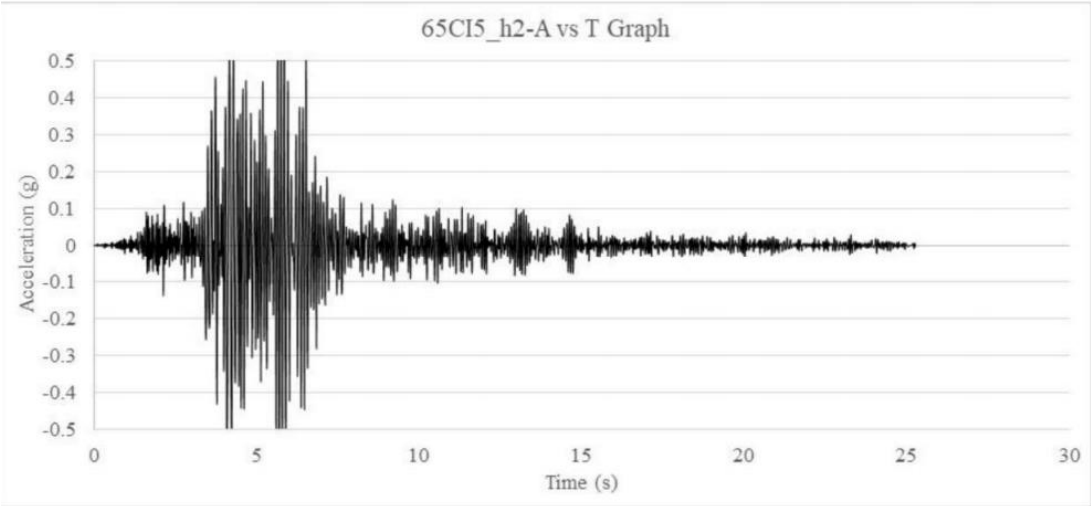
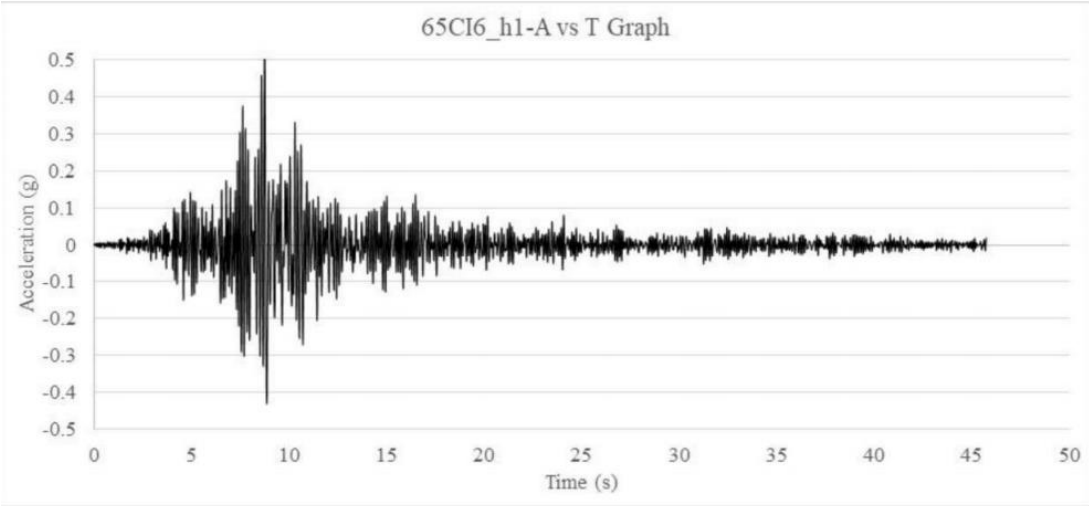


Figure F- 19: Acceleration vs Time Graphs of 65CI5



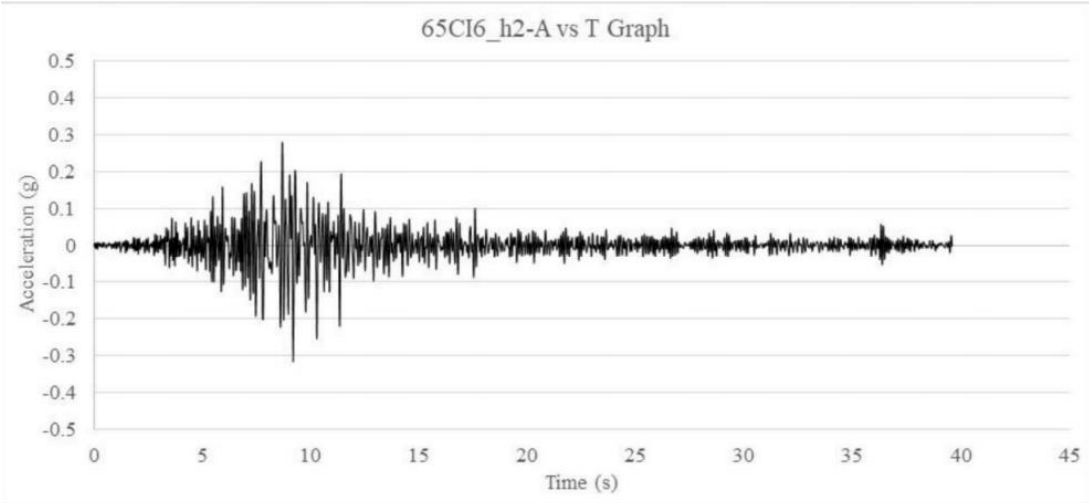
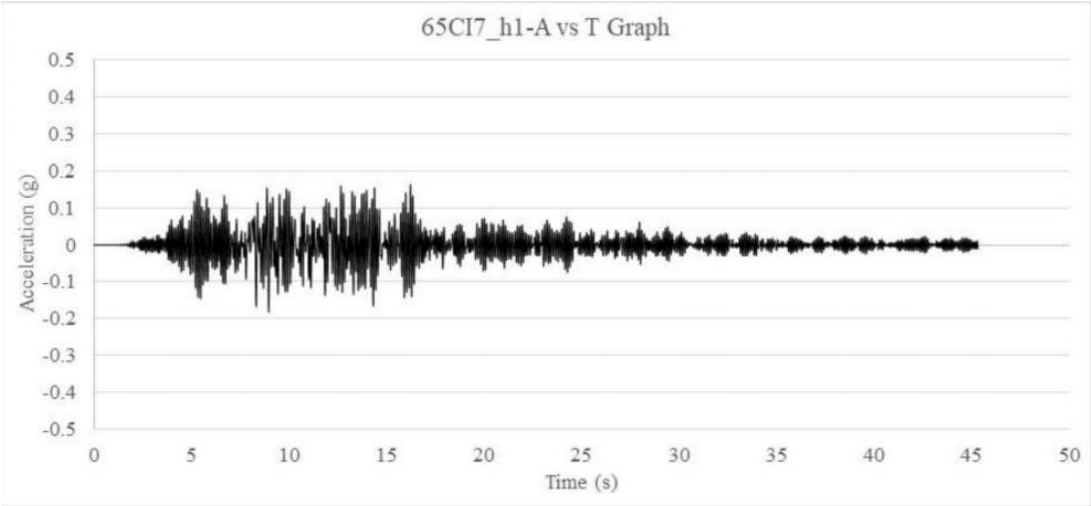


Figure F- 20: Acceleration vs Time Graphs of 65CI6



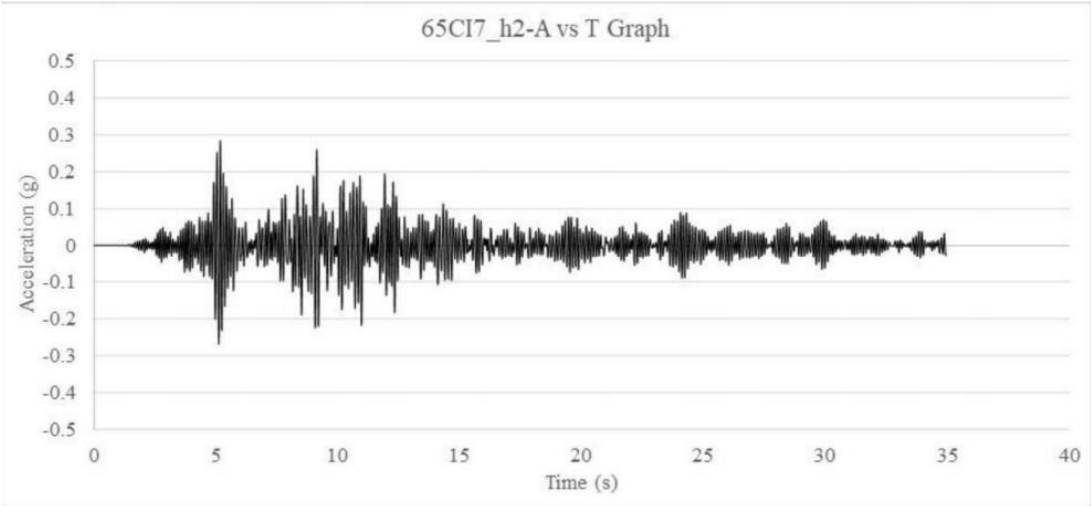
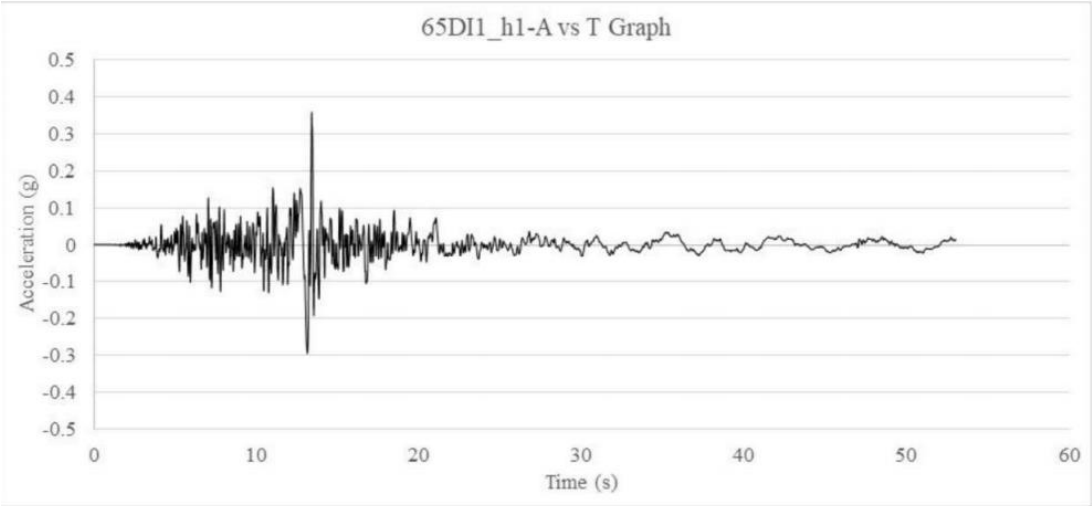


