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DEVELOPMENT OF GROUND MOTION SELECTION AND SCALING FRAMEWORK COMPATIBLE WITH TBEC-2018

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SUMMARY

In the seismic provisions of current building codes and standards, dynamic nonlinear time-history analysis is the ultimate assessment tool for failure mechanisms. Owing to the rapid development of computational methods in structural analysis, there is a growing tendency to perform nonlinear dynamic analysis. However, there is currently no consensus in the earthquake engineering community on how to appropriately select and scale the ground acceleration time series for seismic design and performance assessment of buildings. This study proposes a framework named as "Scalepy" for ground motion selection and scaling, with a focus on selecting the earthquake records that are most compatible with the response spectrum. The challenge of selecting set of accelerograms for time-domain analysis is of practical and academic interest. The algorithm is based on an iterative method to find the record set that causes the least scatter from a given design spectrum. As scaling procedure, the conventional amplitude scaling method is used, to avoid of manipulation the frequency content. Since the largest source of uncertainty comes from ground motion selection, this method aims to obtain optimal time series for engineering demand parameters in amplitude scaling. Scalepy is developed in Python programming language as an open-source project which is shared in GitHub repository to enable any user or developer to contribute the algorithm and methodology without any restriction.

Key Words: Ground motion, Selection, Scaling, Earthquake, Python, Open-Source

ÖZET

Zaman-tanım alanında yapılan doğrusal olmayan dinamik analizler, günümüz deprem şartnameleri için, bina performansını belirlemek için birincil araçlardır. Son yıllarda bilgisayarlı hesap araçlarının gelişen gücü göz önüne alındığında, doğrusal olmayan dinamik analizler ile bina performansı belirlemek, gittikçe daha verimli hale gelmektedir. Buna rağmen, zaman-tanım alanında yapılan analizlerin temel girdisi olan ölçeklenmiş deprem kayıtlarının nasıl seçileceği ve kullanılacağı hakkında, deprem mühendisliği alanında bir fikir birliği bulunmamaktadır. Bu çalışma, tepki spektrumuyla en uyumlu kayıtların bulunmasını sağlayan ve bu kayıtları seçilen bir tasarım spektrumuna uyarınca ölçekleyen bir "Scalepy" isimli bir algoritma geliştirmeyi öngörüyor. Bu algoritma, veri tabanında bulunan deprem kayıtlarından, tepki spektrumuna göre en az saçılım gösteren belirli sayıdaki kaydın, iteratif bir metot yardımıyla bulunması prensibine dayanıyor. Yapısal analizlerdeki en büyük bilinmezlik, binlerce kayıt arasından en uygun olanları belirlemek olduğundan, bu algoritma tepki parametrelerini optimize etmeyi amaçlıyor. Bu çalışma Python programlama dilinde, açık kaynak olarak geliştirilmiş olup Github deposunda paylaşılmış olup kullanıcı ve geliştiricileri herhangi bir engel olmadan algoritma ve yöntemi geliştirmeleri mümkün kılacaktır.

Anahtar Kelimeler: Yer hareketi, Deprem, Seçme Ölçeklenmesi, Python, Acık Kaynak

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I am grateful to my parents and my sister for their love and support.

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviations and Acronyms		**Explanations**
$\mathbf{V_{S30}}$	:	Shear-wave velocity of 30m depth
Sae	:	Spectral Acceleration
$\mathbf{w_i}$	:	Weighting factor for the squared error at period T_i
$\mathbf{y_i}$	:	Ordinate of geometric mean spectrum at period T_i
$\mathbf{y_{ti}}$	:	Ordinate of target spectrum at period T_i

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1. INTRODUCTION

1.1. Motivation

In the seismic provisions of current building codes and standards, time-history analysis is the ultimate and an accurate assessment tool for seismic response of structures in Performance-Based Earthquake Engineering (PBEE). This assessment can be necessary for both to design a new structure or to determine the seismic performance of an existing structure (i.e., high-rise buildings, nuclear power plants). The selection of ground motions for use in nonlinear response history analysis is the most critical step for code-based design checks. Owing to the rapid development of computational methods in structural analysis, there is a growing tendency to perform nonlinear dynamic analysis. One of the objectives of ground motion selection and scaling methodologies is to enable engineers to estimate the median response, or to predict the distribution of structural response, with relatively small number of ground motions. However, there is currently no consensus in the earthquake engineering community on how to appropriately select and scale the ground acceleration time series for time domain analysis.

When nonlinear time history analysis is of concern, an ensemble of accelerograms representing the pre-defined seismic demand is required. This requirement brings forward the significance of obtaining a suitable set of accelerograms since nonlinear structural response can be very sensitive to the employed ground motion time series. Various code-based ground motion selection and scaling methods have been proposed to achieve a reasonably accurate fit between the spectral ordinates of selected accelerograms and target spectrum (Naeim et al., 2004 [1]; Iervolino et al., 2006 [2]; Reyes and Kalkan, 2012 [3]). However, these documents are mostly lack of appropriate guidance for selection and scaling of ground motions used in the analyses. Thus, in practice, it is the engineers call to decide on the procedure for selection and scaling of ground motion records.

Previous versions of ASCE 7 (e.g., ASCE 7-10, American Society of Civil Engineers, 2010 and ASCE 7-16, American Society of Civil Engineers, 2016) presented almost no guidelines on the use of spectrum-compatible records. For the Turkish Seismic Code, in TSC-2007 (Turkish Seismic Code, 2007) [4], a nonlinear time-history analysis was first performed to evaluate the performance of existing structures. With the publication of TBEC-2018 (Turkish Building Seismic Code, 2018) [5], a few methodologies have added for the selection and scaling of time series. However, there is no detailed guideline of the procedure in Turkish Seismic Code also, it is still the researcher's or designer's responsibility to find a reasonable way for selecting an appropriate set of time series.

Therefore, the purpose of this study is to propose a method for record selection to find the optimal set of seismic records that establish the minimum dispersion in the design response spectrum and create a framework for whole selection and scaling procedure. This framework named as "Scalepy" has been developed in Python programming language as an open-source project, which means it is possible to contribute to development of the framework in the future.

1.2. Scope

A valid seismic performance evaluation of structures requires the right selection of input motions for use in nonlinear response history analysis. The current research effort is focused on the creation of strategies for choosing and scaling earthquake records. The primary goal of this dissertation is to propose a novel methodology for determining the optimal ground motion set for a given target spectrum without interfering the frequency content of the motion. Therefore, spectral matching approaches based on signal processing are not in the scope of this study. The critics to the spectral matching have arisen in the academic studies where the magnitude of the natural motions should be arranged rather than the frequency content (Mazzani et al, 2020)

1.3. Organization

This dissertation is composed of seven chapters. The subsequent chapters are organized as follows:

Chapter 1 provides a background about what is the current research situation about selection and scaling of ground motion records and a literature survey about the subject.

Chapter 2 includes the principal of dynamic nonlinear time history analyses and what is the importance of scaled ground motions as an input in dynamic nonlinear time history analyses.

Chapter 3 provides a brief information about the widely used selection and scaling methodologies and seismic code provisions about the subject.

Chapter 4 presents the fundamentals of new proposed methodology, workflow, and iteration steps.

Chapter 5 demonstrates numerical examples with selected scenarios. Four different data set has been prepared for 38 locations in Turkey. These big data set has used to perform sensitivity analysis and assessment of the efficiency of the proposed method.

Finally, Chapter 6 presents the summary and key conclusions of this dissertation and recommendations for future work.

2. GROUND MOTION SELECTION AND SCALING

2.1. Literature Survey

Studies about selection and scaling of ground motion records date back to mid-80s. In the literature it is well documented that the selected ground motions shall possess similar characteristics in terms of both magnitude and distance from the fault.

Nau and Hall (1984) [6] concluded that scaling the records with respect to spectral ordinates reduce the dispersion on the structural response. Kappos and Kyriakakis (2000) [7] emphasized proper scaling of records with respect to the spectrum intensity. Shome et al. (1988) highlighted the correlation between the dispersion in the structural response and number of ground motions to be used in time domain analysis. Stewart et al. (2001) [8] and Bommer and Acevedo (2004) [9] pointed the importance of magnitude and duration match between the selected recordings and the target earthquake scenario. Naeim et al. (2004) [10] emphasized that not only the magnitude but also a proper distance interval that matches the target earthquake scenario.

Cimellaro et al. (2011) [11] observed that the magnitude and distance properties of the selected ground motions affect the dispersion on the engineering demand parameters.

Another important concern about scaling is the value of scaling factors. Watson-Lamprey and Abrahamson (2006) [12] highlighted the shortcomings of excessive scaling that may invoke the bias in the structural response. Hancock et al. (2008) [13] quantified the upper limit upper limit of scaling factor as 10.

According to Al Atik and Abrahamson (2010) [14], regarding the selection process, it is stated that earthquake records in an ideal situation should be selected based on the source, path and site conditions including the magnitude, distance from the fault, the fault type, and directivity.

The time domain scaling approach scale the time histories up or down consistently by a scaling factor that can be either positive or negative to match the target spectrum. While it is hard to match the records to the target spectrum along the whole period, engineers tend to concentrate more on the period of interest of the building that is (0.2Tn to 1.5Tn) according to the Turkish Building Earthquake Code (TBEC 2018). This approach does not change the frequency content of the time history records. Additionally, the records could be scaled separately, or the average of spectra could be scaled to match the target spectrum (Fahjan, 2008) [15].

2.2. Definition of Target Spectrum

A traditional approach for developing design spectra is based on the mean hazard curve of the probabilistic seismic hazard analysis (PSHA). The PSHA produces a suite of hazard curves for spectral ordinates for different response periods. A set of spectral ordinates can be obtained and plotted as a function of response period to form the elastic response spectrum for the selected design return period. This spectrum is known as Uniform Hazard Spectrum (UHS).

The principal regions (acceleration, velocity and displacement) of the design spectrum are identified in which the response is approximately a constant, amplified value. Amplification factors are then applied to the maximum ground motion in these regions to obtain the desired design spectrum.

A target spectrum function is created in the framework which inputs are:

- Spectral acceleration parameter at short periods
- Spectral acceleration parameter at a period of 1 second
- Soil type.

This function returns the target spectrum according to TBEC-2018.

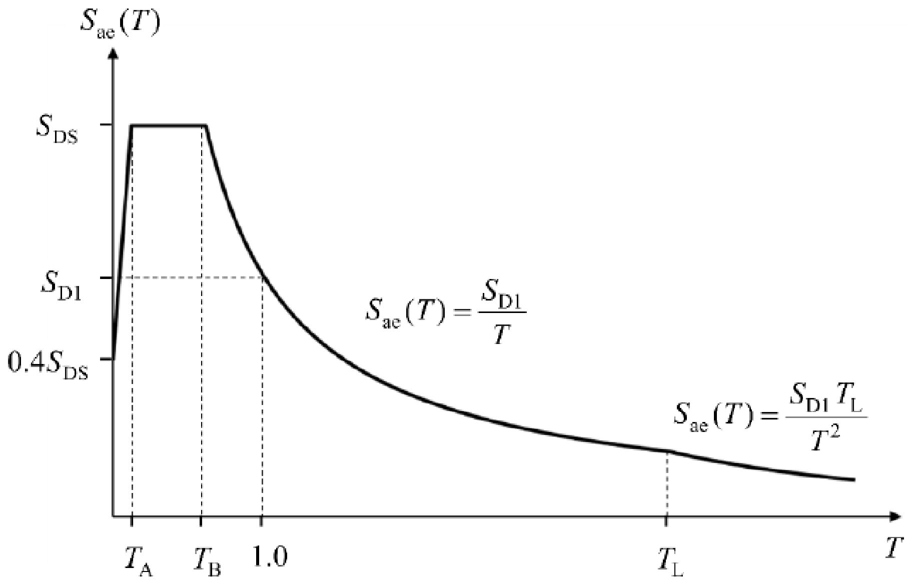

Figure 1. Target Spectrum Definition acc. to TBEC-2108

2.3. Selection Criteria

The current practice for ground motion selection is to assemble earthquake records according to the seismological parameters. Selected earthquakes are expected to have similar parameters with the real earthquake scenario (e.g., magnitude, source-to-site distance, site class, fault mechanism).

The magnitude of the earthquake (M) is the most important parameter for the initial selection of the records because this parameter directly influences the frequency content and the duration of the ground motions. Since the earthquake magnitude (M) and distance (R) of the rupture zone from the site of interest are the most common parameters related to a seismic event, it is evident that every selection procedure must involves these two criteria.

Nevertheless, several studies questioned the effectiveness of these two criteria (e.g., Zengin [16]). Therefore, it is common to use several additional criteria, which can be found in this study, among earthquake engineers.

2.3.1. Additional Selection Criteria

Additional selection criterion complementing both magnitude and distance is the actual soil profile. The geotechnical profile is known to influence seismic motions by modifying the amplitude and the computed response spectra. In this study, shear-wave velocity at the uppermost 30 m (V_{S30}) used as a suitable metric for site classification. Alternatively, site classification can be done according to seismic code provisions and soil categorization schemes can be utilized for the record selection procedure.

Another important issue in the literature is consideration of rupture mechanism or type of faulting. Information generated from the predictive equations developed in the NGA Project demonstrated that earthquakes with reverse-oblique mechanism have similar characteristics to those from reverse faulting events, but there are significant differences with other types of faulting mechanisms. The impact that various studies has showed that, faulting mechanism has an impact of earthquake characteristics led many researchers to use these parameters in the earthquake selection process.

2.4. Scaling Methods

There are certain methods of scaling time histories. These included spectral matching methods where the frequency content of the ground motions is manipulated to establish spectral convergence. The other method, known as amplitude scaling method, is limited to varying only the amplitude of the ground motions. Regardless of the scaling method, there are still no detailed workflow for selecting records. There are some proposed methods, namely spectral matching based selection, and ground motion intensity-based selection.

2.4.1. Amplitude Scaling

In this approach, recorded motion is scaled up or down uniformly to best match the target spectrum within a period range of interest, without changing the frequency content. When dealing with more than one input time history, one can either use the same procedure to fit each record separately or try to best fit the average of the produced to the target spectrum. The proposed algorithm which is used in this study, matches the average and individuals to the target spectrum.

2.4.2. Frequency Matching

This method is based on the concept of using actual records to generate time histories that fit a given target response spectrum. The physical characteristics of the earthquake motion are retained throughout the procedure, which makes the technique powerful in comparison with the classical artificial record generation. In this method, an actual motion is filtered in the frequency domain by its spectral ratio with the design target spectrum.

The Fourier phases of the motions remain unchanged during the entire procedure. The technique is repeated iteratively until the desired matching is achieved for a certain range of periods. A frequency domain scaling methodology uses an actual record to produce a similar motion that matches almost perfectly a target (design) spectrum. The resulting time histories should be investigated in terms of suitability as input for linear and nonlinear time history analyses of engineering structures.

2.5. Seismic Code Provisions

Seismic codes describe general guidelines but do not provide specifics for selecting earthquake records for nonlinear dynamic analysis purposes. There are three main reasons for that:

- Time-history analysis are rather recent.
- Research on this topic is still under development.
- Full agreement has not yet been reached.

Most contemporary seismic codes, such as Eurocode 8 [17], ASCE Standards and TBEC-2018 describe relatively similar procedures for earthquake simulation. However, TBEC – 2018 include no guideline for selection criteria.

This framework is adapted to requirements according to the TBEC-2018 (Turkish Building Seismic Code, 2018). The selection and scaling requirements were first mentioned in TSC-2007 (Turkish Seismic Code – 2007). According to the TSC-2007, requirements concerning real earthquake records are:

- At least 3 ground motions should be considered.
- The duration of the strong ground motion shall not be less than 5 times the first natural vibration period of the building and 15 seconds.

- The mean of the spectral acceleration values of the generated earthquake ground motion corresponding to the zero period will not be less than Ao (effective ground acceleration coefficient x gravitational acceleration).
- The mean of re-calculated spectral acceleration values shall not be less than 90% of the elastic spectral accelerations (Sae(T)) for periods between 0.2T1 and 2T1 (T1 as first natural vibration period) in the earthquake direction considered. In the case of linear elastic analysis, the spectral acceleration values (SaR(Tn)) to be taken as basis of determining the reduced earthquake ground motion, will be calculated with the reduced acceleration spectrum coordinate formula.