Figure F- 21: Acceleration vs Time Graphs of 65CI7



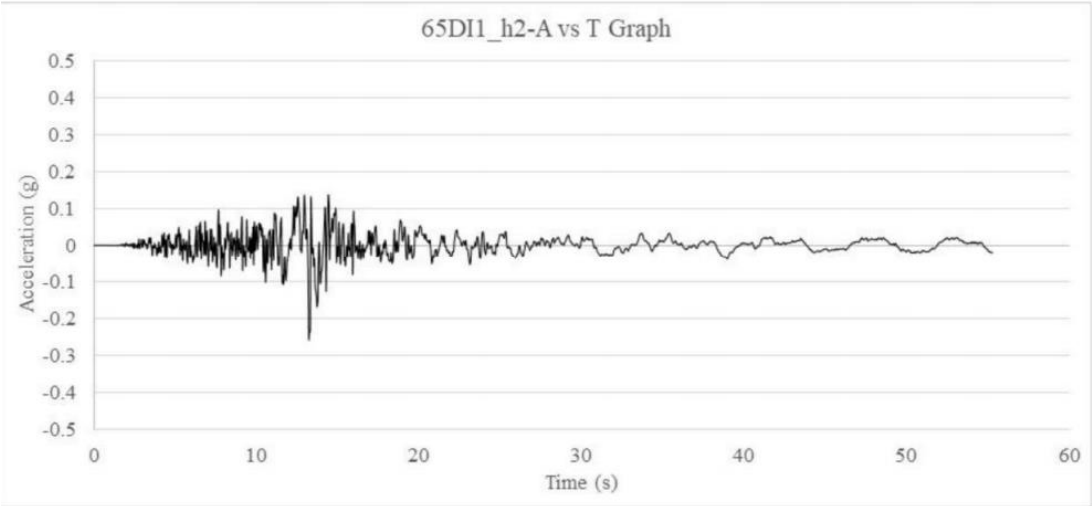
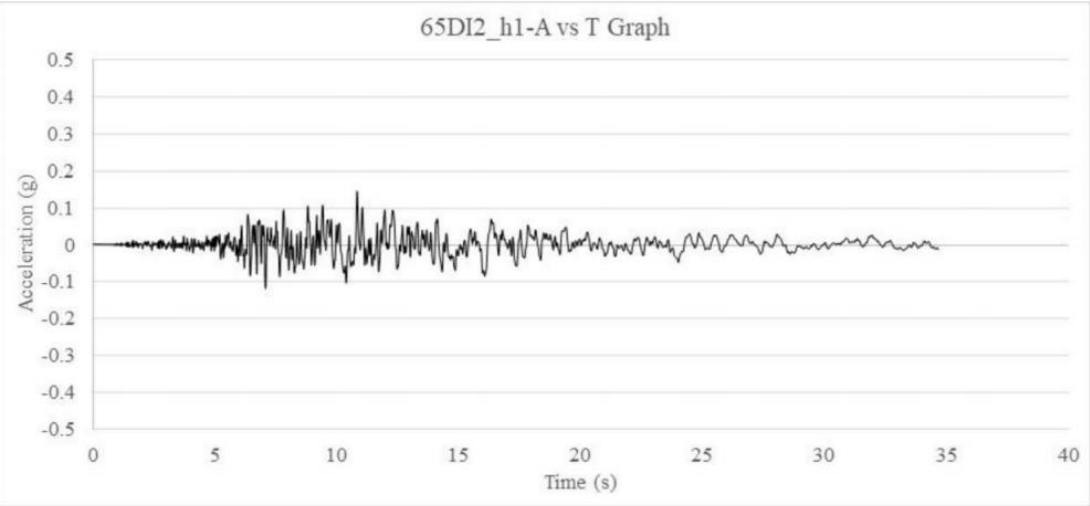


Figure F- 22: Acceleration vs Time Graphs of 65DI1



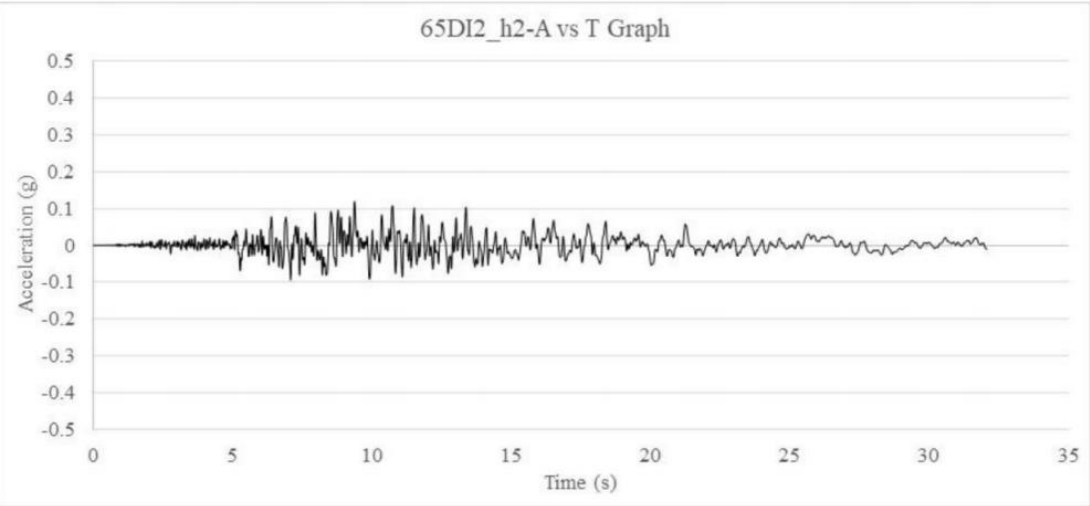
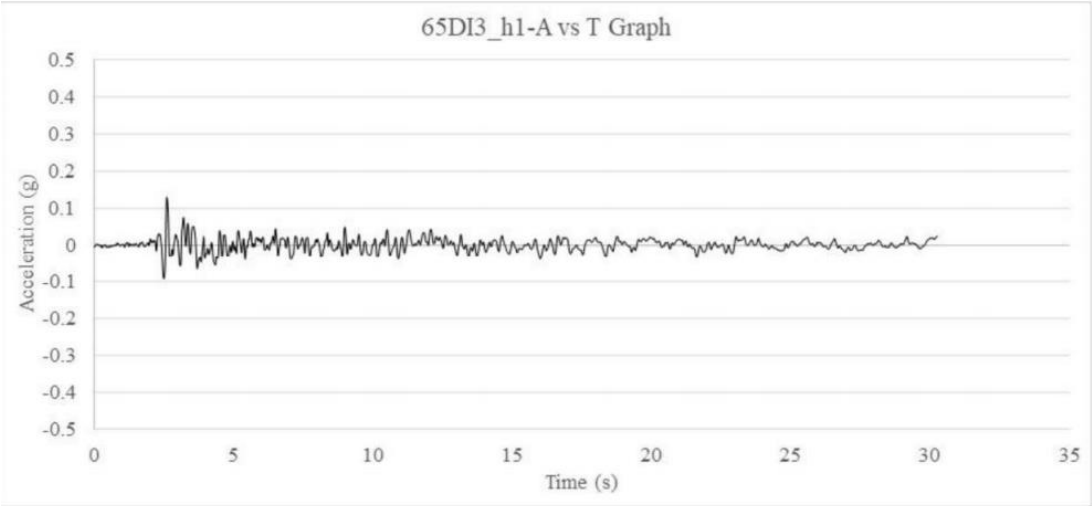


Figure F- 23: Acceleration vs Time Graphs of 65DI2



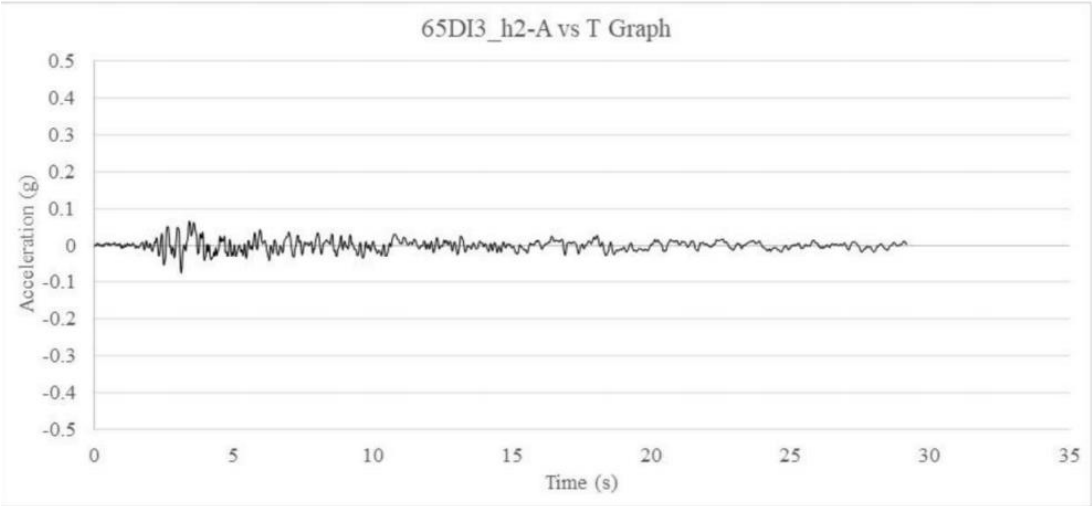
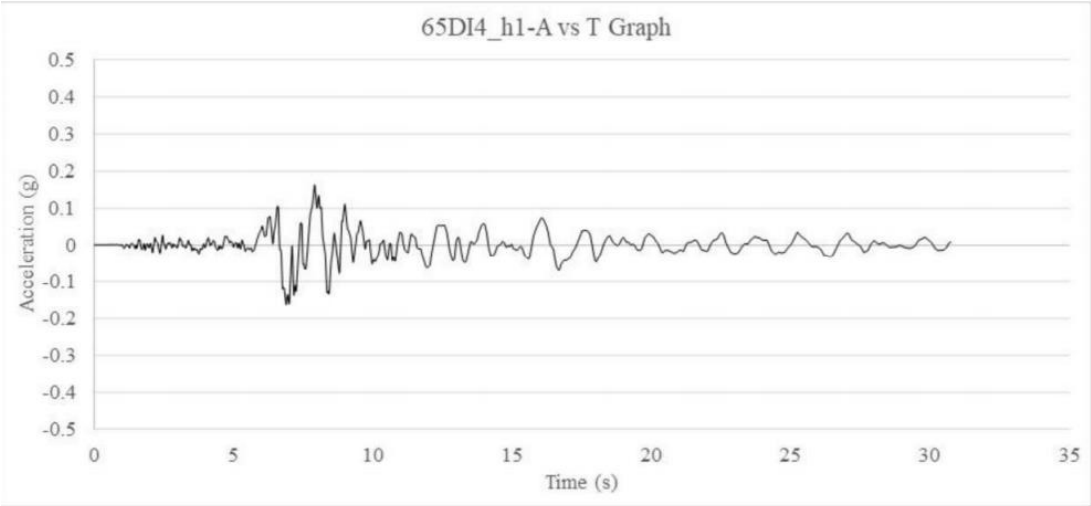


Figure F- 24: Acceleration vs Time Graphs of 65DI3



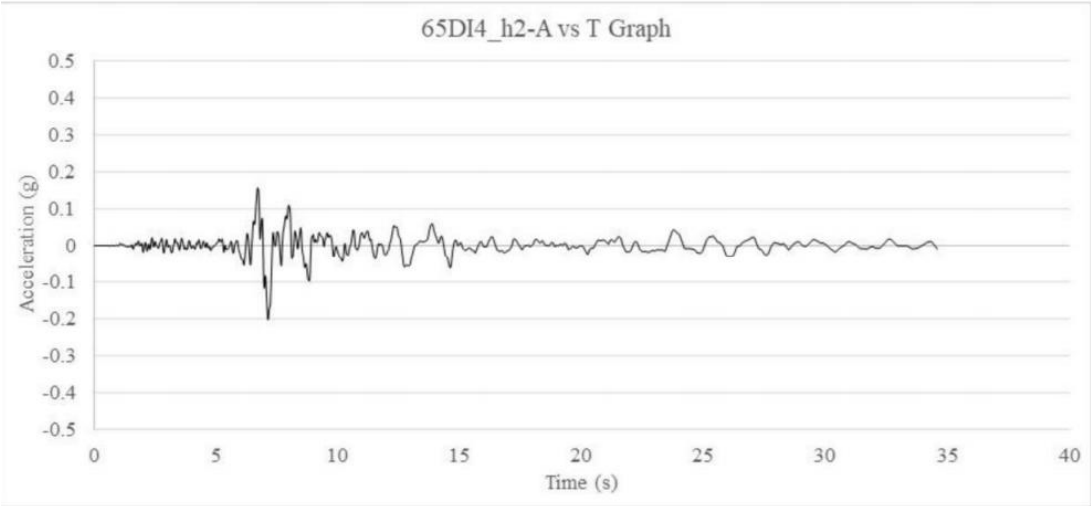
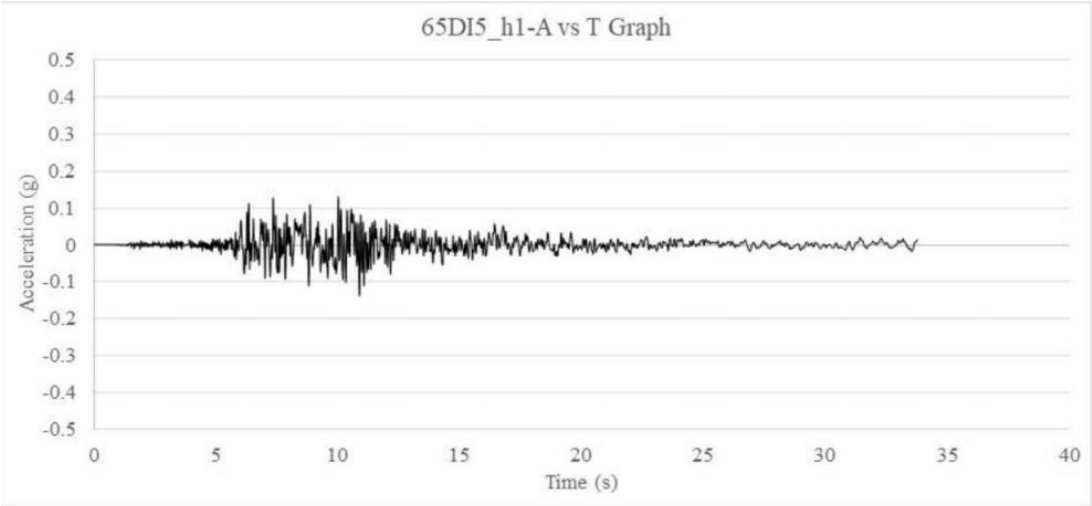


Figure F- 25: Acceleration vs Time Graphs of 65DI4



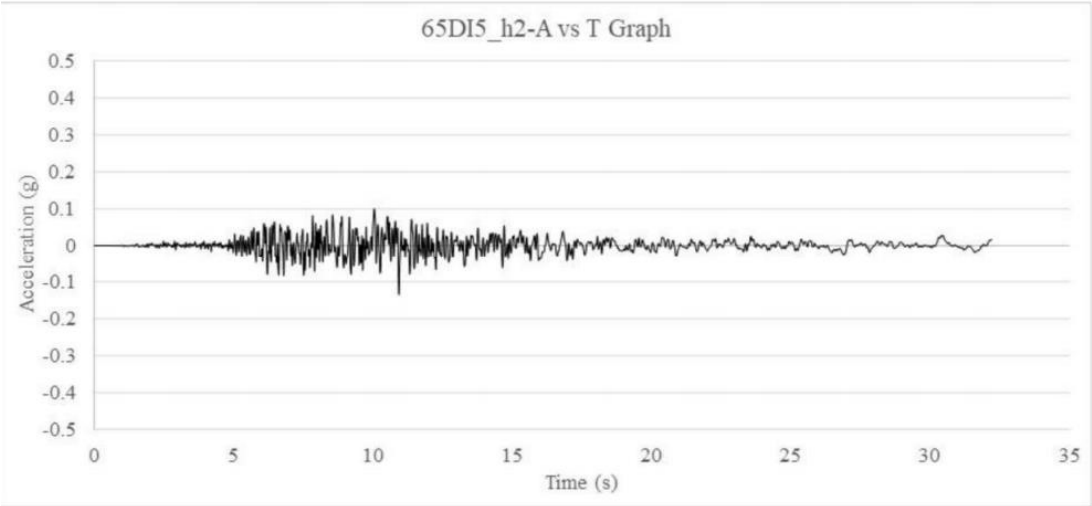
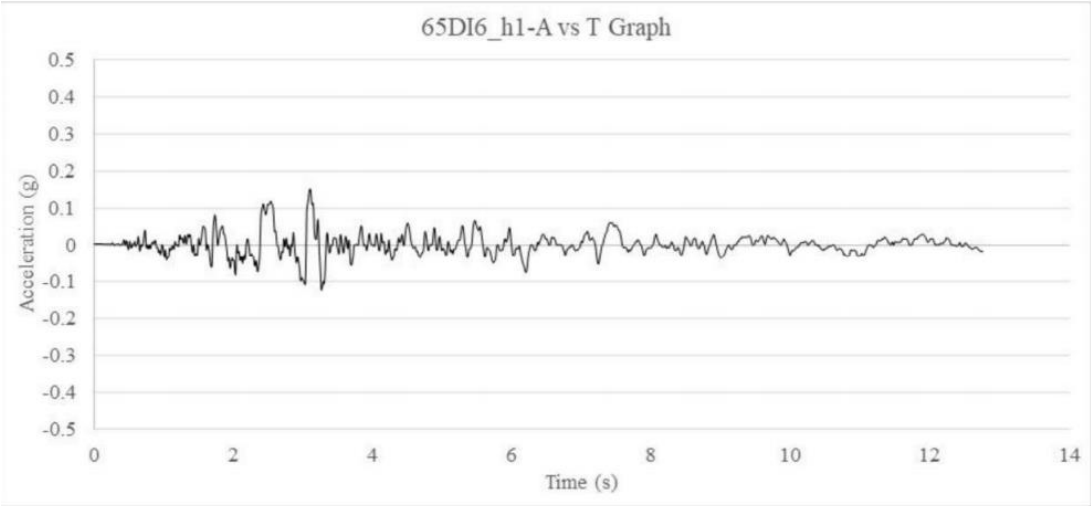


Figure F- 26: Acceleration vs Time Graphs of 65DI5



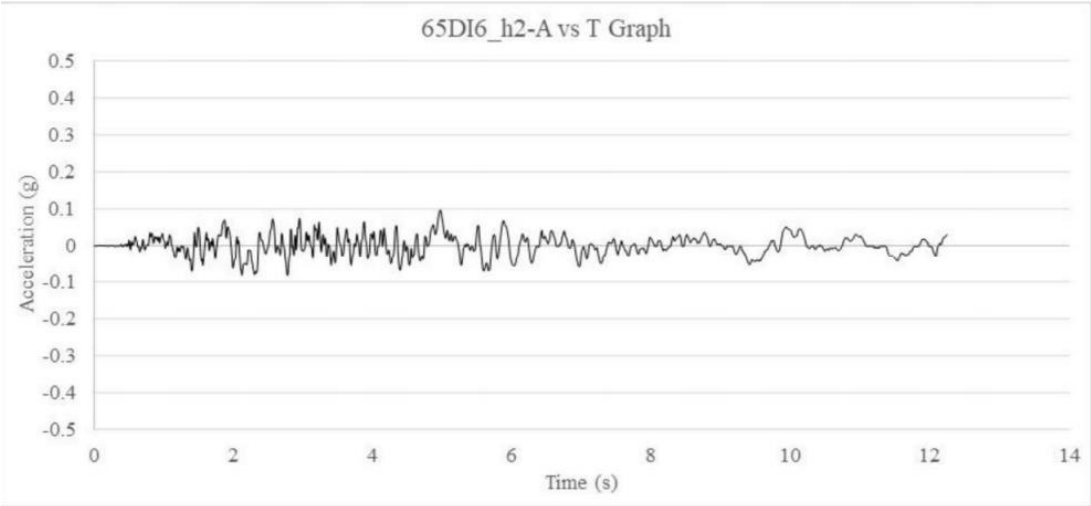
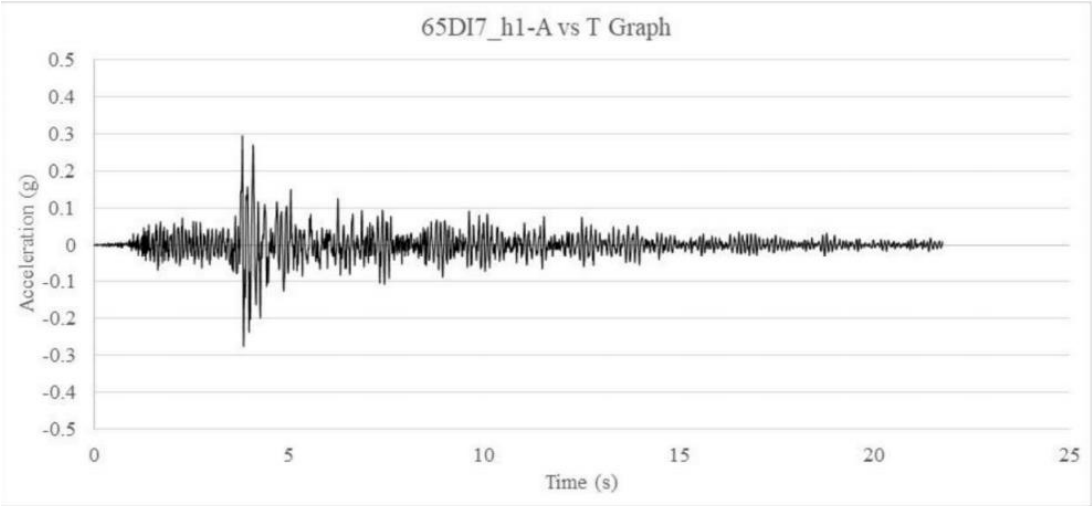