According to the TBEC-2018, requirements for selection and scaling are:

- Seismic acceleration records to be used in the time domain analyses must be compatible with the Design Acceleration Spectrum. Appropriate acceleration records must be selected accordingly, scaled, and modified for this operation.
- In the selection of acceleration records the following properties must be taken into consideration: Fault distances, source mechanisms and local ground conditions, past earthquake records, number of acceleration sets must be at least eleven. Maximum 3 record can be selected from same event.
- Amplitudes of the average of the selected acceleration records between 0.2T and 1.5T periods are scaled so that they are not smaller than the design acceleration spectrum, where T is the fundamental period of the building. [17]

3. PROPOSED METHODOLOGY

3.1. Algorithm

To find the earthquake record set which has minimum diversity with the target response spectrum, an iterative algorithm is used. This algorithm is searching PEER Ground Motion Database. There are several stages of selection procedures:

1. Filtering earthquake according to given magnitude range, soil type, fault distance, fault mechanism, 5-75% significant duration, 5-95% significant duration, and arias intensity.

2. Eliminate the selected earthquake records in the first stage if there are more than 3 records from the same event.
3. Use the curve similarity algorithm to find most similar records to the design spectrum.

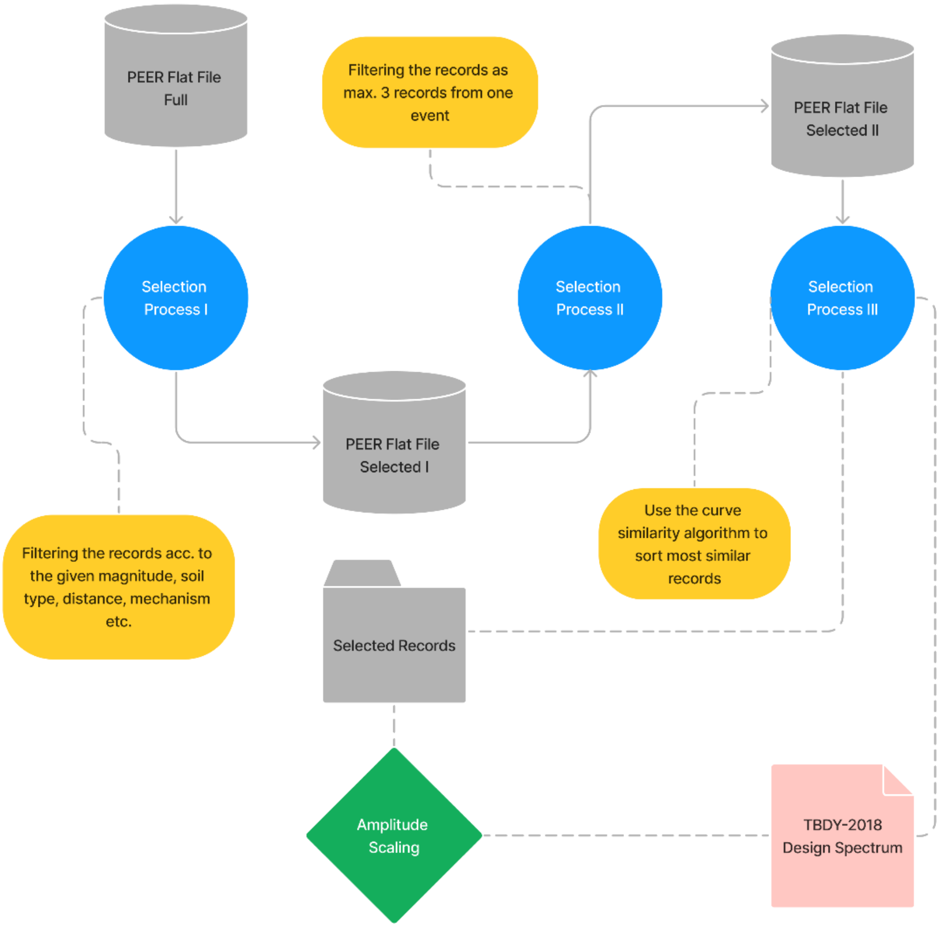

Figure 2. Algorithm Flowchart

Selection algorithm can be used to find most similar 11 ground motion records to the design spectrum. This method is reducing the uncertainties in the scaling procedure because the dispersion of the acceleration content is minimum.

After the selection procedure, this framework enables us to compare two new concepts for selection and scaling of ground motions. First one is, the possibility to calculate orientation-independent spectrums (RotDnn) and the second one is a different amplitude scaling method in P695 [18].

3.2. Orientation-Independent Spectrum

Chapter 16 of ASCE7-16 proposed two methodologies to select and scale real ground motions to perform nonlinear time history analysis:

- First method proposes to produce a maximum-direction (RotD100) MCEr spectrum according to provisions in Chapter 11 along with mapped acceleration parameters.
- Second method proposes to produce two or more site-specific response spectrum which is not less than 75% of the spectral values in the MCEr (Method 1) over the period of range of interest.

This methodology allows engineers to use two new methods to produce response spectrum. RotD100 is maximum spectral acceleration observed in any orientation of horizontal ground motion shaking and RotD50 is median spectral accelerations over all orientations.

Current approaches to the matching methods are mostly matching a single component to a target spectrum. This produces no issues when the load resisting system is split into two dimensional multiple models. This analysis models requires only one horizontal accelerogram input. On the other hand, when it comes to calculate the lateral response a three-dimensional complex model with time-history analysis, uncertainties of the ground motion input have increased. The approach of RotDnn concept is the solution to decrease these uncertainties with the orientation-independent spectrums.

These approaches still not recognized by the Turkish Seismic Code and its applications, but when we consider that Turkish Earthquake Code mostly follows the provisions of ASCE, most probably these approaches will take place in the next Turkish Seismic Code.

In this framework, a function to calculate RotD100 spectrums has added to compare the results with the SRSS approach.

3.3. FEMA P695 Scaling Procedure

A different scaling procedure has added to the framework to compare the results of the existing scaling procedure. Amplitude scaling method mentioned in FEMA P695 is developed as a function in the framework. This function includes two steps:

- Individual records of a given set are normalized by their respective peak ground velocities. In essence, some records are factored upwards (and some factored downwards), while maintaining the same overall ground motion strength of the record set. The following formulas define the normalization factor *NM* and calculation of normalized horizontal components.

$$\mathrm{NM_i} = Median(PGV_{PEER,i})/PGV_{PEER,i} \tag{3.1}$$

$$NTH_{1,i} = NM_i x TH_{1,i} \tag{3.2}$$

$$NTH_{2,i} = NM_i x TH_{2,i} \tag{3.3}$$

Where:

$\mathrm{NM_i}$ = Normalization factor of both horizontal components of the i^{th} record (of the set of interest),

$\mathrm{PGV_{peer,\,i}}$ = Peak ground velocity of the i^{th} record (PEER NGA Database),

$Median\left(PGV_{PEER,i}\right)$ = Median of $PGV_{PEER,i}$ values of records in the set,

$NTH_{1,i}$ = Normalized i^{th} record, horizontal component 1,

$NTH_{2,i}$ = Normalized i^{th} record, horizontal component 2,

$TH_{1,i}$ = Record *i*, horizontal component 1 (PEER NGA Database)

$TH_{2,i}$ = Record *i*, horizontal component 2 (PEER NGA Database)

- Second step in this procedure is the scaling of the normalized set. For collapse evaluation, the Methodology requires the set of normalized ground motion records to be collectively scaled upward (or downward) to the point that causes 50 percent of the ground motions to collapse the archetype analysis model being evaluated. This approach is used to determine the median collapse capacity S_{ct}, of the model. Once this has been established, the Methodology requires that the collapse margin ratio, CMR, be computed between median collapse capacity, S_{ct} , and MCE demand, S_{mt}.

3.4. Ground Motion Database

The ground-motion record library used in this study is gathered from the PEER (Pacific Earthquake Engineering Research)-NGA (http://peer.berkeley.edu) database. This web-based database includes a very large set of ground motions recorded in worldwide in active tectonic regimes. The database has a comprehensive meta-data, which includes various characteristics of the earthquake source data. This source data is used in this study as selection database. Due to copyright issues, all databases cannot be linked to source-code. After iteration and scaling, our algorithm returns selected earthquakes record sequence number and scaling factors.

This web-based database has also a tool for scaling selected ground motions. This tool is not using an iteration or optimization of records. Therefore, in this study, this scaling tool is used for the comparison of results.

3.5. Iteration and Correlation

Dealing with multiple time histories requires to fit each record separately, besides fitting the average of the ground motions to the target spectrum. In this study, the scaling method applied to the ground motion records is an amplitude scaling method. In this approach, records adjusting by multiplying with a scalar called as scale factor, over the period range of interest, without changing the frequency content. Following procedure is used to find this scalar:

1. Filter ground motion database acc. to selected magnitude range, soil type, mechanism etc.

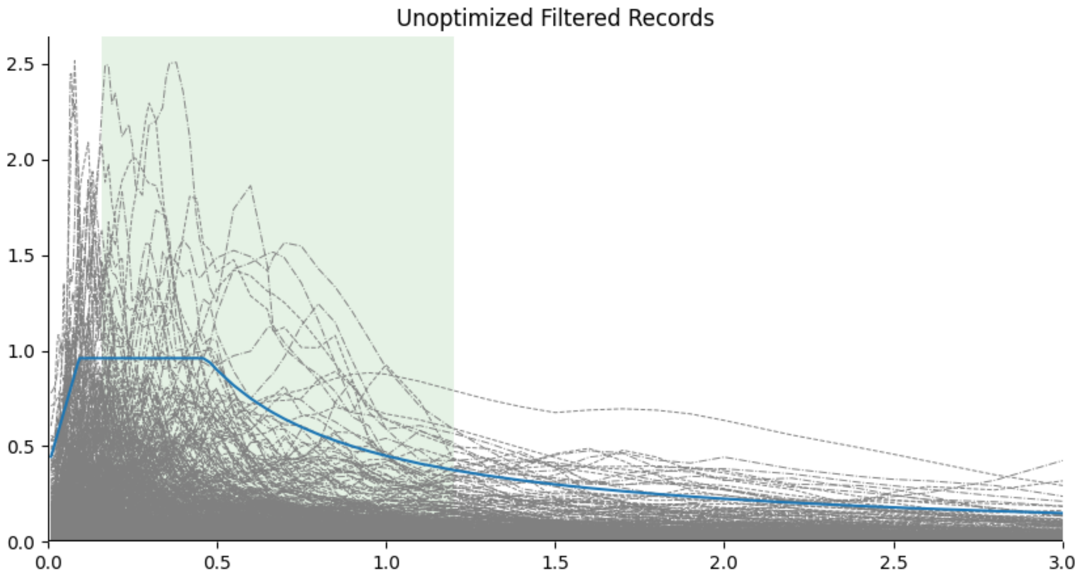

Figure 3. Orthogonal Horizontal Components of Unoptimized Ground Motions

2. Find most similar 11 ground motion record.

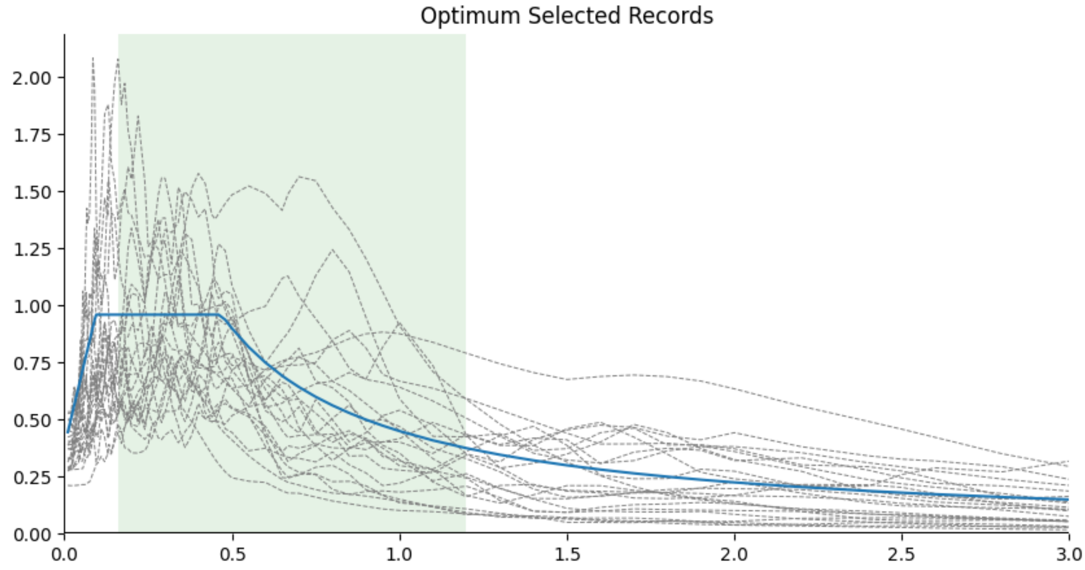

Figure 4. Orthogonal Horizontal Components of Optimized Ground Motions

3. Compute geometric mean spectra of orthogonal horizontal components of ground motion records

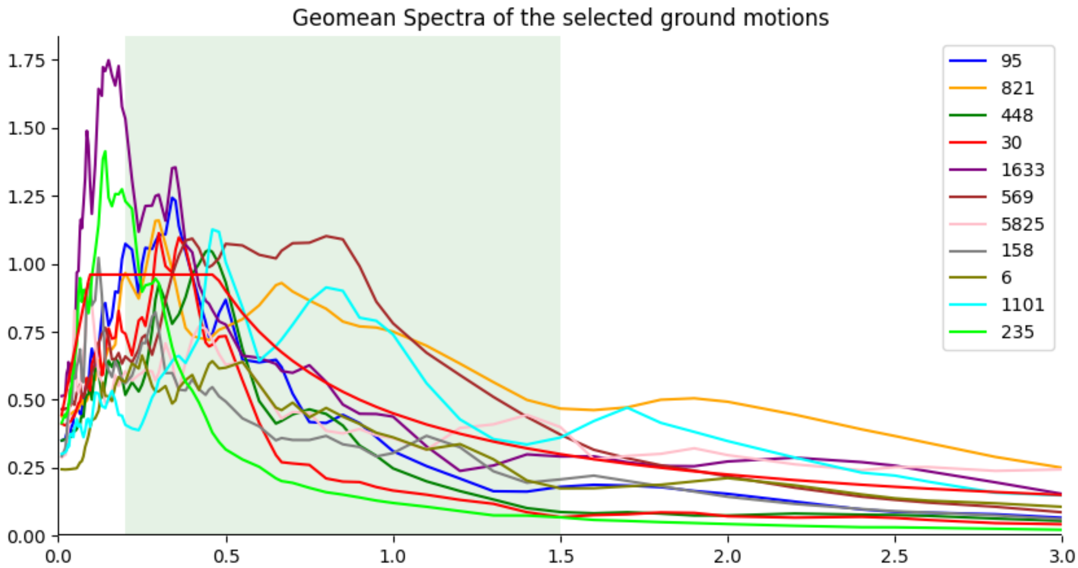

Figure 5. Geometric Mean Spectra of Components

3. Compute pre-scale factor with the following equation.

$$SF = \frac{\sum_{i=0}^{n}(w_i.y_i y_{ti})}{\sum_{i=0}^{n}(w_{i.}y_i^2)} \tag{3.4}$$

SF = Scale factor

w_i = Weighting factor for the squared error at period T_i

y_i= Ordinate of geometric mean spectrum at period T_i

y_{ti}= Ordinate of target spectrum at period T_i

4. Modify each orthogonal horizontal components of the ground motion records by pre-scaled factor computed in step 3.

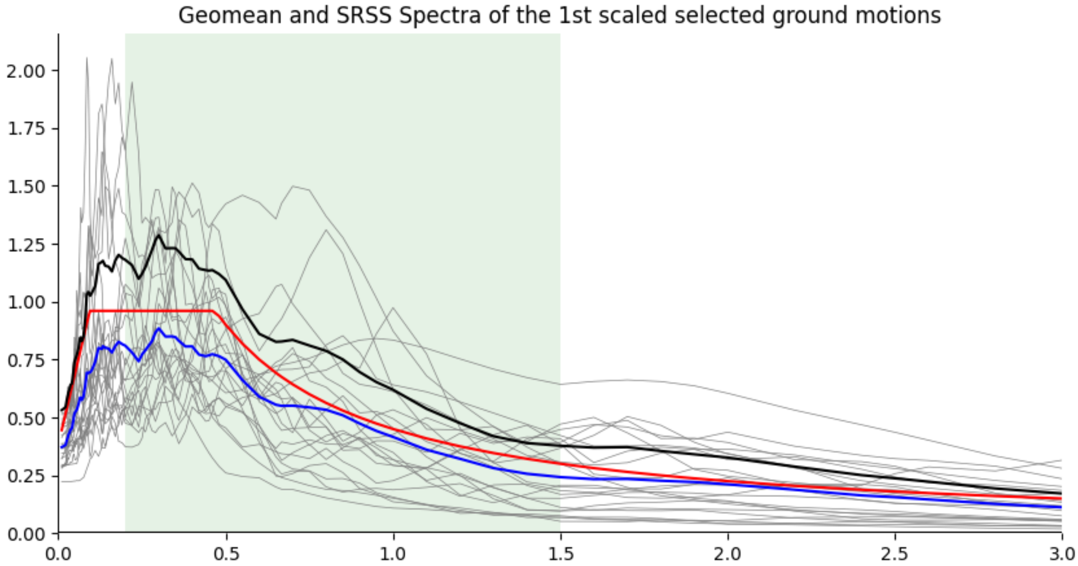

Figure 6. Geometric Mean Scaled Average

4. Compute the SRSS spectra of modified ground motion records and take their average. This SRSS average shall not be less than 1.3 times of the target spectra within period limits. Hence, obtain a further scalar for every ground motion records to meet this requirement if necessary.

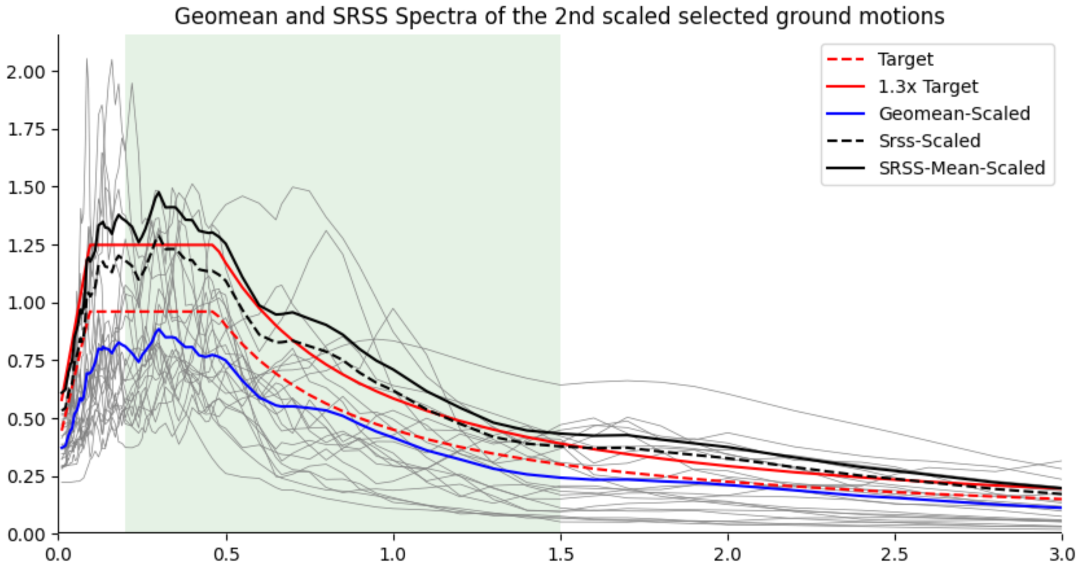

Figure 7. SRSS Scaled Spectra

5. Find the scale factor which is computed by multiplying the pre-scale factor and the scalar found in step 5. [19]

4. Numerical Example

For the numerical comparison, 19 locations have selected with different soil types and predicted mechanisms and distances. These locations have analyzed two different earthquake intensity levels.

	Location	Lat	Lon	Level	Soil	Mechanism	Distance
0	Küçükçekmece-İstanbul	40.996	28.775	DD-1	ZA	Oblique	60
1	Erzurum-Erzurum	39.9097	41.276	DD-1	ZB	Oblique	60
2	Soma-Manisa	39.1833	27.606	DD-1	ZC	Strike Slip	40
3	Dikili-İzmir	39.071	26.89	DD-1	ZD	Oblique	60
4	Besni-Adıyaman	37.6928	37.861	DD-1	ZE	Strike Slip	60
5	İntepe-Çanakkale	40.0133	26.333	DD-1	ZA	Oblique	40
6	Toprakkale-Osmaniye	37.0639	36.147	DD-1	ZB	Oblique	40
7	Aksu-Antalya	36.9539	30.848	DD-1	ZC	Strike Slip	60
8	Bağlıca-Siirt	37.8697	41.751	DD-1	ZD	Strike Slip	100
9	Bozyazı-Mersin	36.1049	32.972	DD-1	ZE	Oblique	160
10	Bartın-Bartın	41.6344	32.338	DD-1	ZA	Strike Slip	120
11	Karakasım-Edirne	41.5172	26.644	DD-1	ZB	Oblique	140
12	Dargeçit-Mardin	37.5462	41.717	DD-1	ZC	Strike Slip	100
13	Kuzucubelen-Mersin	36.84	34.438	DD-1	ZD	Strike Slip	140
14	Akıncı-Mardin	37.1664	40.847	DD-1	ZE	Strike Slip	180
15	Yenimehmetli-Ankara	39.42	32.169	DD-1	ZA	Oblique	160
16	Çamlıdere-Şanlıurfa	37.1544	39.067	DD-1	ZB	Strike Slip	80
17	Akarsu-Mardin	37.2342	41.06	DD-1	ZC	Strike Slip	160
18	Kızıltepe-Mardin	37.1939	40.586	DD-1	ZD	Strike Slip	180
19	Küçükçekmece-İstanbul	40.996	28.775	DD-2	ZA	Oblique	60
20	Erzurum-Erzurum	39.9097	41.276	DD-2	ZB	Oblique	60
21	Soma-Manisa	39.1833	27.606	DD-2	ZC	Strike Slip	40
22	Dikili-İzmir	39.071	26.89	DD-2	ZD	Oblique	60
23	Besni-Adıyaman	37.6928	37.861	DD-2	ZE	Strike Slip	60
24	İntepe-Çanakkale	40.0133	26.333	DD-2	ZA	Oblique	40
25	Toprakkale-Osmaniye	37.0639	36.147	DD-2	ZB	Oblique	40
26	Aksu-Antalya	36.9539	30.848	DD-2	ZC	Strike Slip	60
27	Bağlıca-Siirt	37.8697	41.751	DD-2	ZD	Strike Slip	100
28	Bozyazı-Mersin	36.1049	32.972	DD-2	ZE	Oblique	160
29	Bartın-Bartın	41.6344	32.338	DD-2	ZA	Oblique	120
30	Karakasım-Edirne	41.5172	26.644	DD-2	ZB	Oblique	140
31	Dargeçit-Mardin	37.5462	41.717	DD-2	ZC	Strike Slip	100
32	Kuzucubelen-Mersin	36.84	34.438	DD-2	ZD	Strike Slip	140
33	Akıncı-Mardin	37.1664	40.847	DD-2	ZE	Strike Slip	180
34	Yenimehmetli-Ankara	39.42	32.169	DD-2	ZA	Oblique	160
35	Çamlıdere-Şanlıurfa	37.1544	39.067	DD-2	ZB	Strike Slip	80
36	Akarsu-Mardin	37.2342	41.06	DD-2	ZC	Strike Slip	160
37	Kızıltepe-Mardin	37.1939	40.586	DD-2	ZD	Strike Slip	180

Table 1. Test Case Locations

For all the cases 4 data sets has been prepared to perform a sensitivity analysis of the scale factors.

- Data Set 1: Results obtained by conventional PEER NGA selection and scaling procedure.
- Data Set 2: Results obtained by developed framework selection and scaling procedure with SRSS spectrum.
- Data Set 3: Results obtained by developed framework selection and scaling procedure with RotD100 spectrum.
- Data Set 4: Results obtained by developed framework selection and scaling procedure with using FEMA P695 scaling method.

After all the iterative procedure, 152 sets of scale factors have obtained to test the efficiency of the developed framework. 3 data cases with different earthquake intensity levels, soil types and mechanisms has selected to document on this study, all the results can be found on Appendix A.

4.1. Numerical Example Case 1

For first numerical example case, test case 29 has selected. This numerical analysis has conducted for DD-2 earthquake intensity level at Bartin location which has a ZA type soil and oblique type fault mechanism.

- Data Set 1

RSN	Scale Factor
98	10.449
146	1.190
455	3.326
879	0.214
6336	29.678
6428	5.216
6429	9.499
6434	7.224
8521	36.669
8569	22.088
9828	16.224

Table 2. Test Case 29 Data Set 1 Scale Factors

- Data Set 2

RSN	Scale Factor
146	6.3058
455	6.8979
98	7.2535
3920	7.8063
3799	8.2653
6051	8.7178
5967	8.9405
8168	9.1692
14430	9.2484
9828	9.3243
18072	9.3842

Table 3. Test Case 29 Data Set 2 Scale Factors

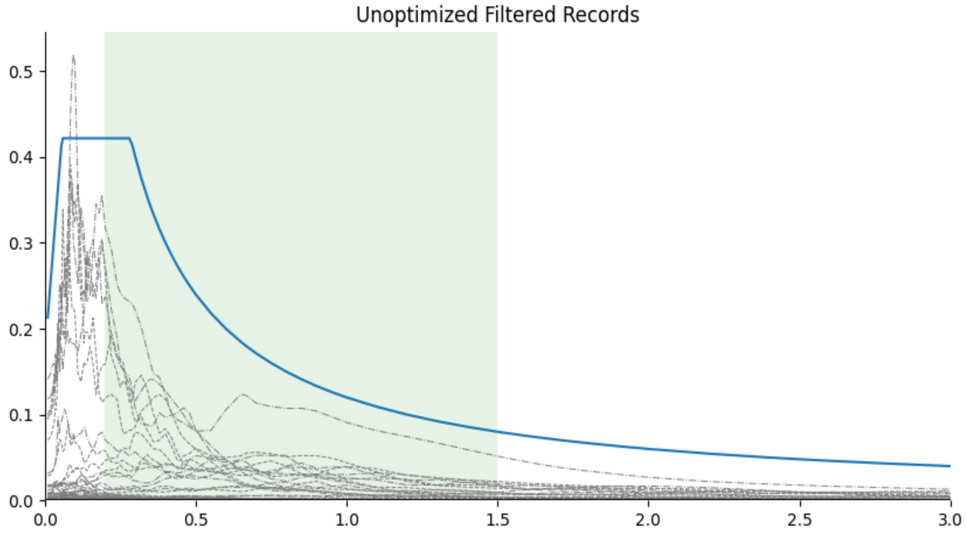

Figure 8. Test Case 29 Data Set 2 Unoptimized Filtered Records

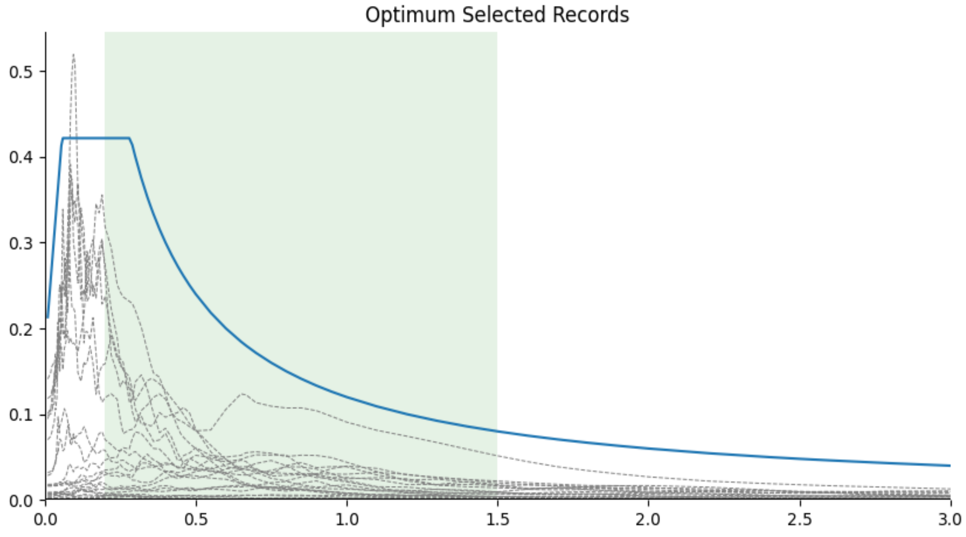

Figure 9. Test Case 29 Data Set 2 Optimum Selected Records

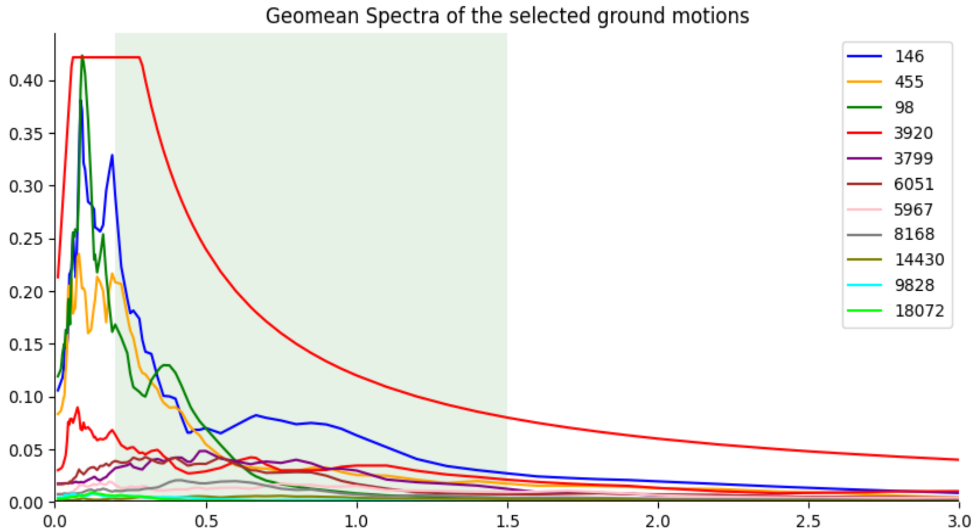

Figure 10. Test Case 29 Data Set 2 Geometric Mean of Selected Ground Motions

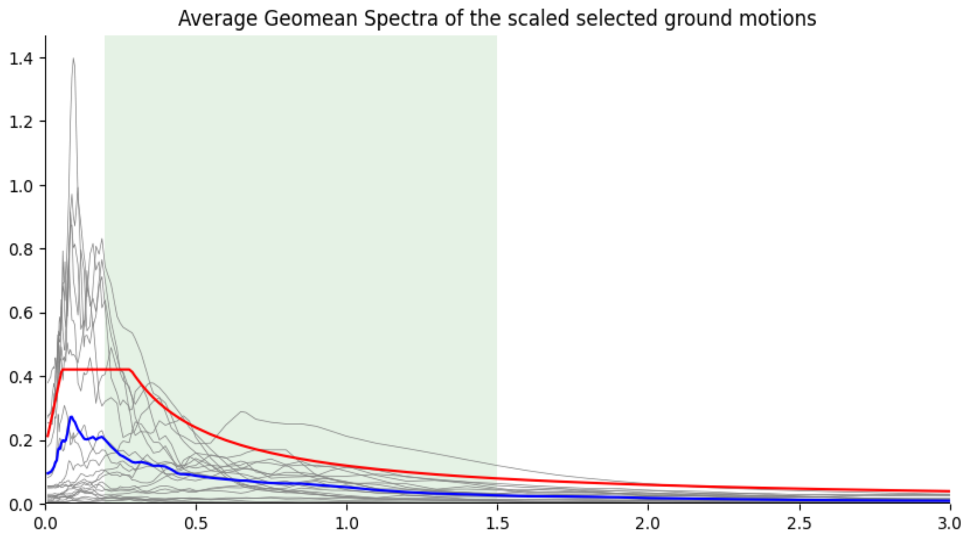

Figure 11. Test Case 29 Data Set 2 Average Geometric Mean of Selected Ground Motions