Figure F- 27: Acceleration vs Time Graphs of 65DI6



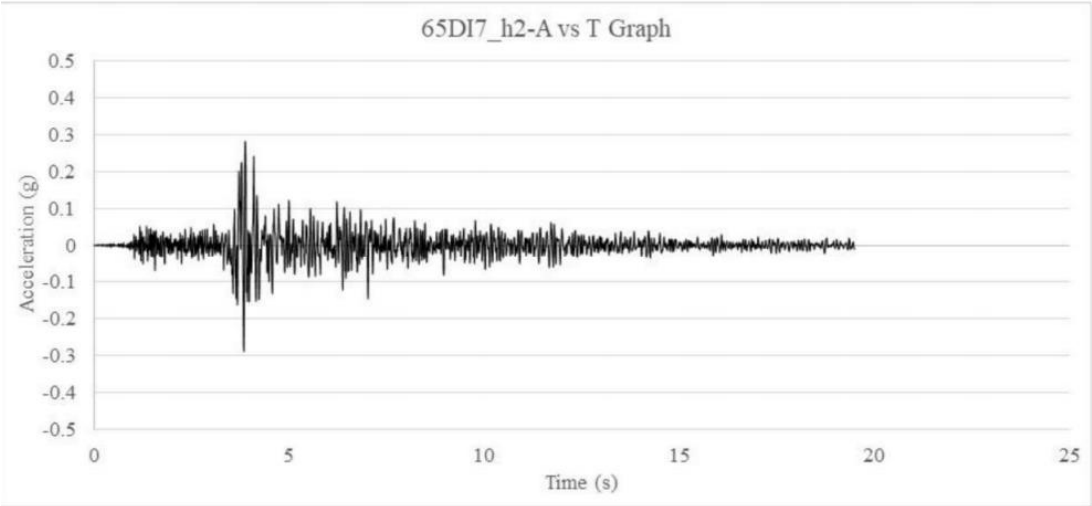
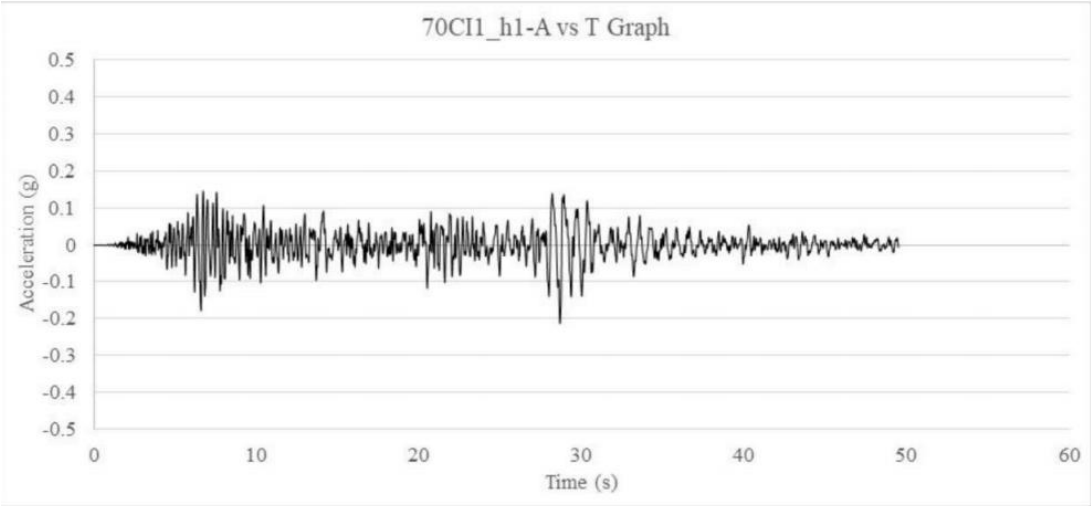


Figure F- 28: Acceleration vs Time Graphs of 65DI7



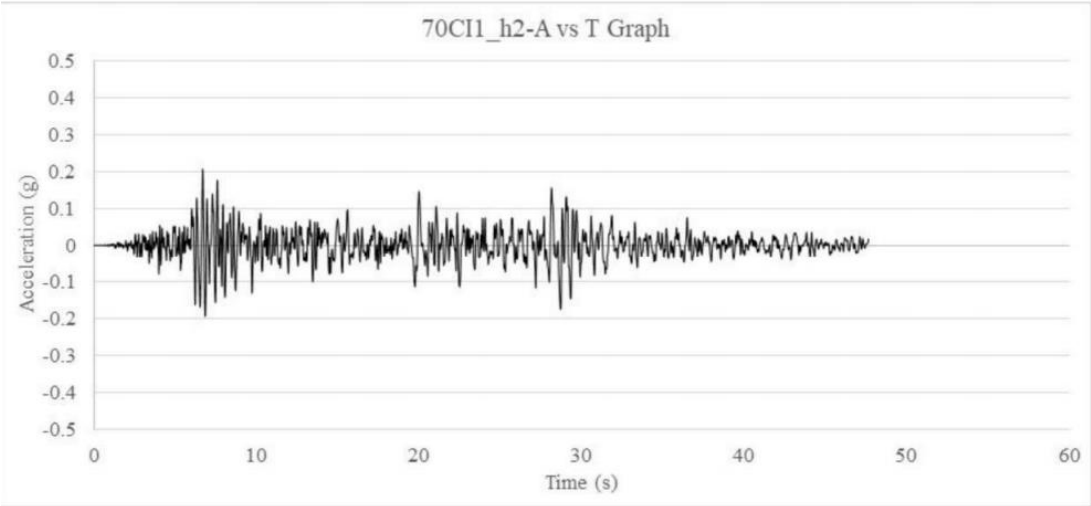
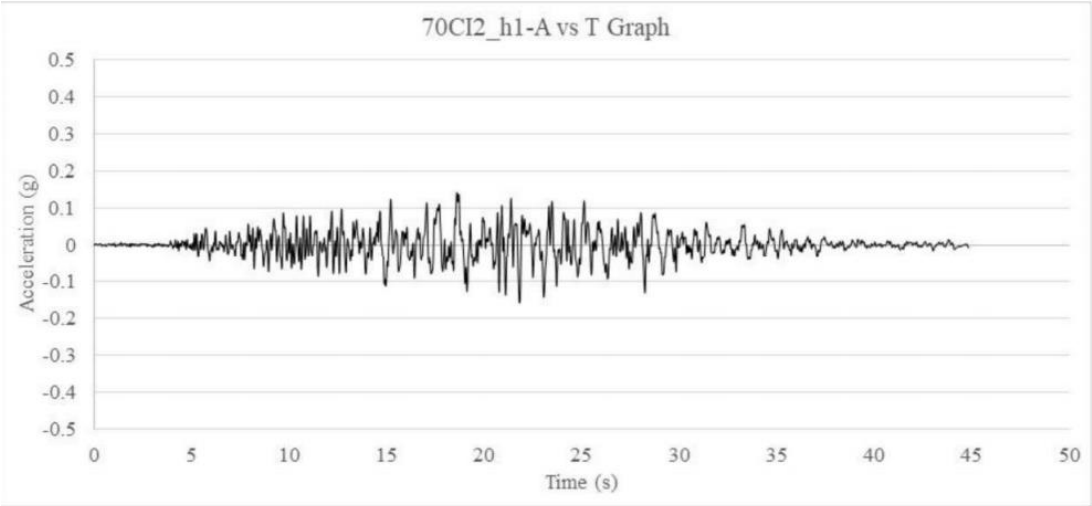


Figure F- 29: Acceleration vs Time Graphs of 70CI1



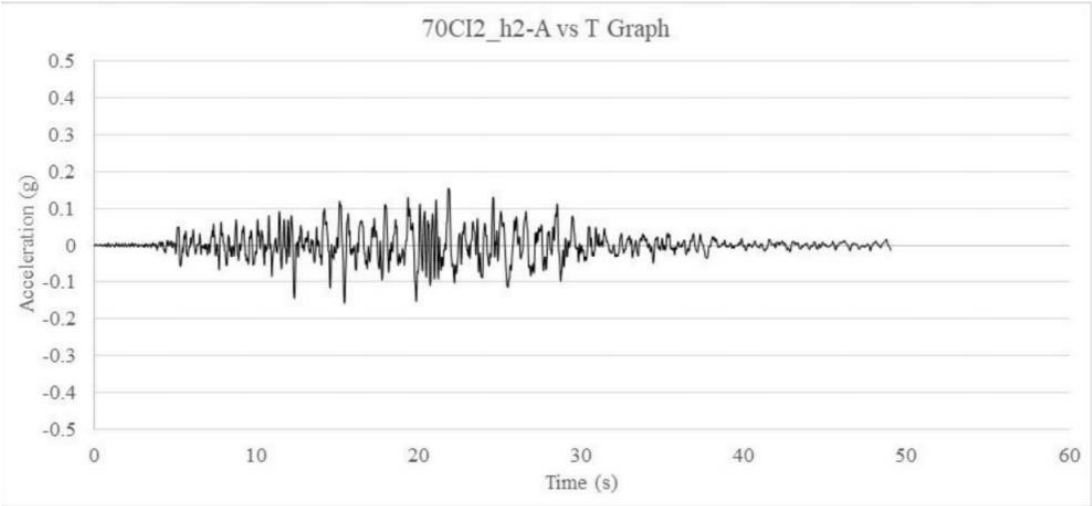
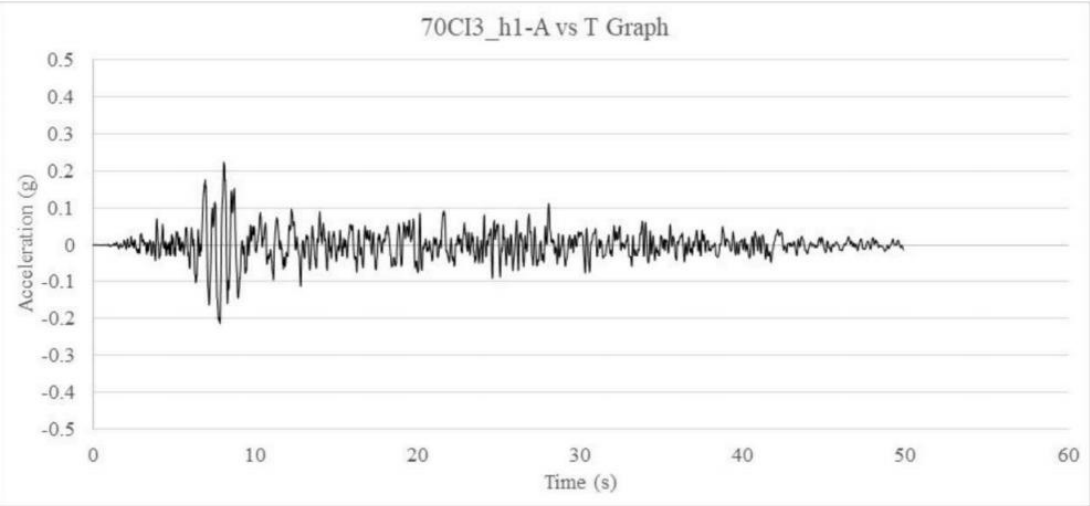