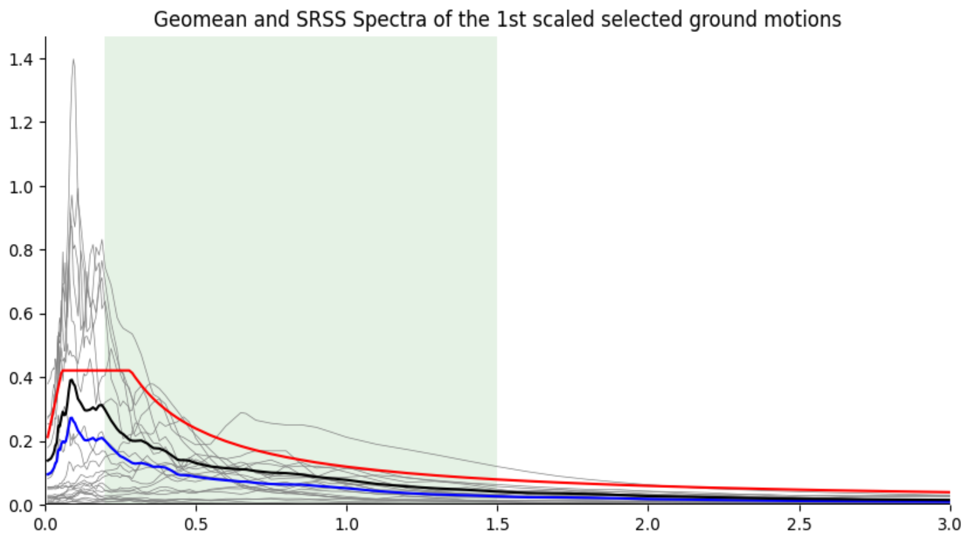

Figure 12. Test Case 29 Data Set 2 SRSS Spectra of Selected Ground Motions

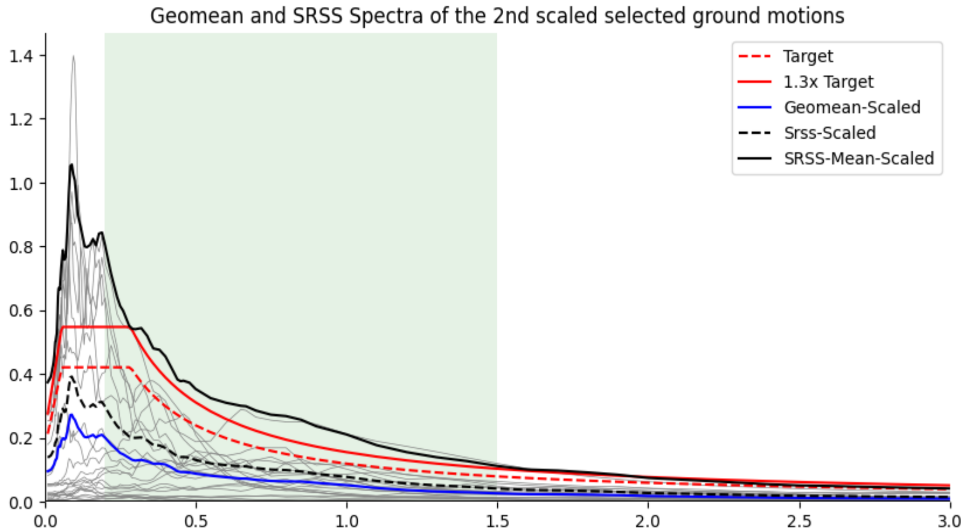

Figure 13. Test Case 29 Data Set 2 Scaled Ground Motions

- Data Set 3

RSN	Scale Factor
146	7.593
455	8.306
98	8.734
3920	9.400
3799	9.952
6051	10.497
5967	10.765
8168	11.041
14430	11.136
9828	11.228
18072	11.300

Table 4. Test Case 29 Data Set 3 Scale Factors

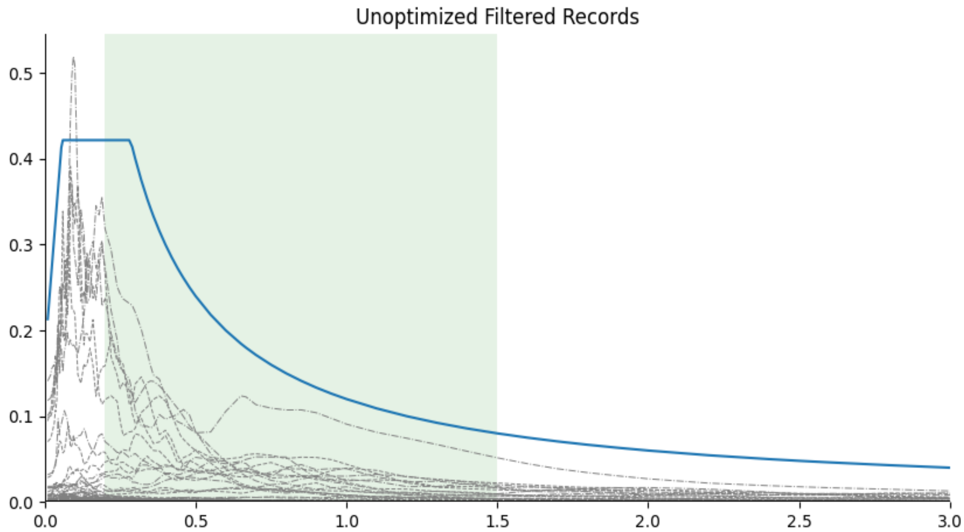

Figure 14. Test Case 29 Data Set 3 Unoptimized Filtered Records

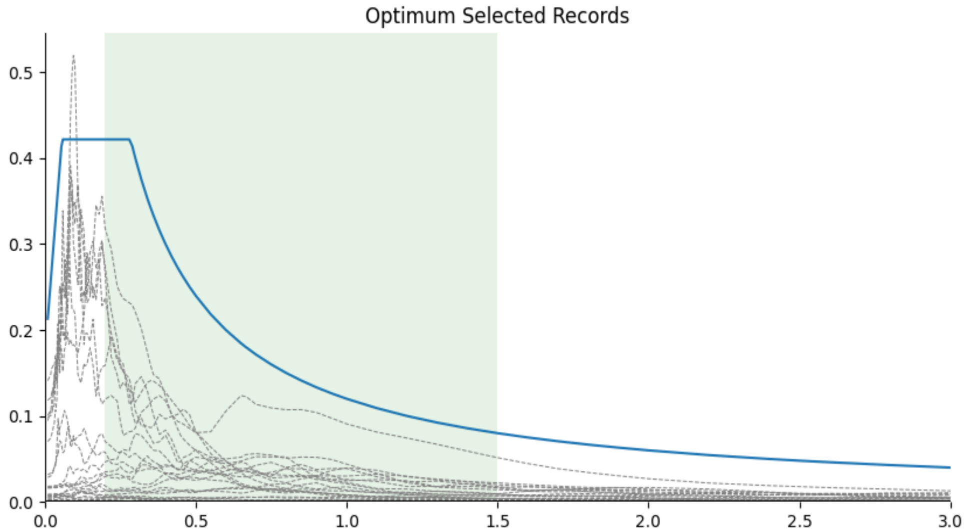

Figure 15. Test Case 29 Data Set 3 Optimum Selected Records

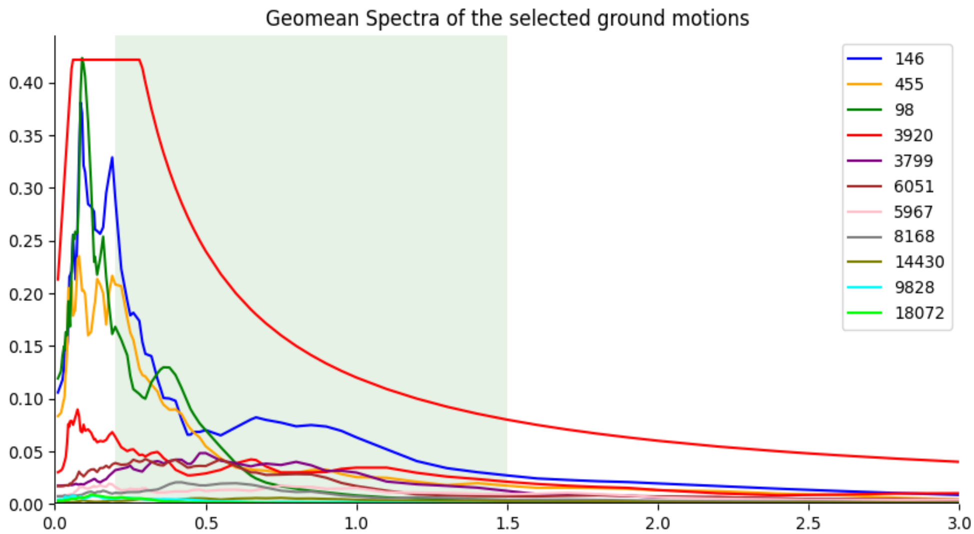

Figure 16. Test Case 29 Data Set 3 Geometric Mean of Selected Ground Motions

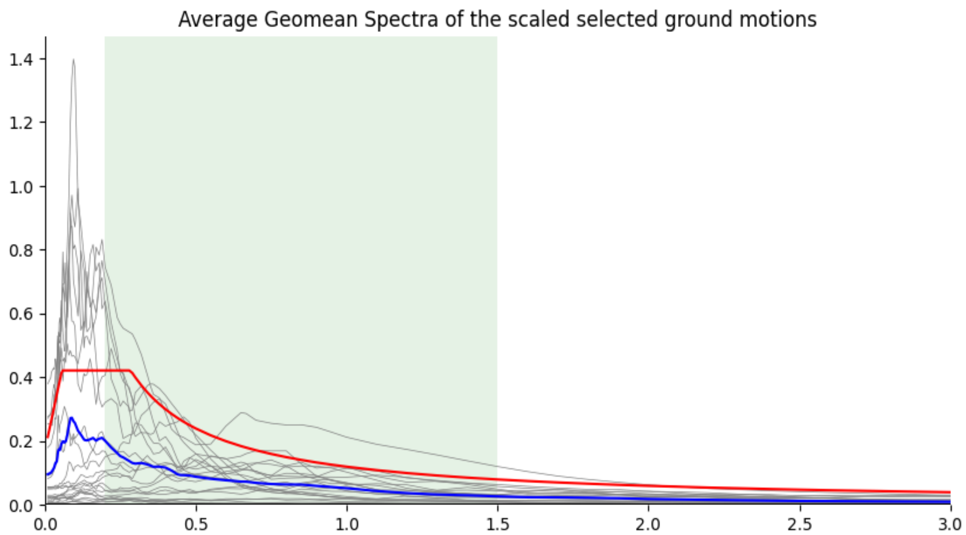

Figure 17. Test Case 29 Data Set 3 Average Geometric Mean of Selected Ground Motions

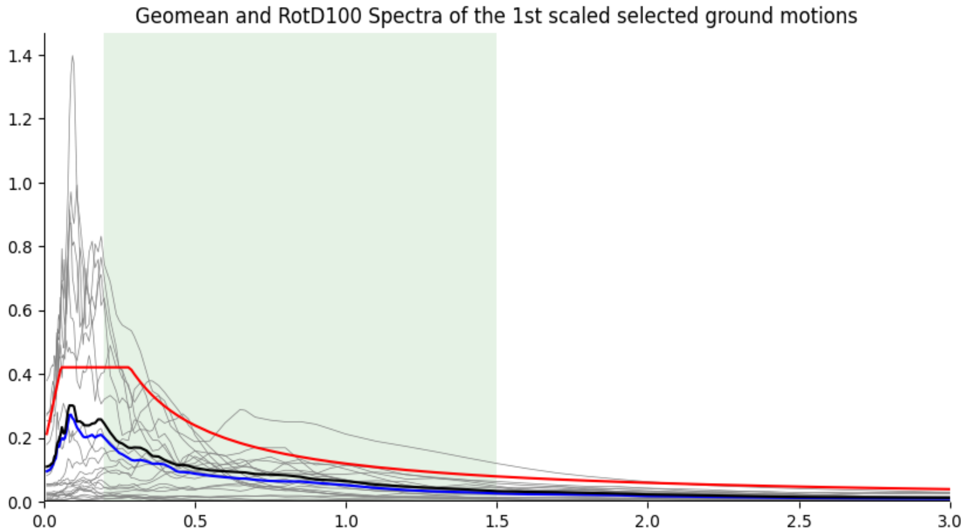

Figure 18. Test Case 29 Data Set 3 RotD100 of Selected Ground Motions

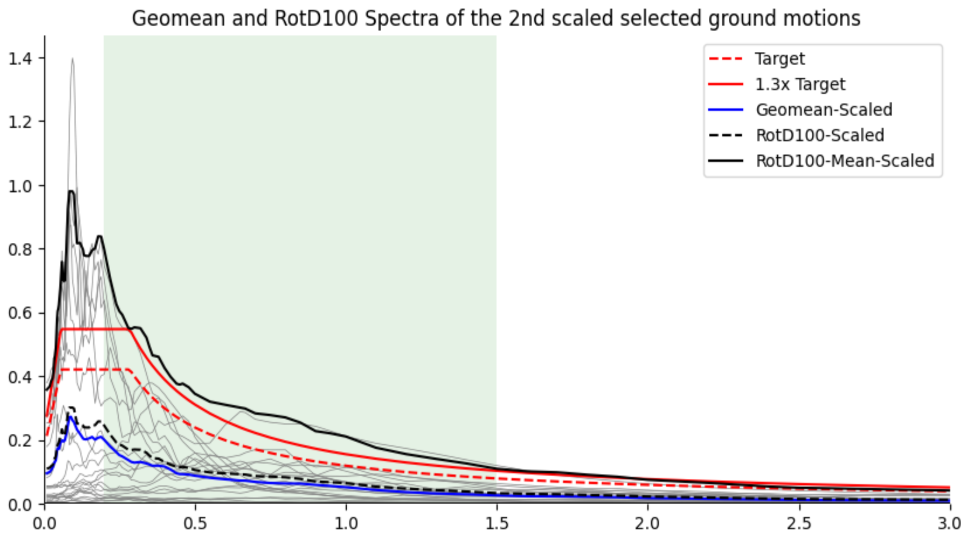

Figure 19. Test Case 29 Data Set 3 Scaled Ground Motions

- Data Set 4

RSN	Scale Factor
146	4.858
455	4.858
98	4.858
3920	4.858
3799	4.858
6051	4.858
5967	4.858
8168	4.858
14430	4.858
9828	4.858
18072	4.858

Table 5. Test Case 29 Data Set 4 Scale Factors

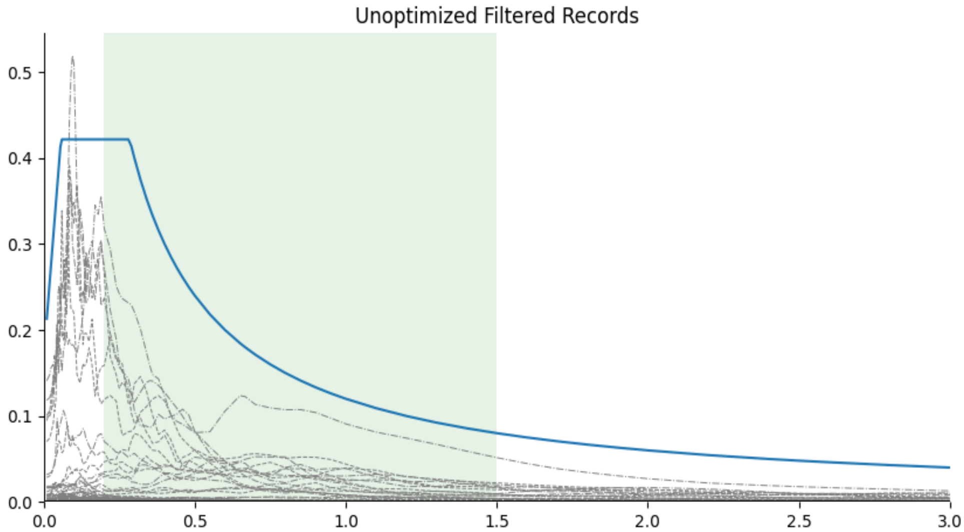

Figure 20. Test Case 29 Data Set 4 Unoptimized Filtered Records

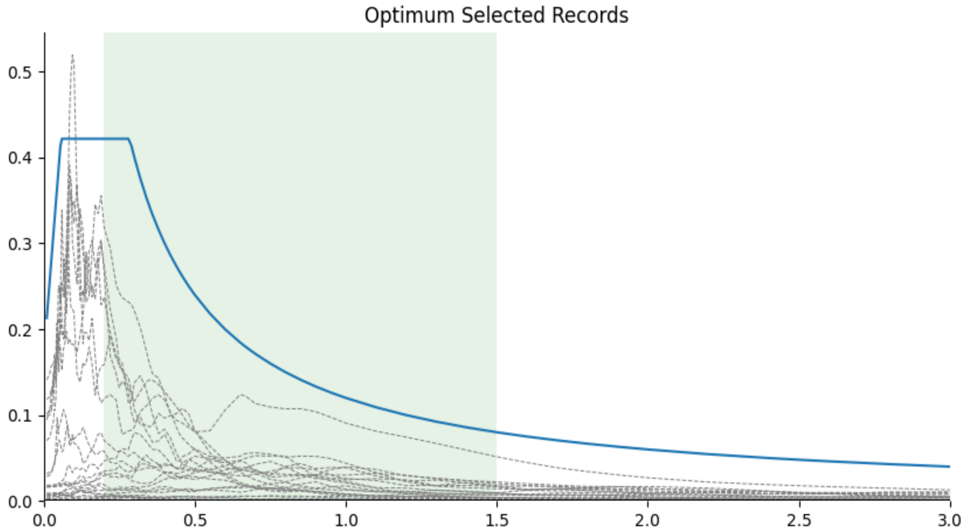

Figure 21. Test Case 29 Data Set 4 Optimum Selected Records

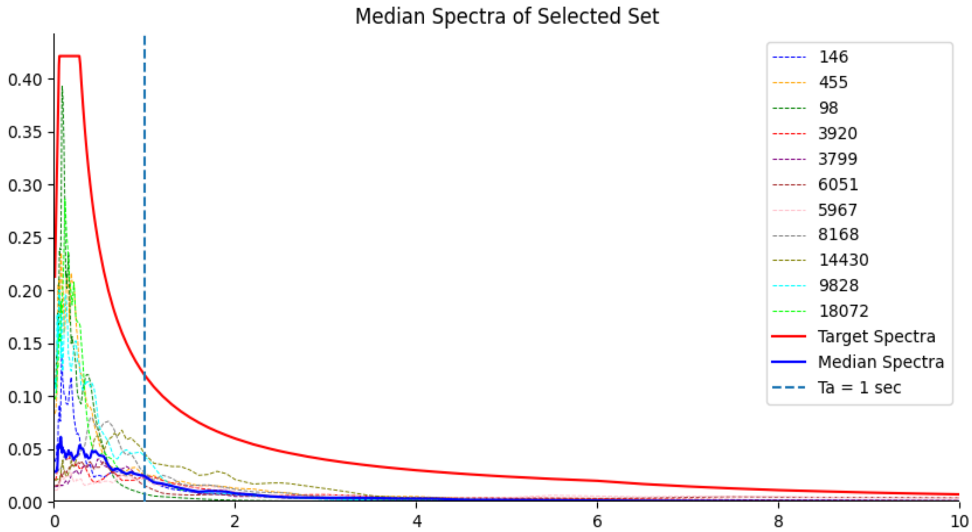

Figure 22. Test Case 29 Data Set 4 Median Spectra of Selected Set

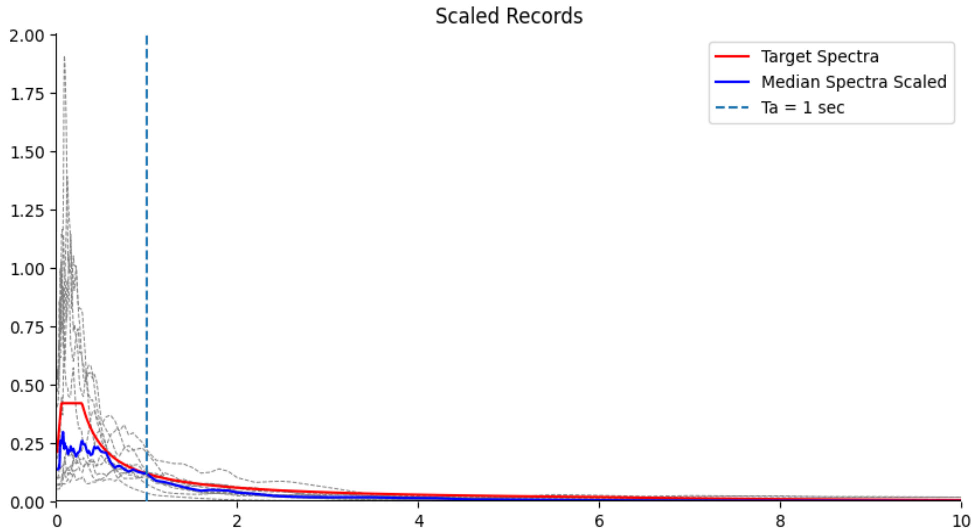

Figure 23. Test Case 29 Data Set 4 Scaled Records

- Numerical Example 1 Comparison Table

	PEER	Scalepy SRSS	Scalepy RotD100	Scalepy P695
	10.449	6.3058	7.593	4.858
	1.190	6.8979	8.306	4.858
	3.326	7.2535	8.734	4.858
	0.214	7.8063	9.400	4.858
	29.678	8.2653	9.952	4.858
	5.216	8.7178	10.497	4.858
	9.499	8.9405	10.765	4.858
	7.224	9.1692	11.041	4.858
	36.669	9.2484	11.136	4.858
	22.088	9.3243	11.228	4.858
	16.224	9.3842	11.300	4.858
Average	***12.889***	***8.301***	***9.996***	***4.858***
Standard Deviation	***11.443***	***1.033***	***1.244***	**-**

Table 6. Numerical Example 1 Comparison Table

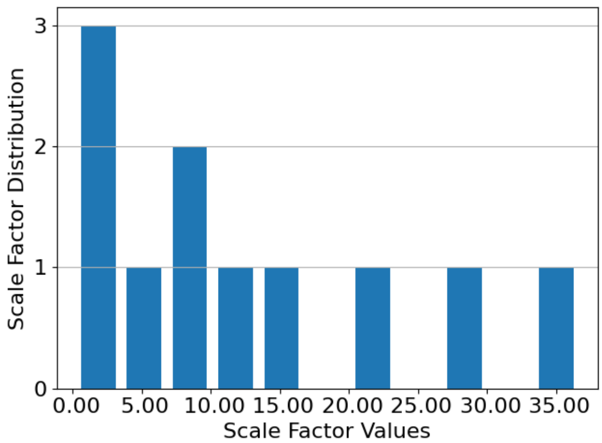

Figure 24. Numerical Example 1 Scale Factor Distribution PEER

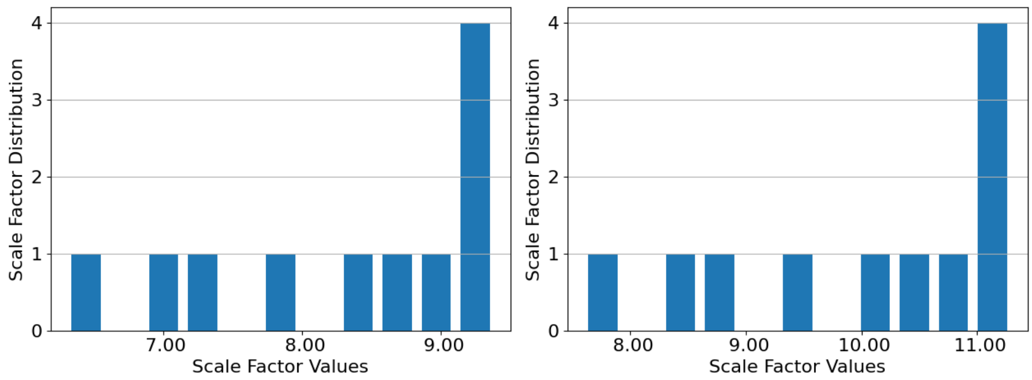

Figure 25. Numerical Example 1 Scale Factor Distribution Scalepy SRSS and RotD100

4.2. Numerical Example Case 2

For second numerical example case, test case 7 has selected. This numerical analysis has conducted for DD-1 earthquake intensity level at Antalya location which has a ZC type soil and strike-slip type fault mechanism.

- Data Set 1

RSN	Scale Factor
103	4.655
212	2.218
246	3.275
450	1.935
548	1.198
838	1.424
1160	3.056
1166	1.243
1762	1.331
1794	0.981
1813	2.038

Table 7. Test Case 7 Data Set 1 Scale Factors

- Data Set 2

RSN	Scale Factor
1633	1.290
727	1.163
495	1.151
407	1.138
150	1.198
230	1.248
825	1.187
1111	1.160
125	1.193
568	1.161
901	1.158