Figure F- 30: Acceleration vs Time Graphs of 70CI2



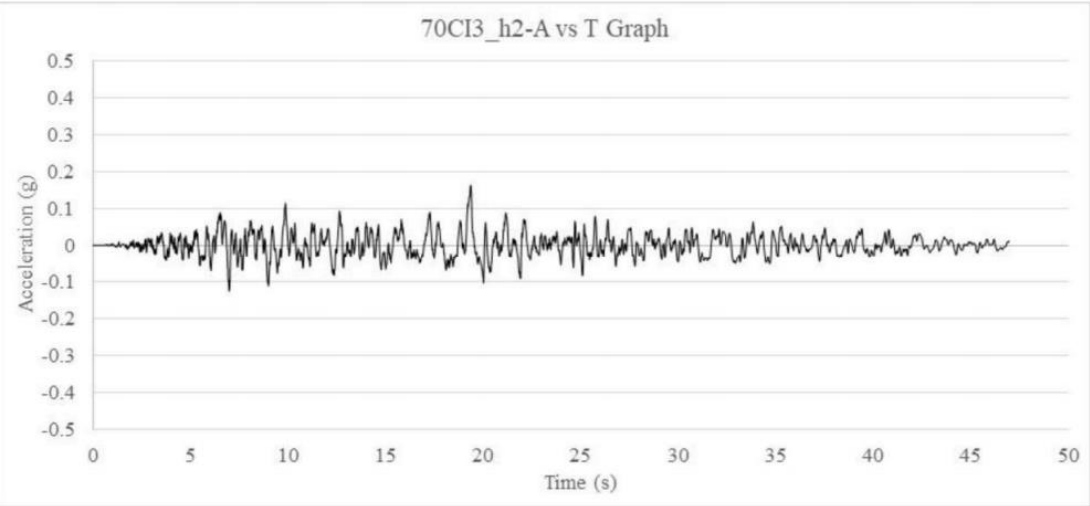
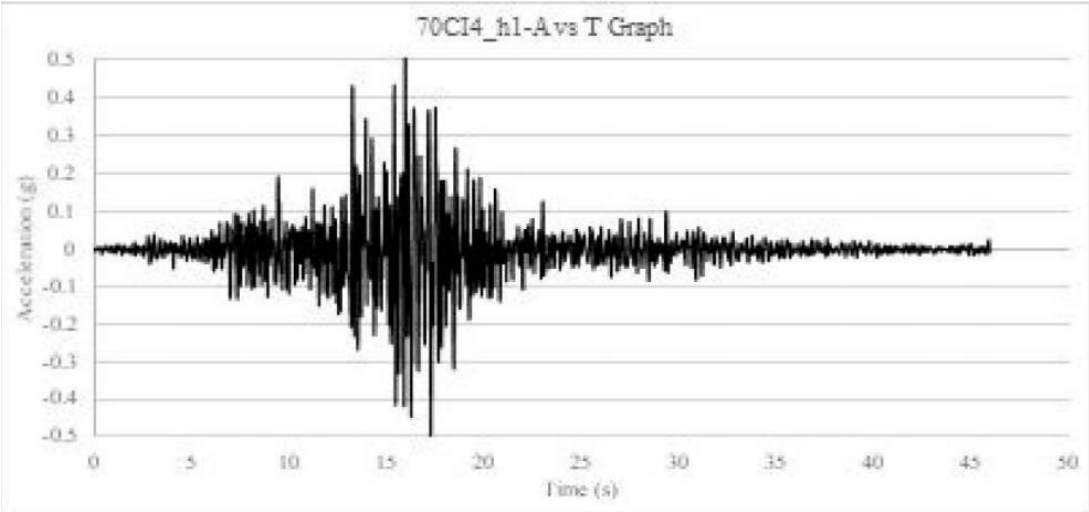


Figure F- 31: Acceleration vs Time Graphs of 70CI3



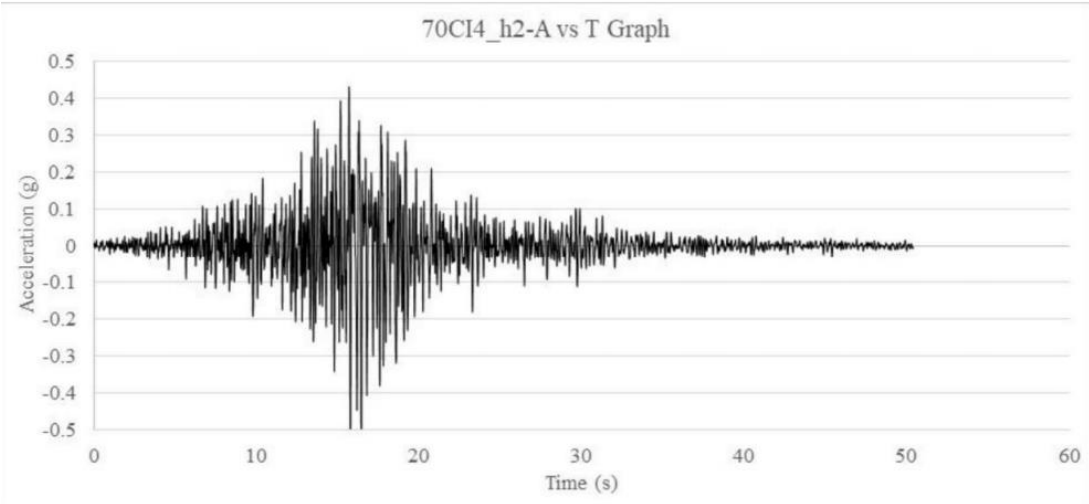
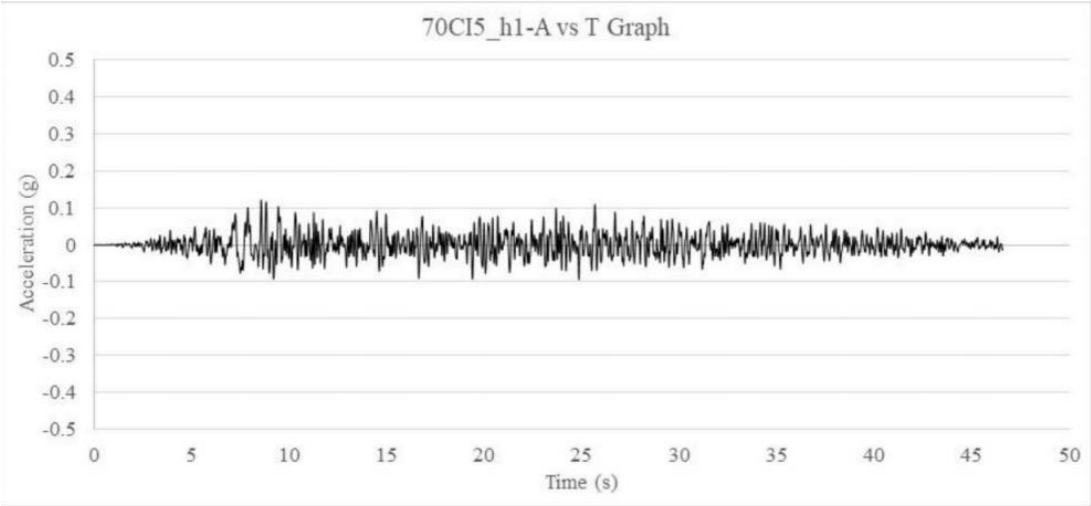


Figure F- 32: Acceleration vs Time Graphs of 70CI4



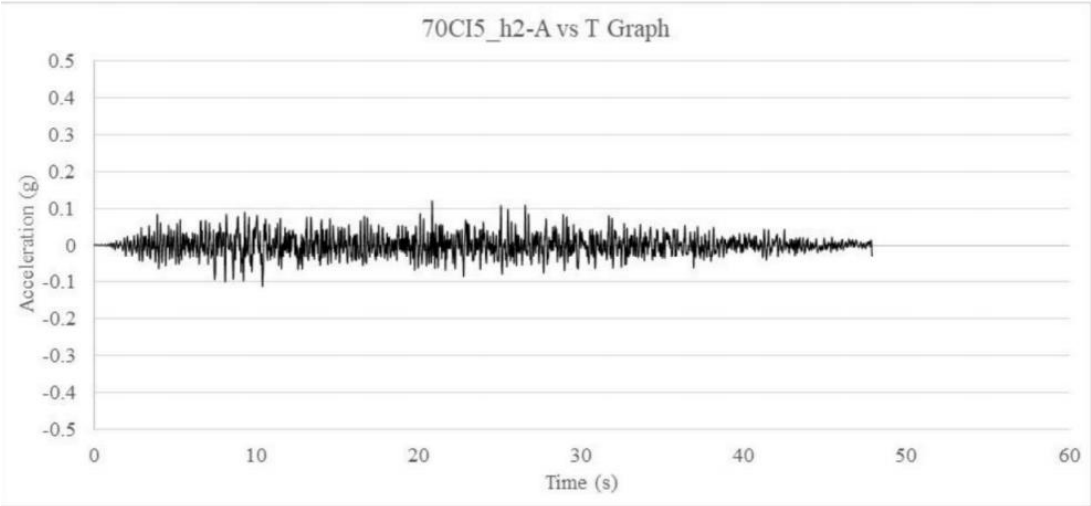
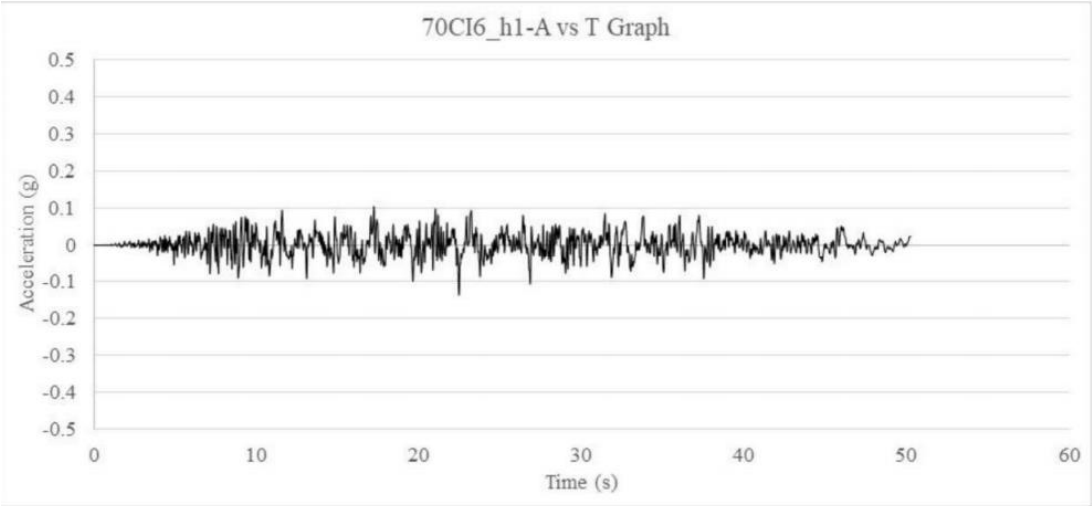


Figure F- 33: Acceleration vs Time Graphs of 70CI5



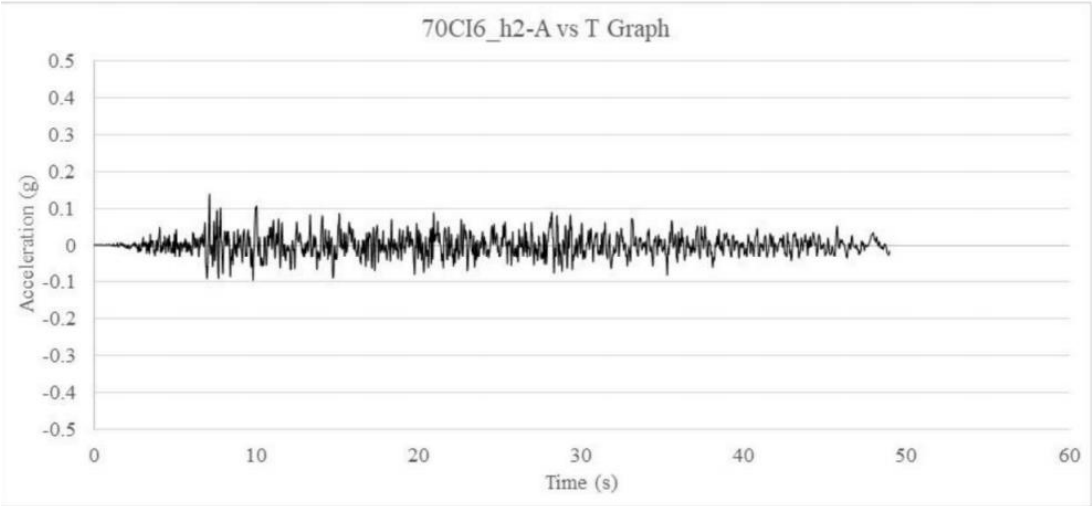
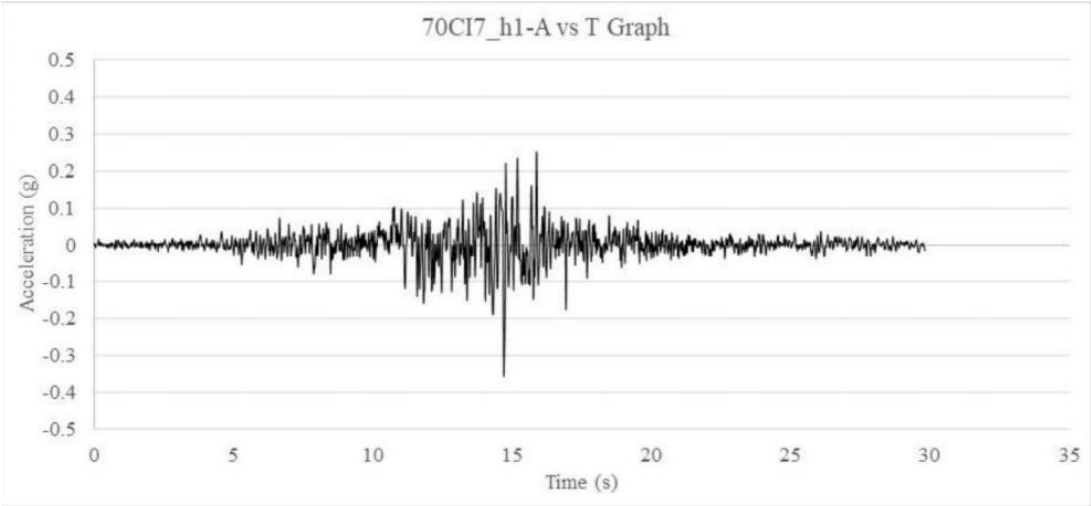


Figure F- 34: Acceleration vs Time Graphs of 70CI6



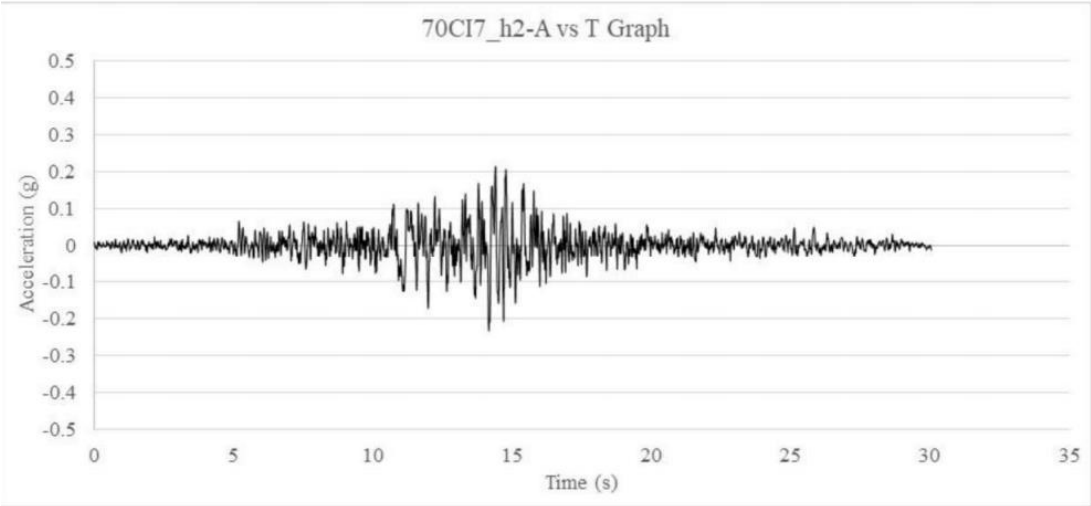
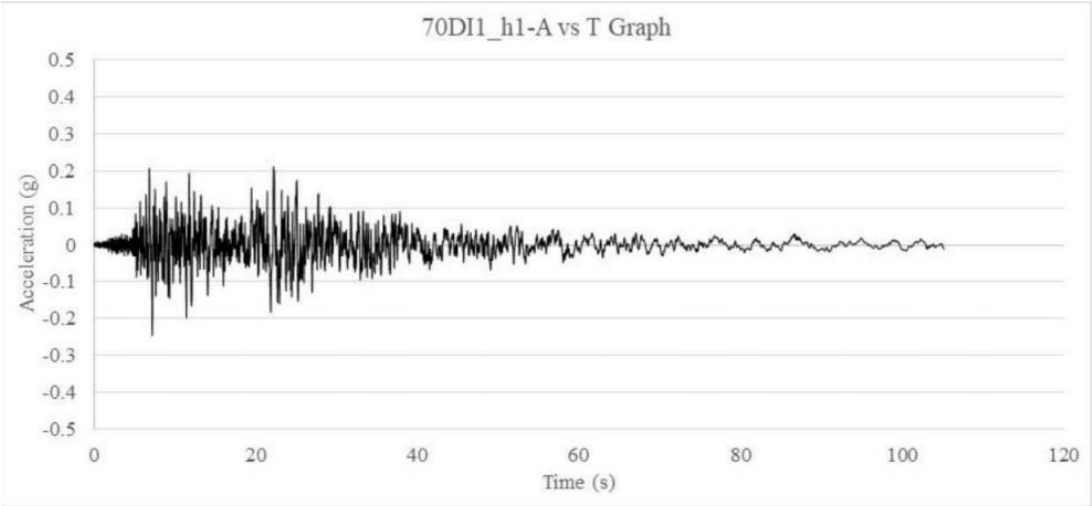


Figure F- 35: Acceleration vs Time Graphs of 70CI7



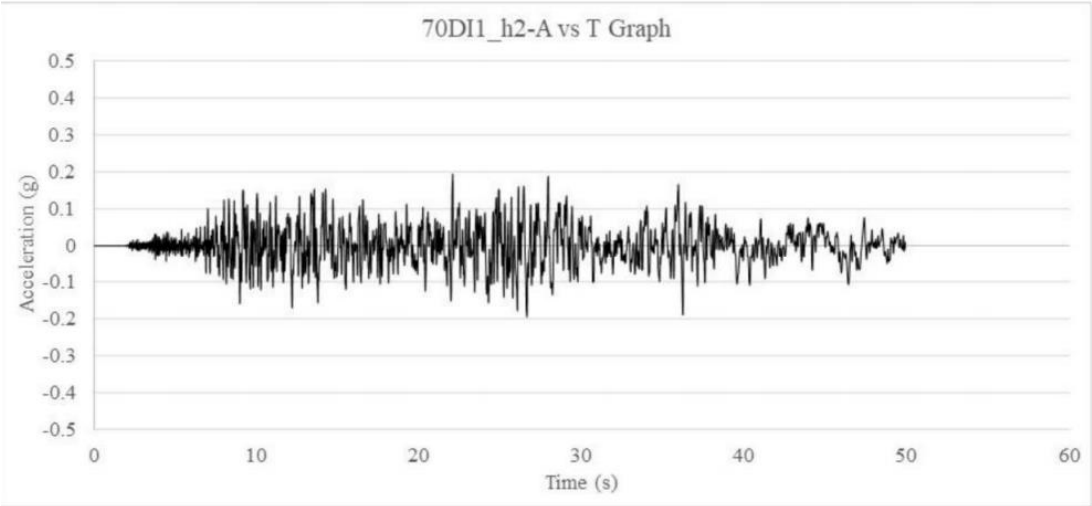
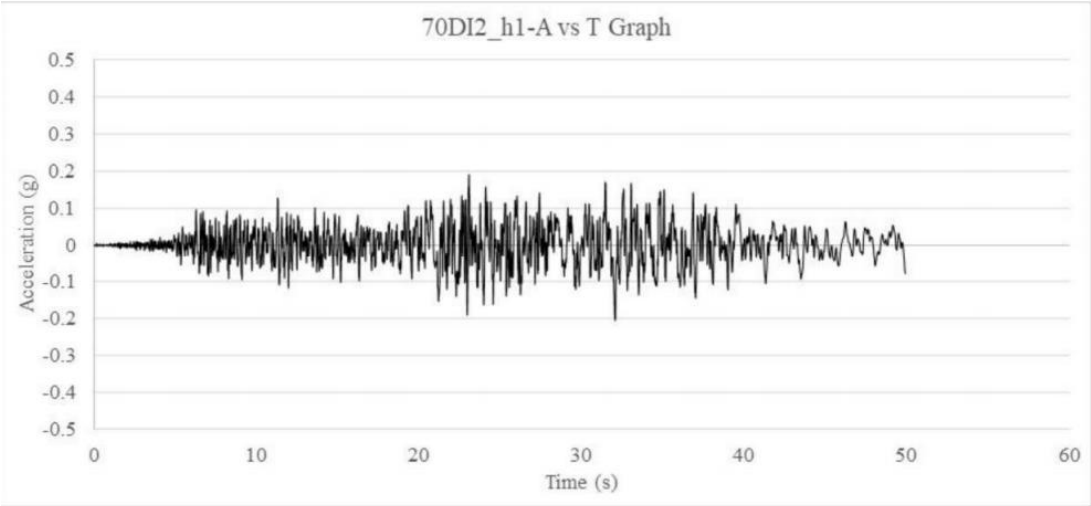