Table 8. Test Case 7 Data Set 2 Scale Factors

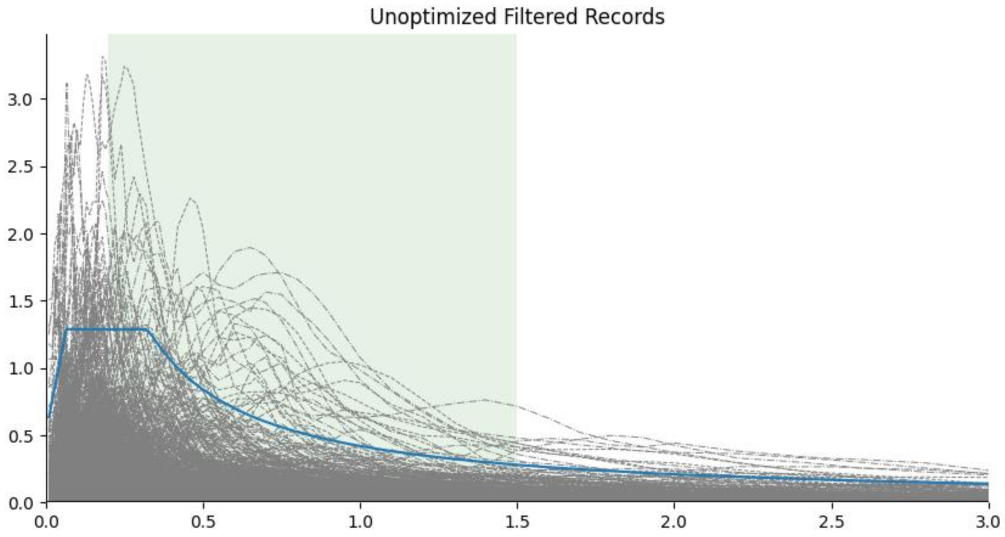

Figure 26. Test Case 7 Data Set 2 Unoptimized Filtered Records

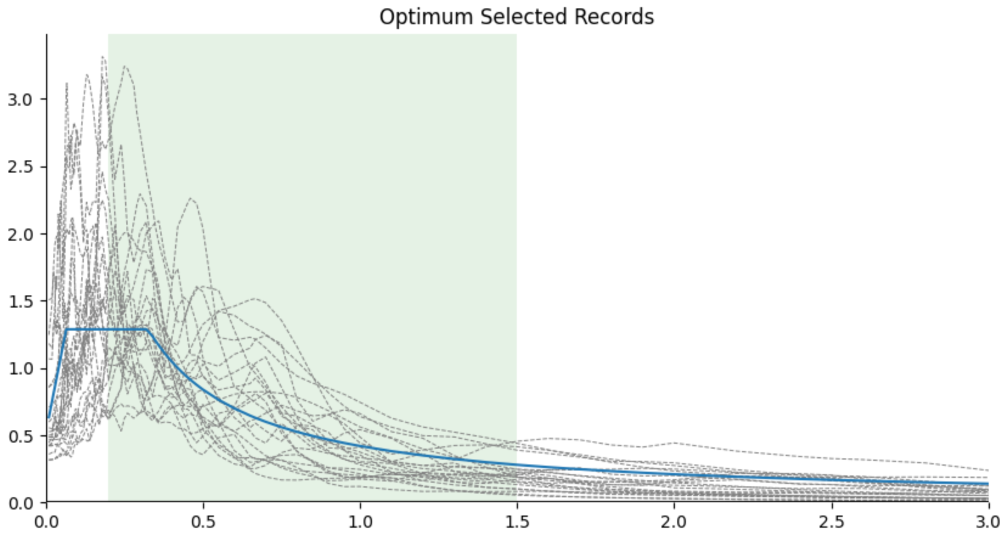

Figure 27. Test Case 7 Data Set 2 Optimum Selected Records

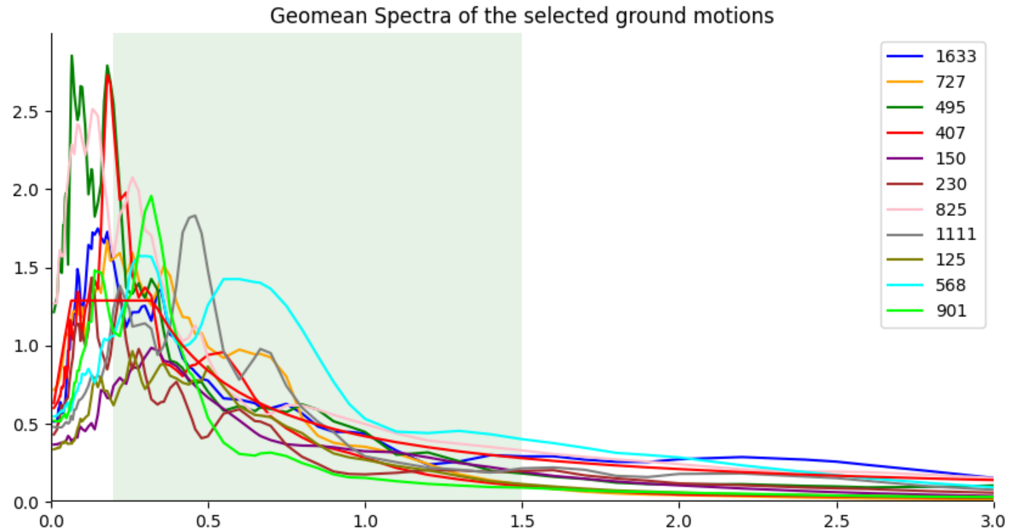

Figure 28. Test Case 7 Data Set 2 Geometric Mean of the Records

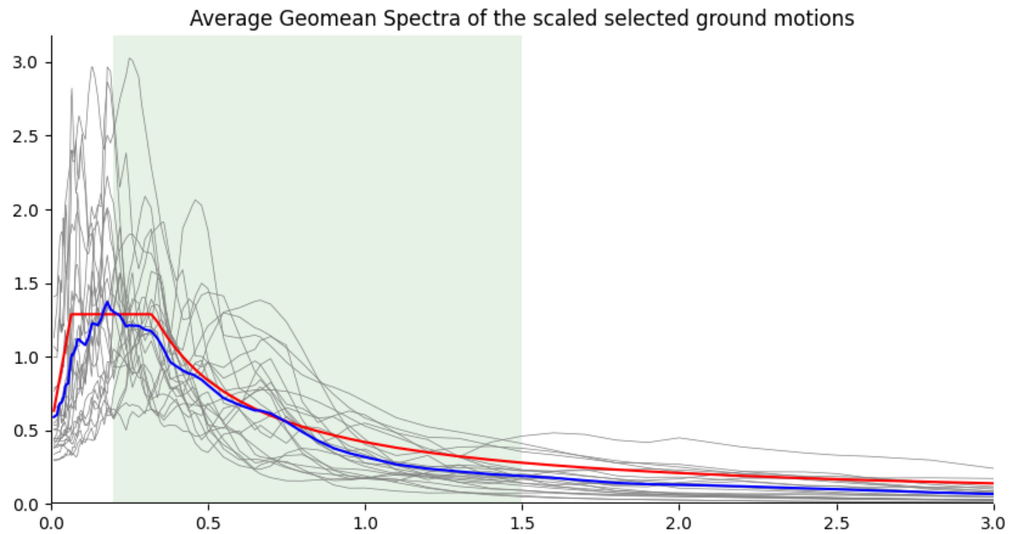

Figure 29. Test Case 7 Data Set 2 Average Geometric Mean of the Records

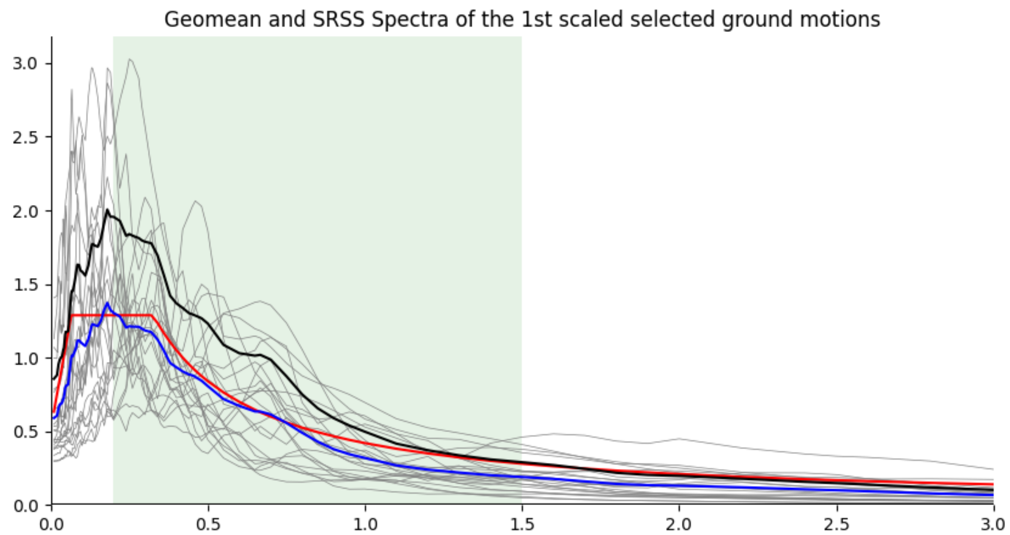

Figure 30. Test Case 7 Data Set 2 SRSS Mean of the Records

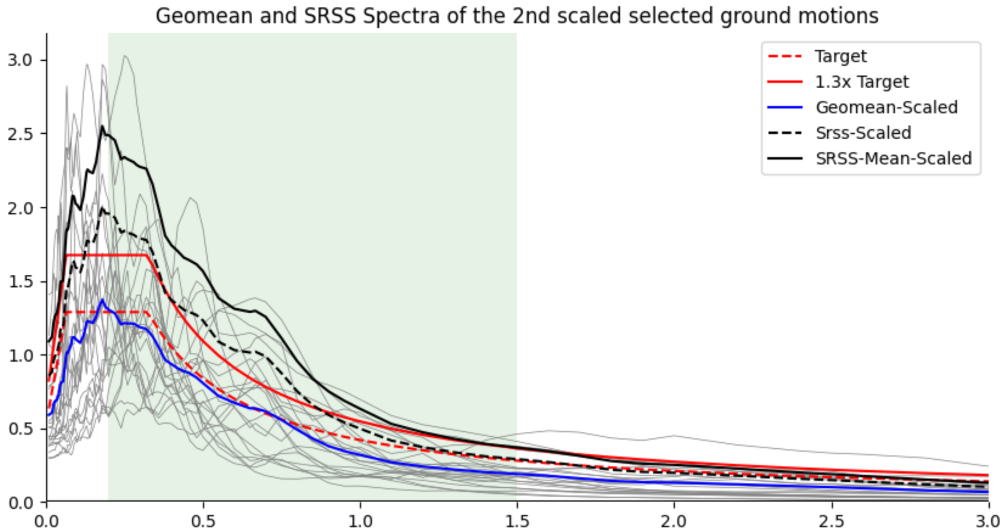

Figure 31. Test Case 7 Data Set 2 Scaled Records

- Data Set 3

RSN	Scale Factor
1633	1.541
727	1.390
495	1.376
407	1.360
150	1.431
230	1.491
825	1.418
1111	1.387
125	1.425
568	1.387
901	1.383

Table 9. Test Case 7 Data Set 3 Scale Factors

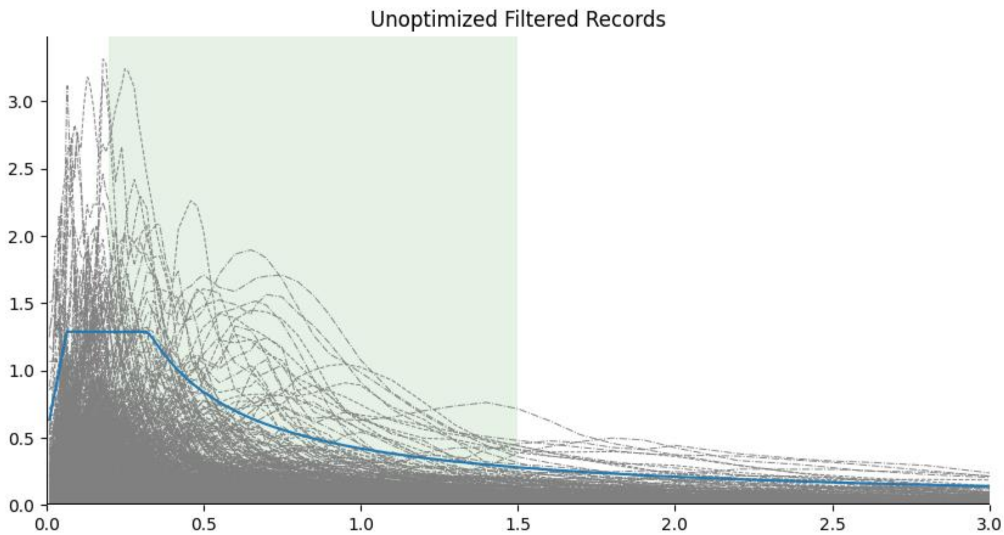

Figure 32. Test Case 7 Data Set 3 Unoptimized Filtered Records

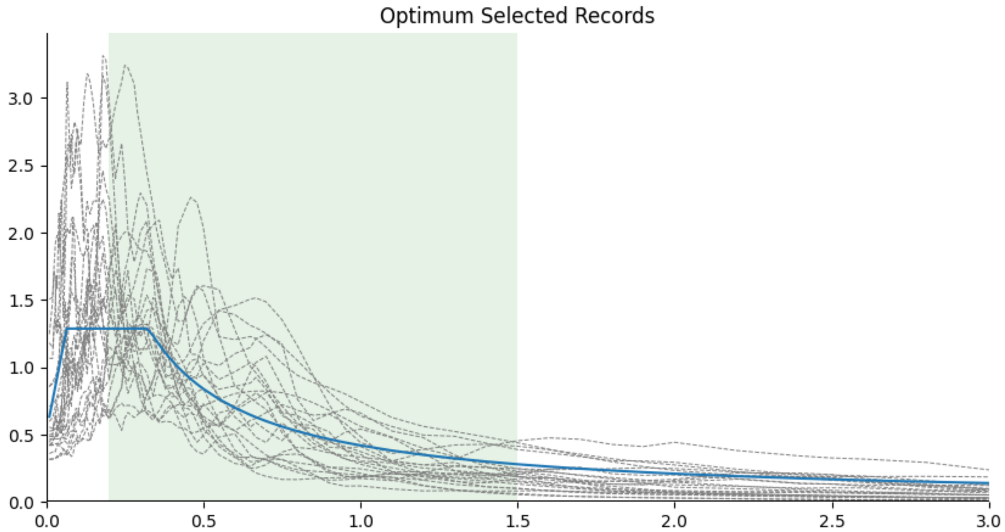

Figure 33. Test Case 7 Data Set 3 Optimum Selected Records

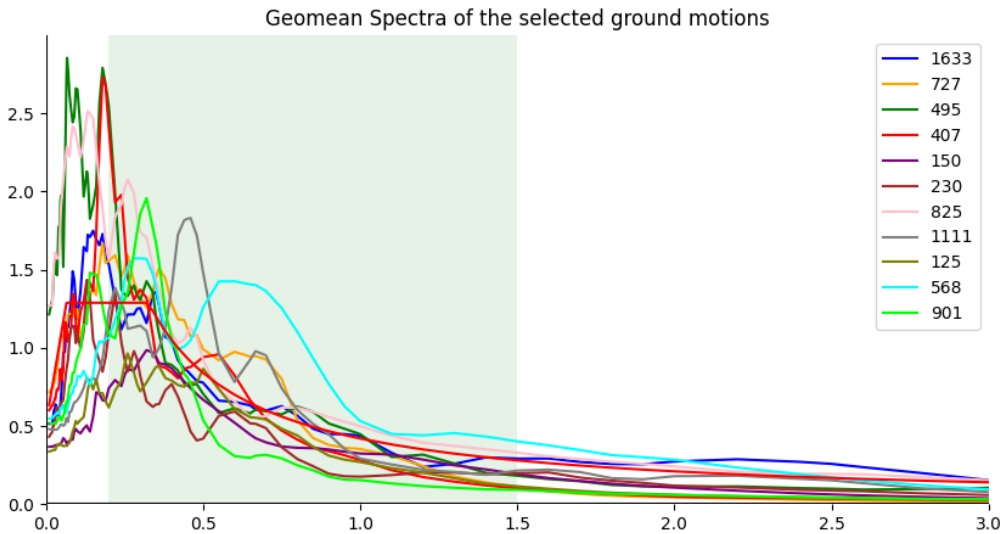

Figure 34. Test Case 7 Data Set 3 Geometric Mean Spectra of the Records

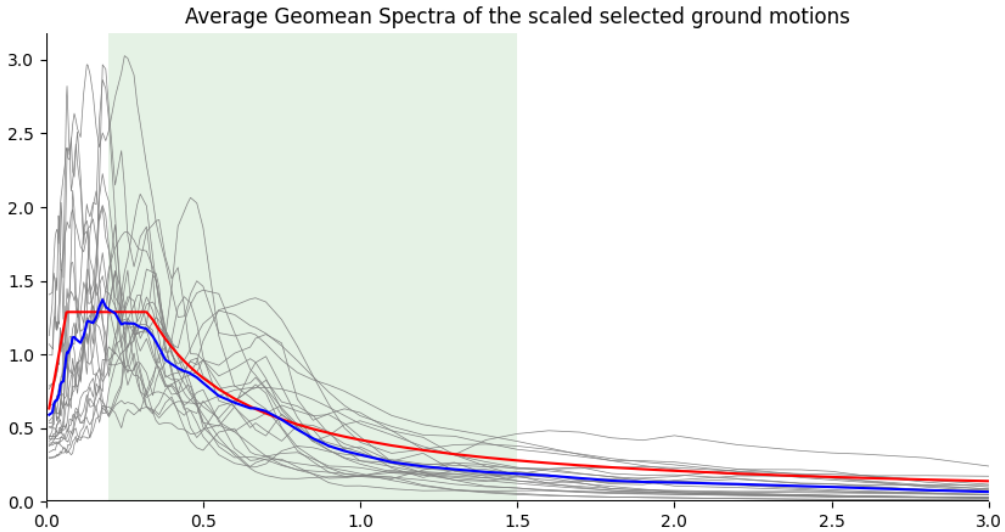

Figure 35. Test Case 7 Data Set 3 Average Geometric Mean Spectra of the Records

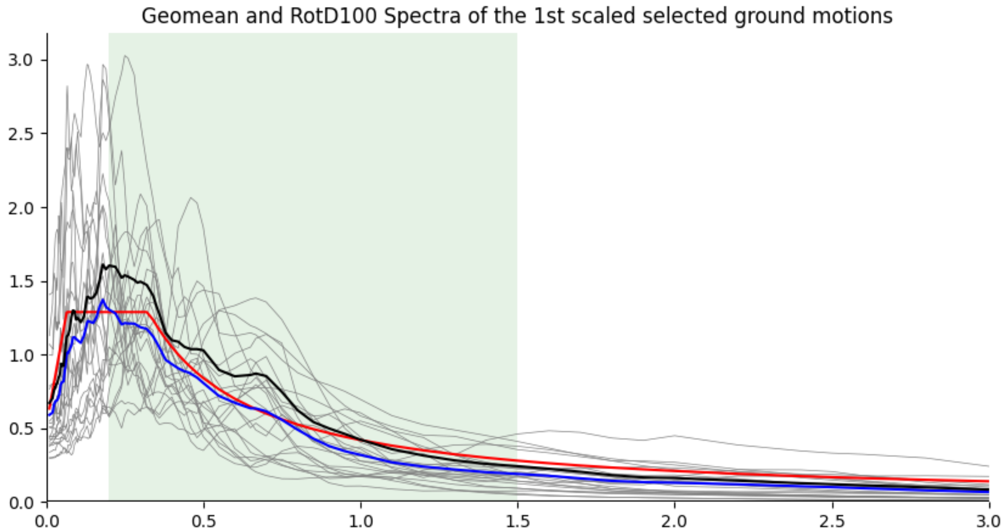

Figure 36. Test Case 7 Data Set 3 RotD100 Mean Spectra of the Records

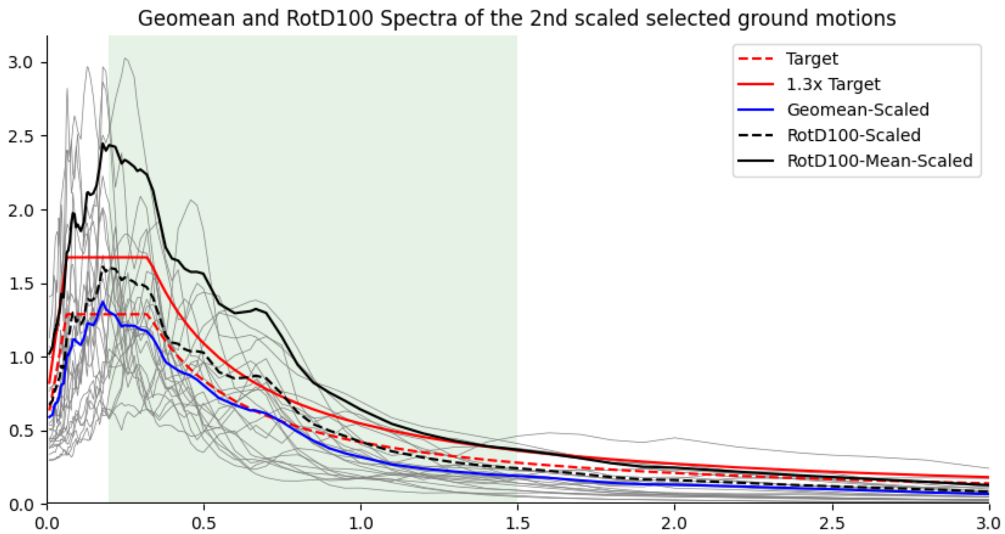

Figure 37. Test Case 7 Data Set 3 Scaled Records

- Data Set 4

RSN	Scale Factor
1633	1.327
727	1.327
495	1.327
407	1.327
150	1.327
230	1.327
825	1.327
1111	1.327
125	1.327
568	1.327
901	1.327