Figure F- 36: Acceleration vs Time Graphs of 70DI1



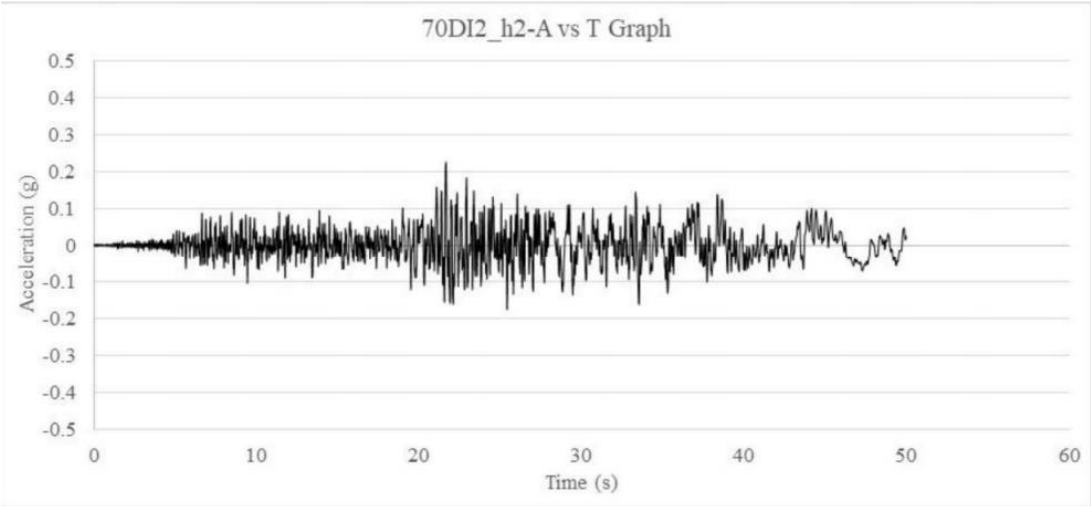
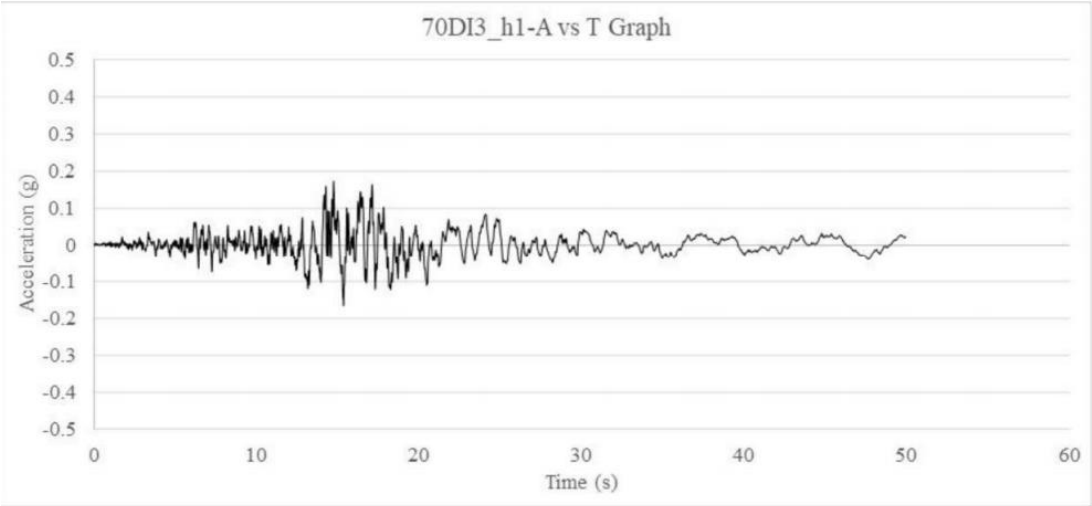


Figure F- 37: Acceleration vs Time Graphs of 70DI2



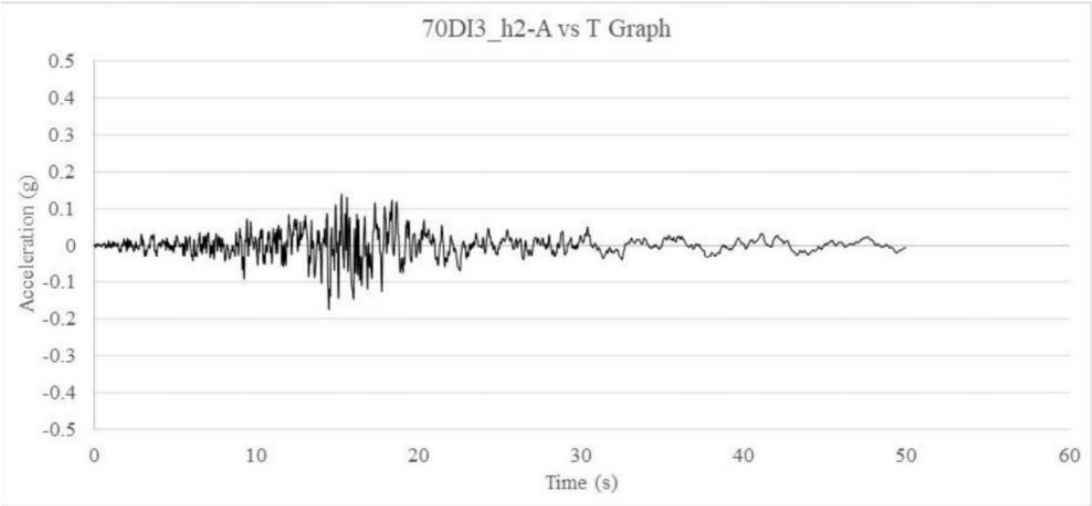
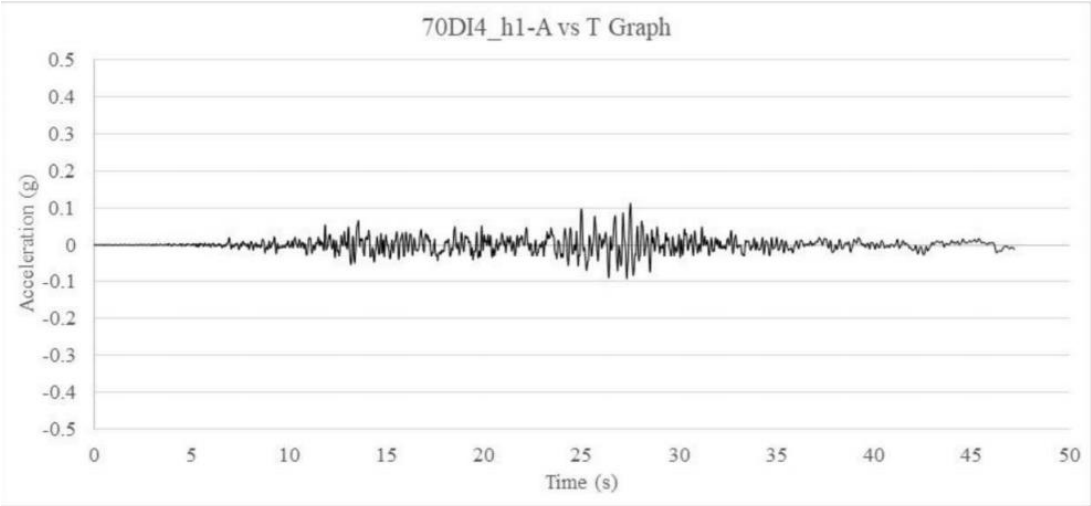


Figure F- 38: Acceleration vs Time Graphs of 70DI3



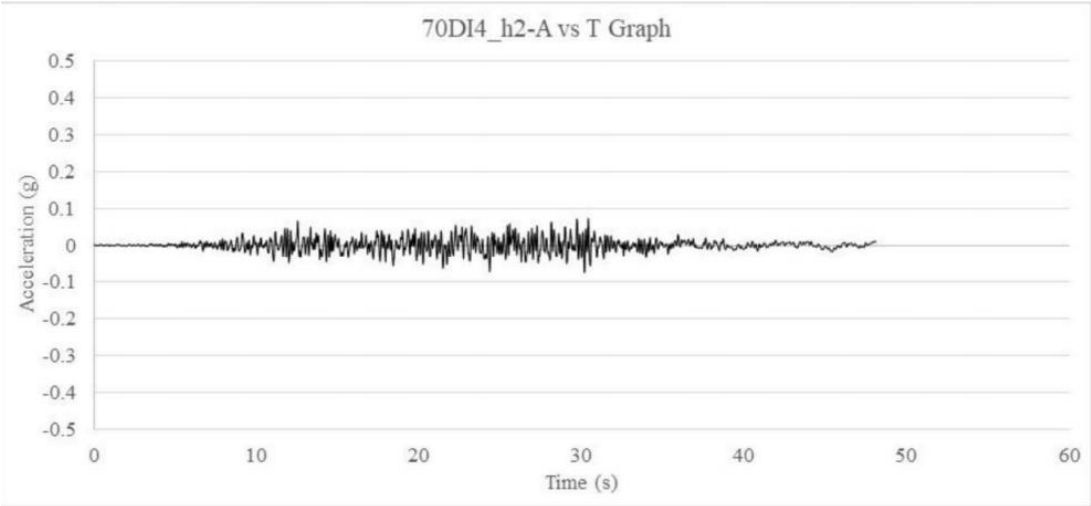
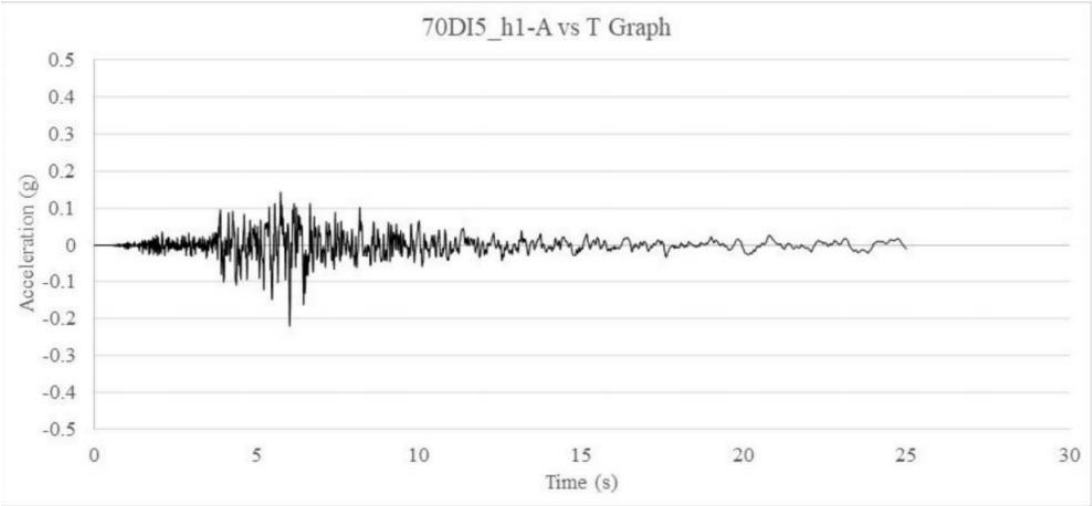


Figure F- 39: Acceleration vs Time Graphs of 70DI4



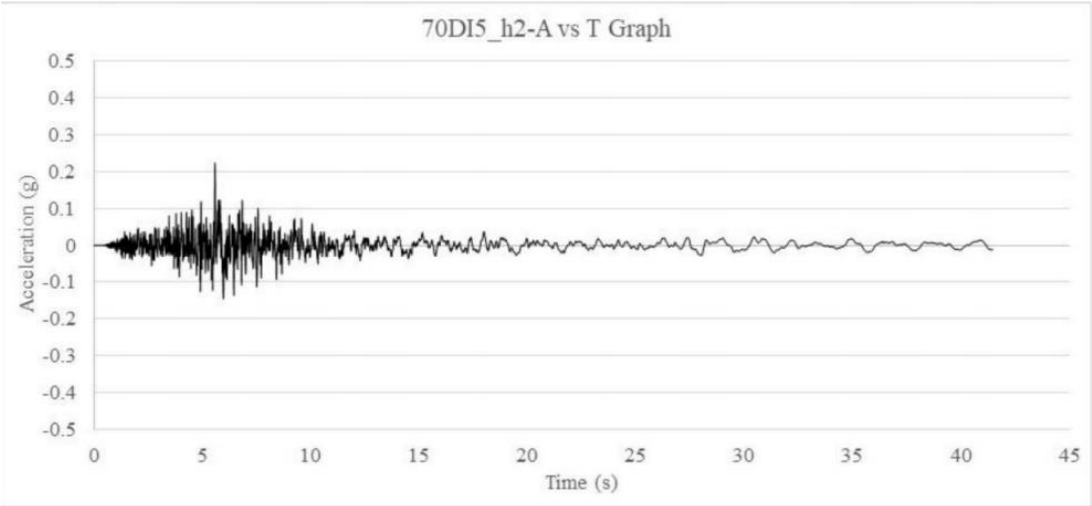
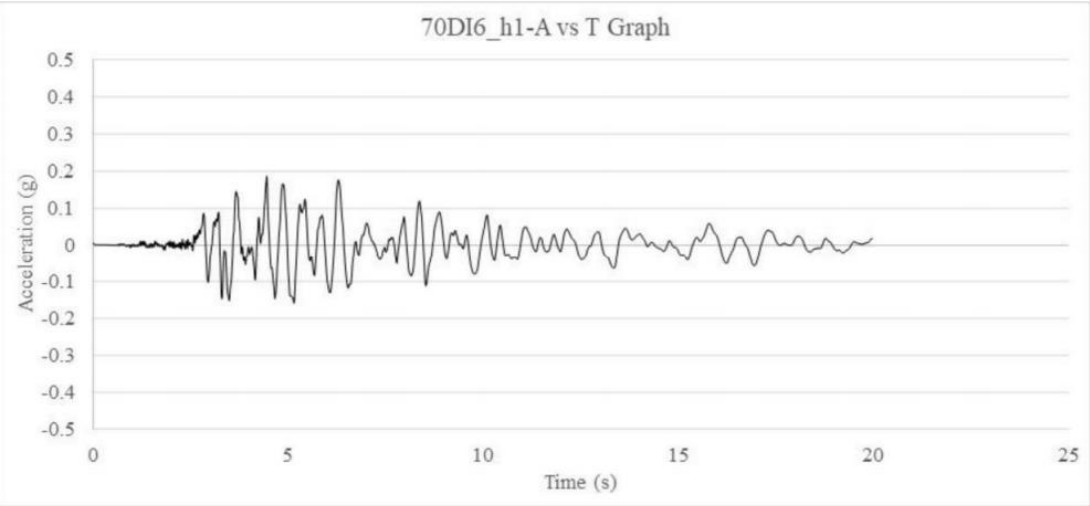


Figure F- 40: Acceleration vs Time Graphs of 70DI5



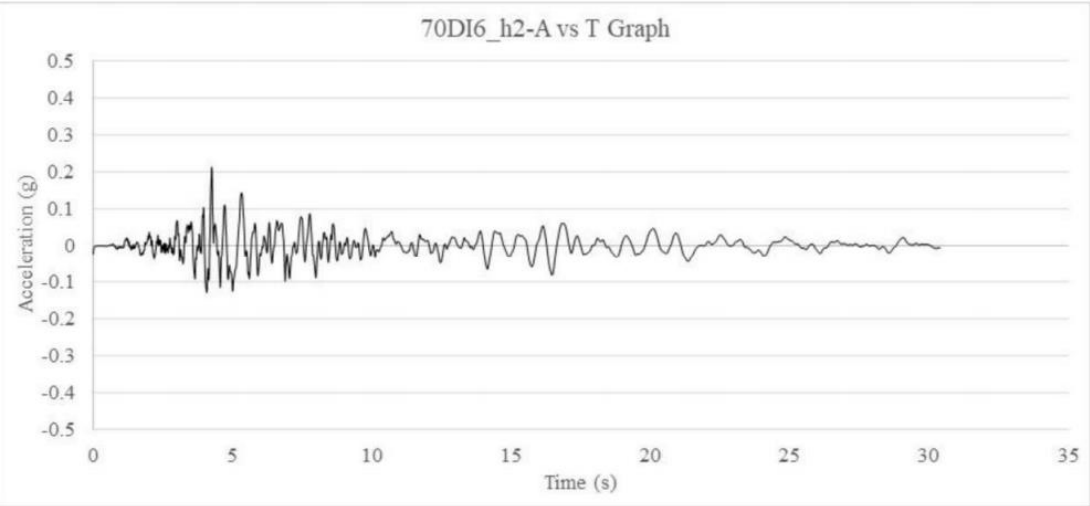
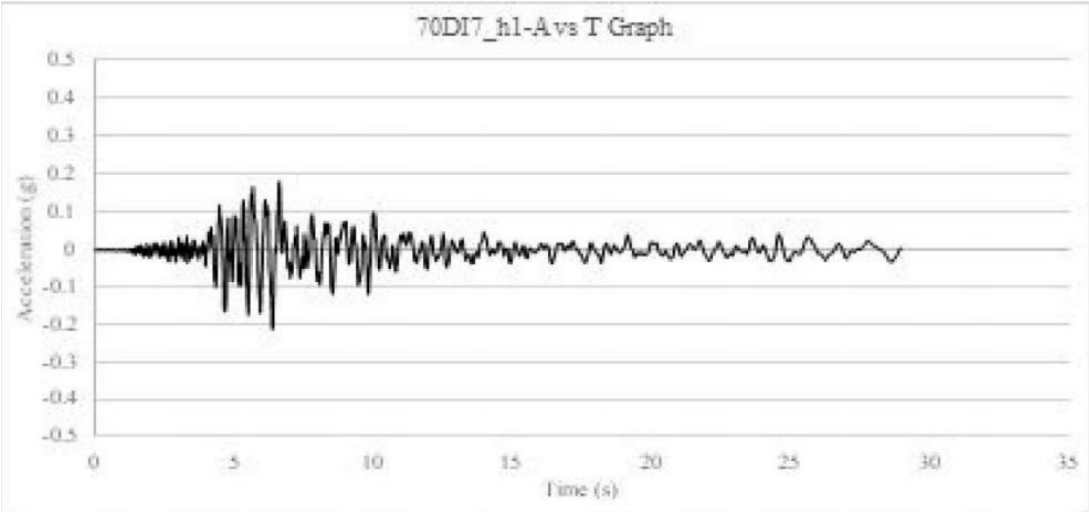


Figure F- 41: Acceleration vs Time Graphs of 70DI6



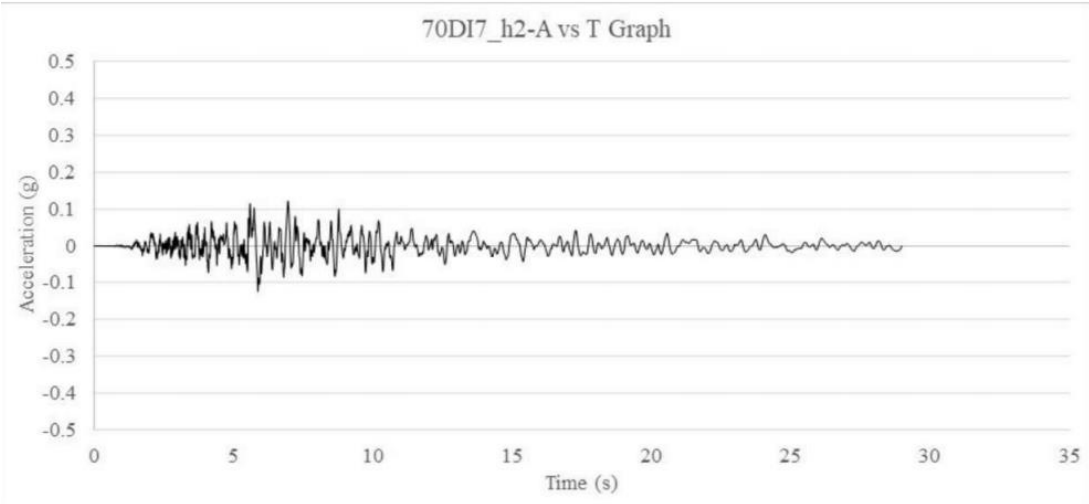


Figure F- 42: Acceleration vs Time Graphs of 70DI7