Table 10. Test Case 7 Data Set 4 Scale Factors

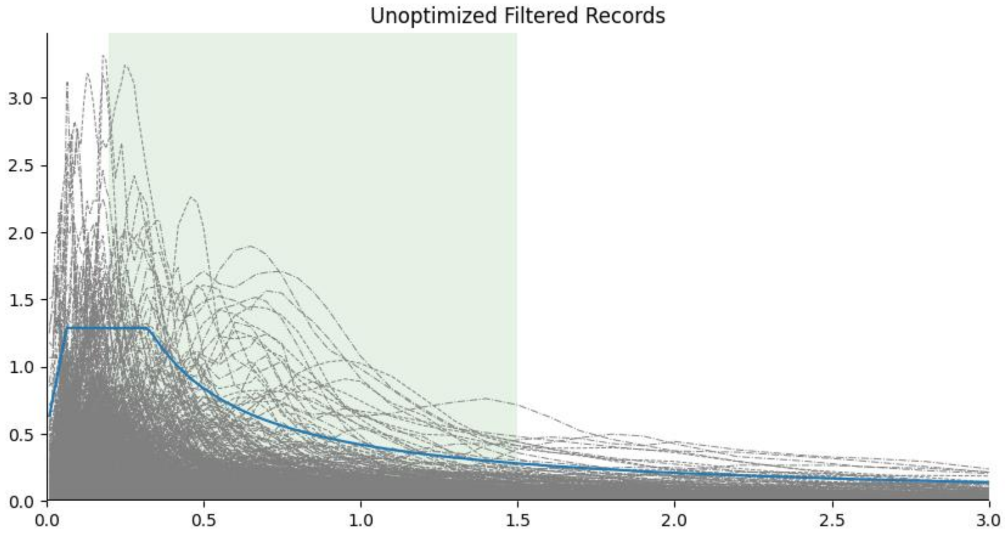

Figure 38. Test Case 7 Data Set 4 Unoptimized Records

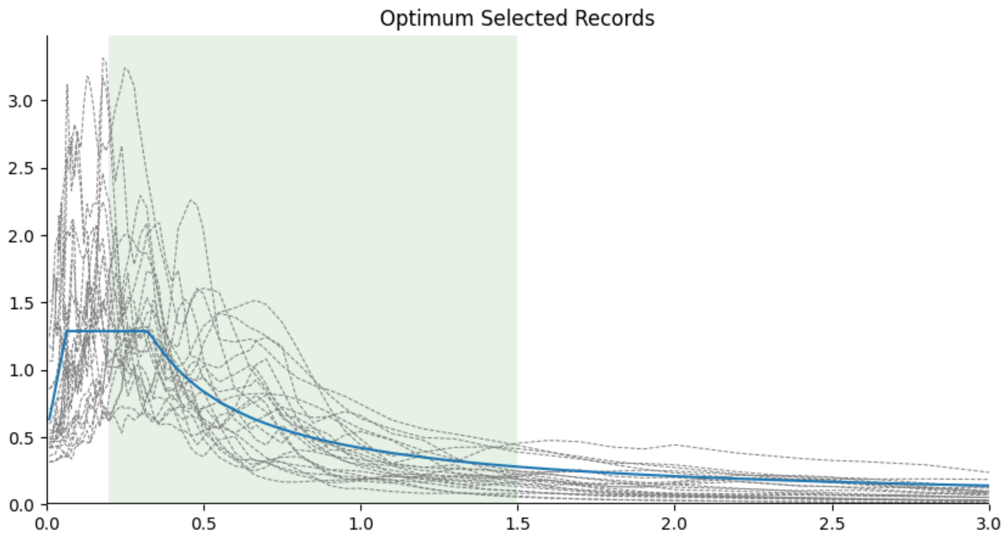

Figure 39. Test Case 7 Data Set 4 Optimum Selected Records

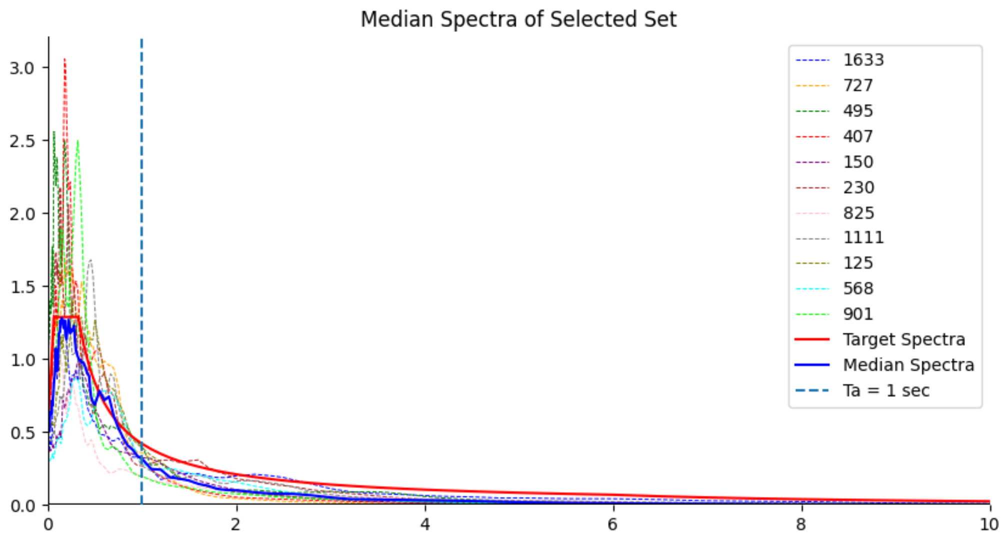

Figure 40. Test Case 7 Data Set 4 Median Spectra of Selected Set

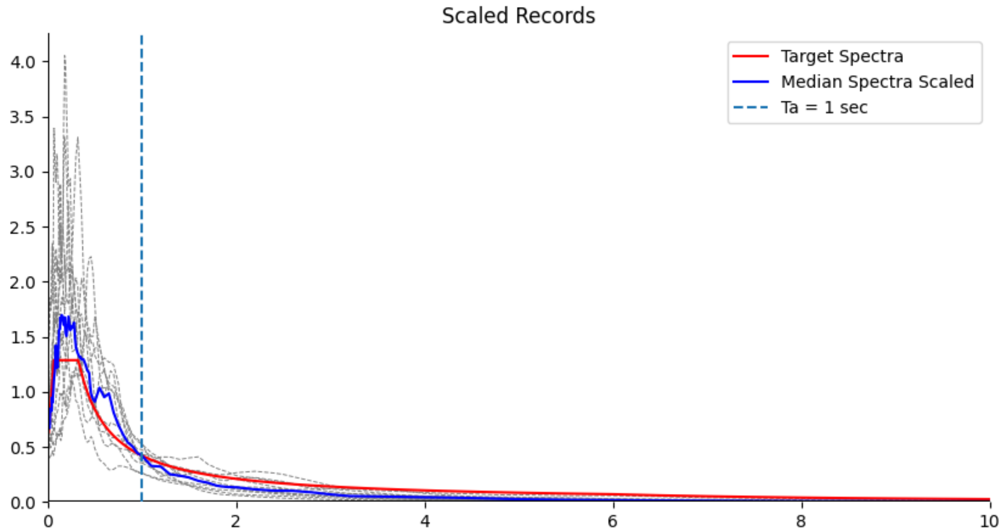

Figure 41. Test Case 7 Data Set 4 Scaled Records

- Numerical Example 2 Comparison Tables

	PEER	Scalepy SRSS	Scalepy RotD100	Scalepy P695
	4.655	1.290	1.541	1.327
	2.218	1.163	1.390	1.327
	3.275	1.151	1.376	1.327
	1.935	1.138	1.360	1.327
	1.198	1.198	1.431	1.327
	1.424	1.248	1.491	1.327
	3.056	1.187	1.418	1.327
	1.243	1.160	1.387	1.327
	1.331	1.193	1.425	1.327
	0.981	1.161	1.387	1.327
	2.038	1.158	1.383	1.327
Average	***2.123***	***1.186***	***1.417***	***1.327***
Standard Deviation	***1.075***	***0.044***	***0.052***	-

Table 11. Numerical Example 2 Comparison Table

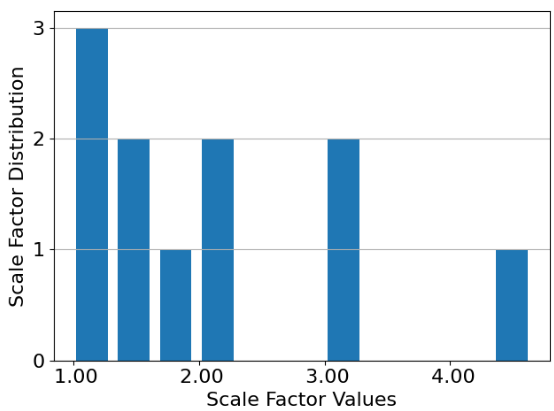

Figure 42. Numerical Example 2 Scale Factor Distribution PEER

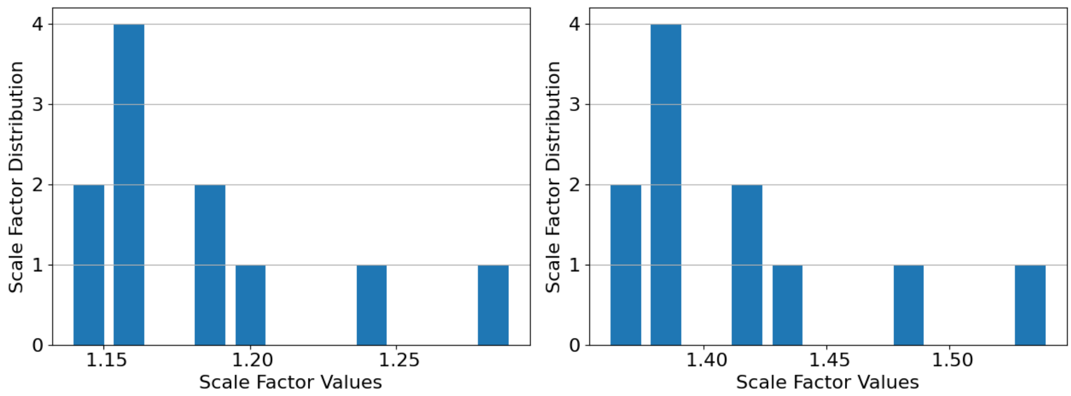

Figure 43. Numerical Example 2 Scale Factor Distribution Scalepy SRSS and RotD100

4.3. Numerical Test Case 3

For third numerical example case, test case 32 has selected. This numerical analysis has conducted for DD-2 earthquake intensity level at Mersin location which has a ZD type soil and strike-slip type fault mechanism.

- Data Set 1

RSN	Scale Factor
916	1.086
918	2.567
1788	1.497
1825	1.254
1826	1.485
1827	1.617
1828	2.324
1829	3.455
6014	1.816
6420	1.891
6242	2.484

Table 12. Test Case 32 Data Set 1 Scale Factors

- Data Set 2

RSN	Scale Factor
1100	1.197
148	1.029
6887	1.021
549	0.976
1634	0.948
6886	0.954
902	0.935
6874	0.944
96	0.928
316	0.918
147	0.912

Table 13. Test Case 32 Data Set 2 Scale Factors

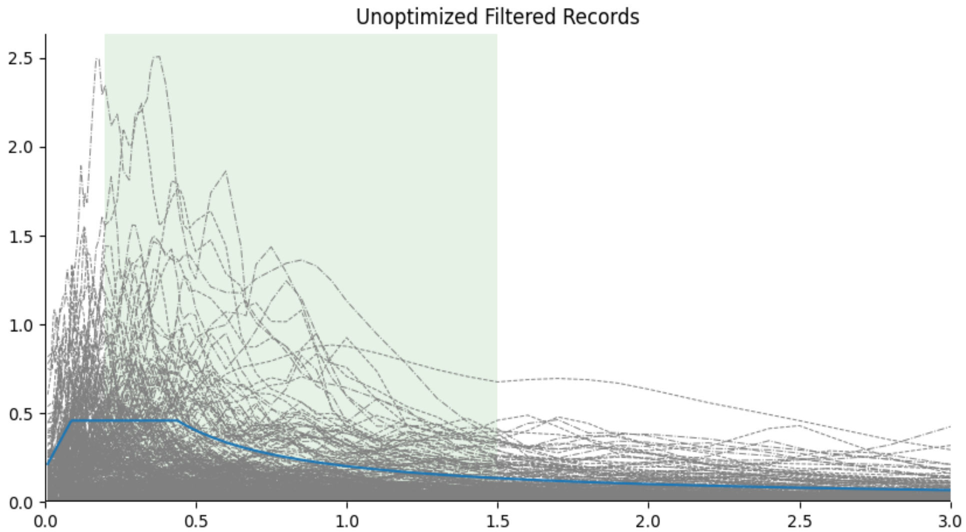

Figure 44. Test Case 32 Data Set 2 Unoptimized Filtered Records

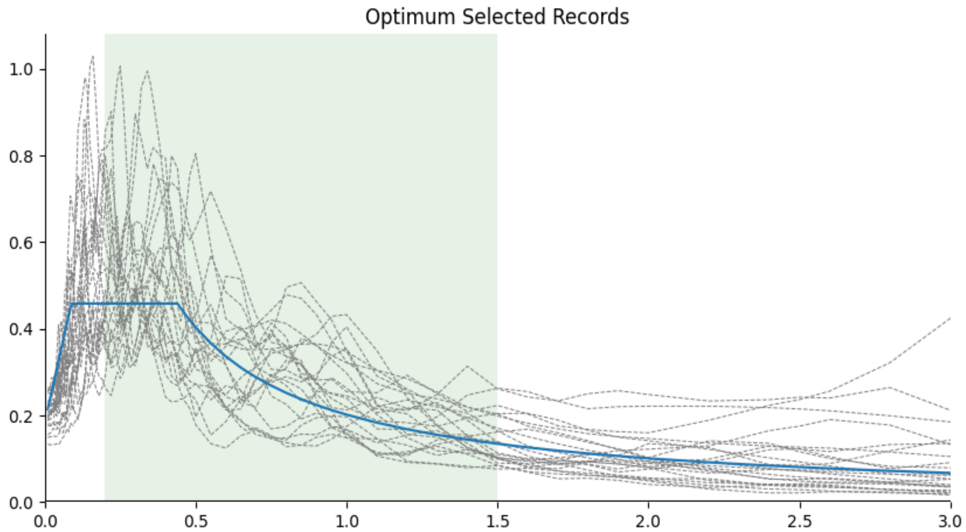

Figure 45. Test Case 32 Data Set 2 Optimum Selected Records

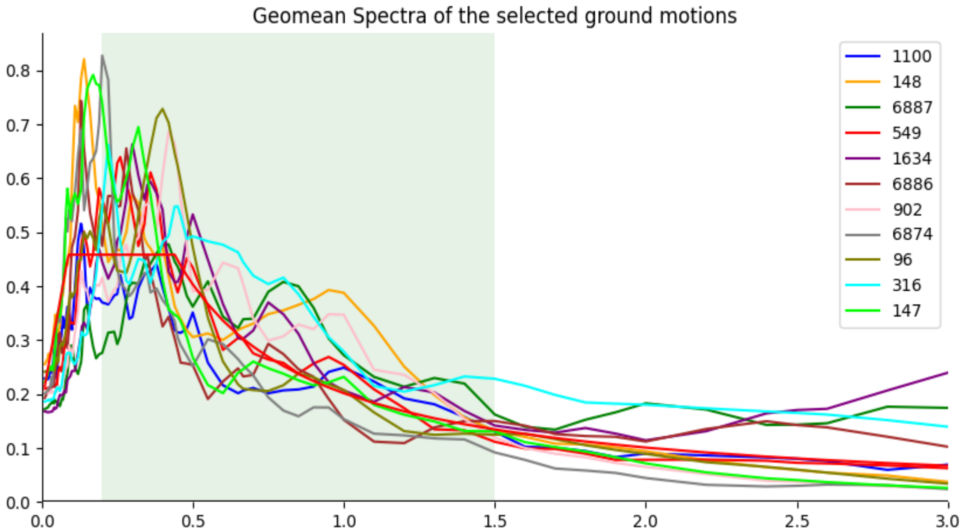

Figure 46. Test Case 32 Data Set 2 Geometric Mean of Records

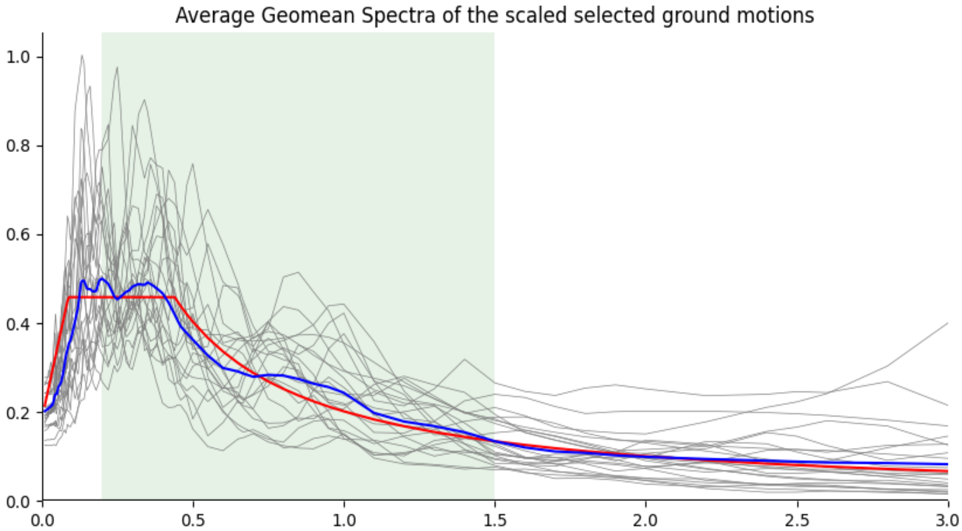

Figure 47. Test Case 32 Data Set 2 Average Geometric Mean of Records

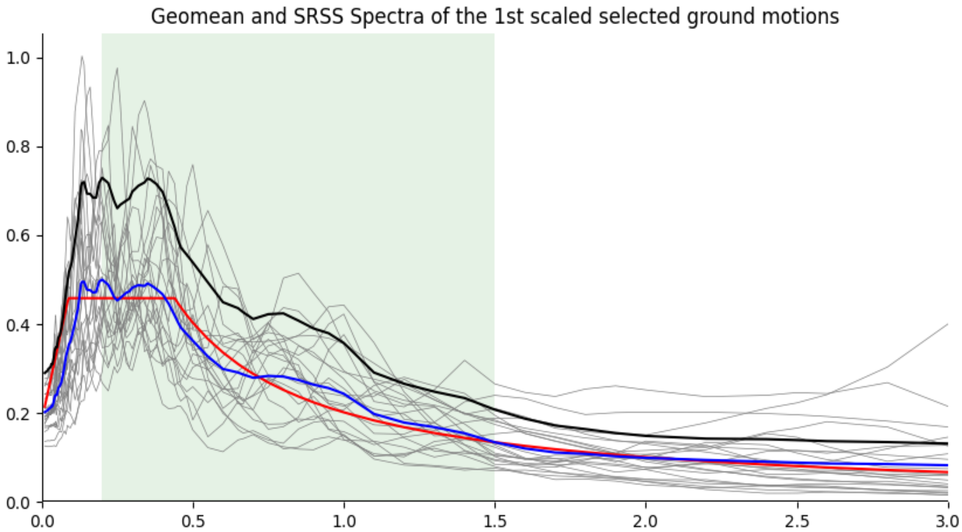

Figure 48. Test Case 32 Data Set 2 SRSS Mean of Records

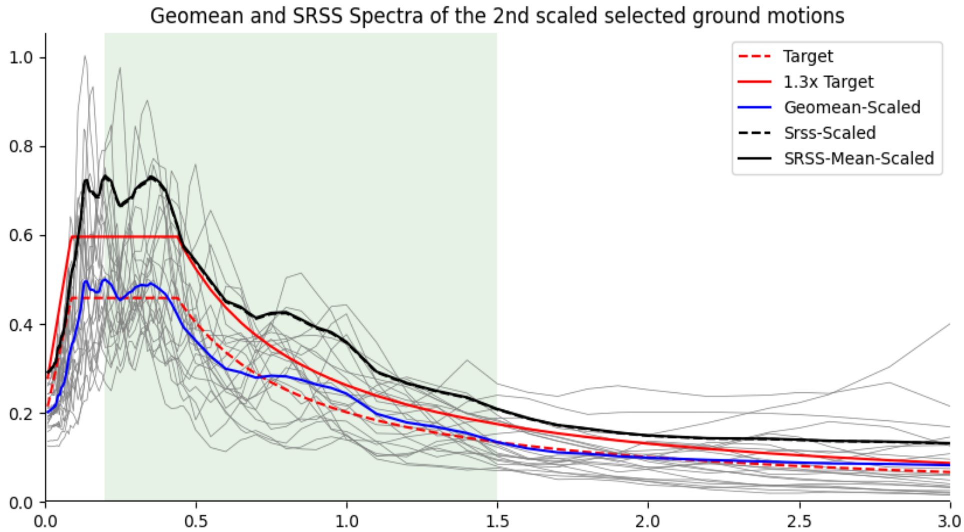

Figure 49. Test Case 32 Data Set 2 Scaled Records

- Data Set 3

RSN	Scale Factor
1100	1.499
148	1.290
6887	1.280
549	1.223
1634	1.188
6886	1.195
902	1.172
6874	1.183
96	1.163
316	1.150
147	1.143

Table 14. Test Case 32 Data Set 3 Scale Factors

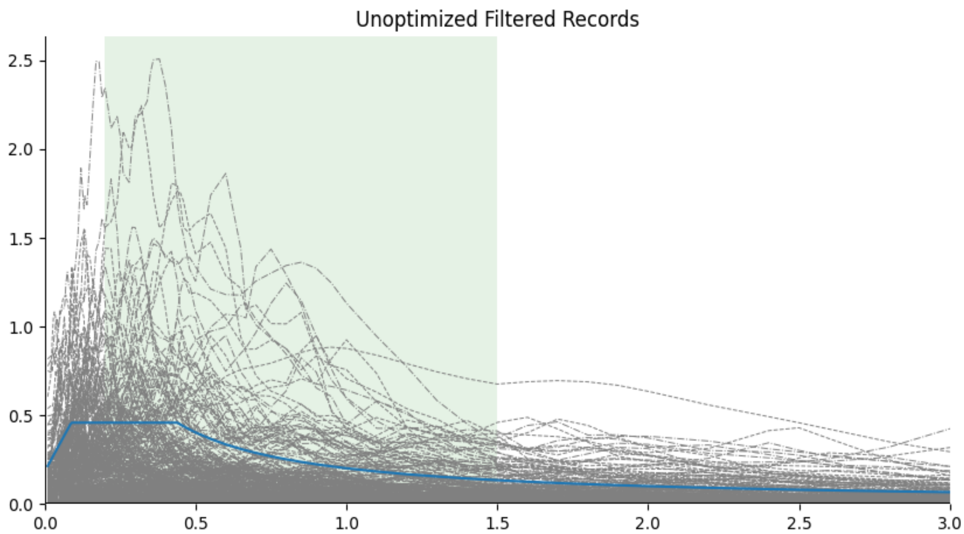

Figure 50. Test Case 32 Data Set 3 Unoptimized Filtered Records

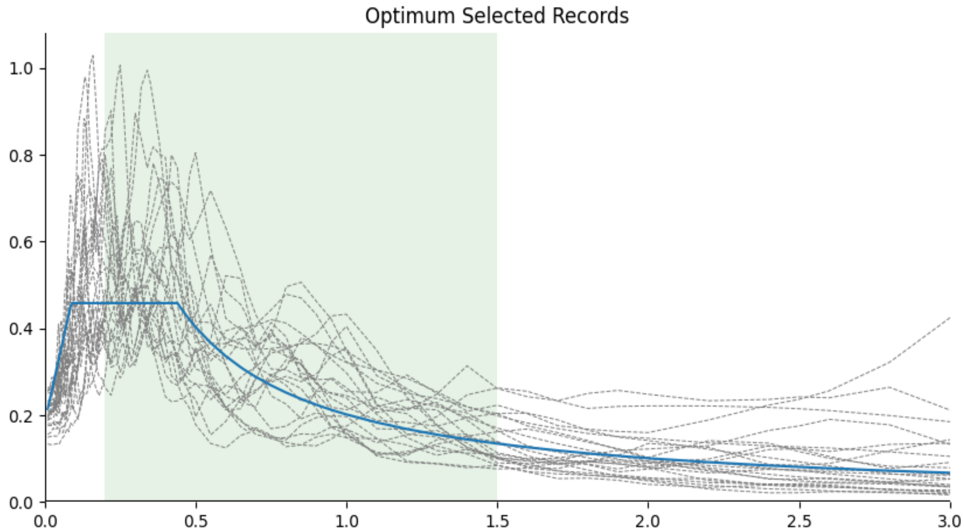

Figure 51. Test Case 32 Data Set 3 Optimum Selected Records

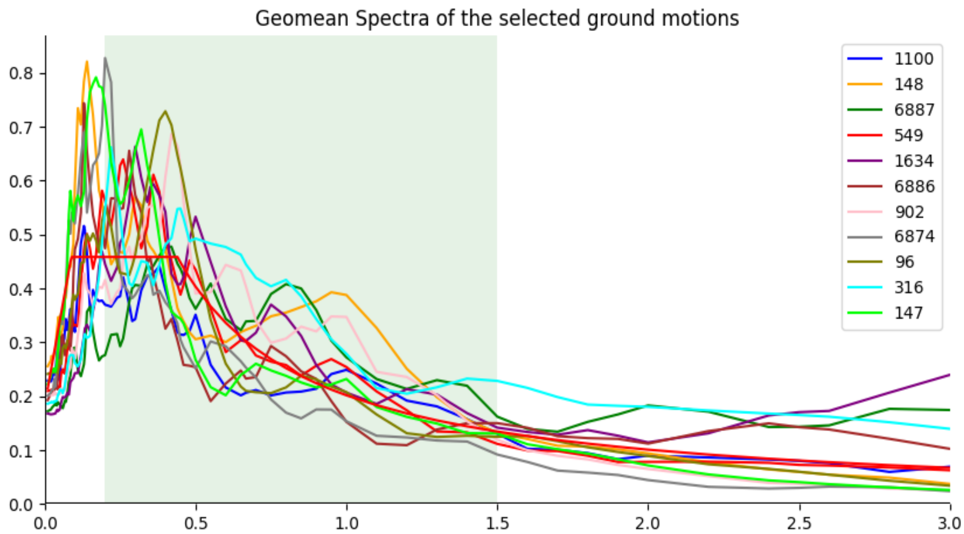

Figure 52. Test Case 32 Data Set 3 Geometric Mean of Records

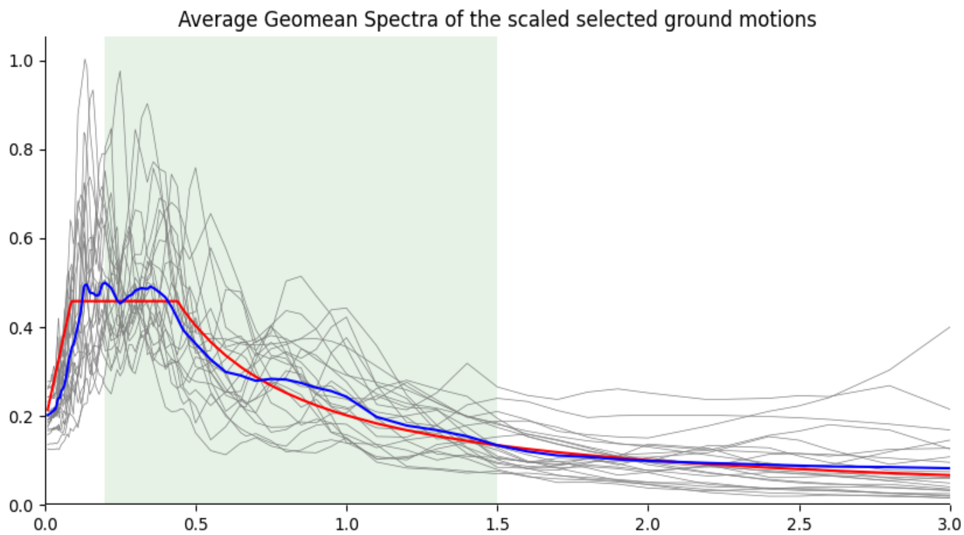

Figure 53. Test Case 32 Data Set 3 Average Geometric Mean of Records

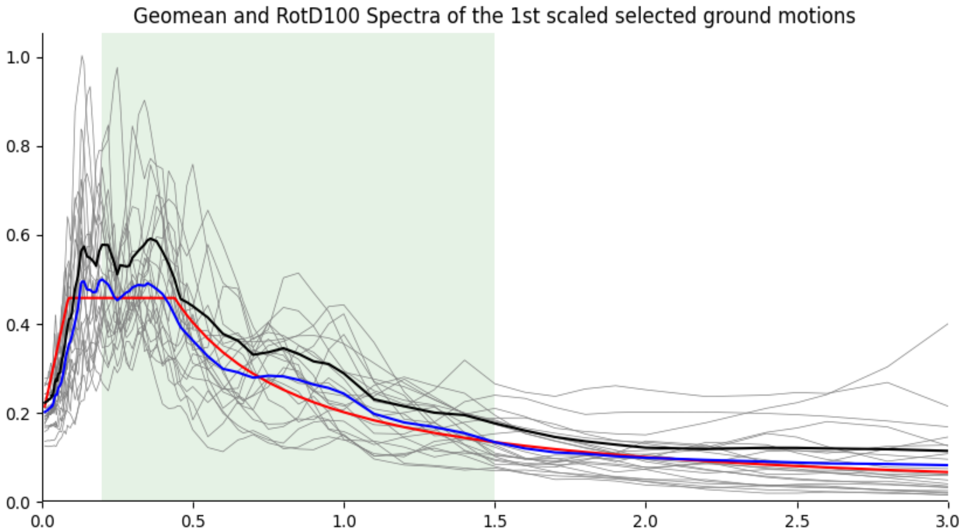

Figure 54. Test Case 32 Data Set 3 RotD100 Mean of Records

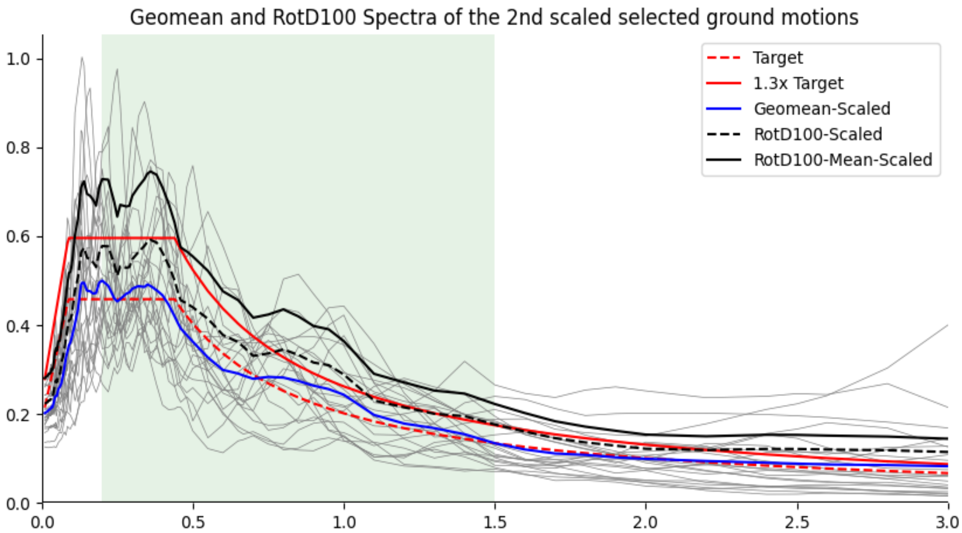

Figure 55. Test Case 32 Data Set 3 Scaled Records

- Data Set 4

RSN	Scale Factor
1100	0.885
148	0.885
6887	0.885
549	0.885
1634	0.885
6886	0.885
902	0.885
6874	0.885
96	0.885
316	0.885
147	0.885

Table 15. Test Case 32 Data Set 4 Scale Factors

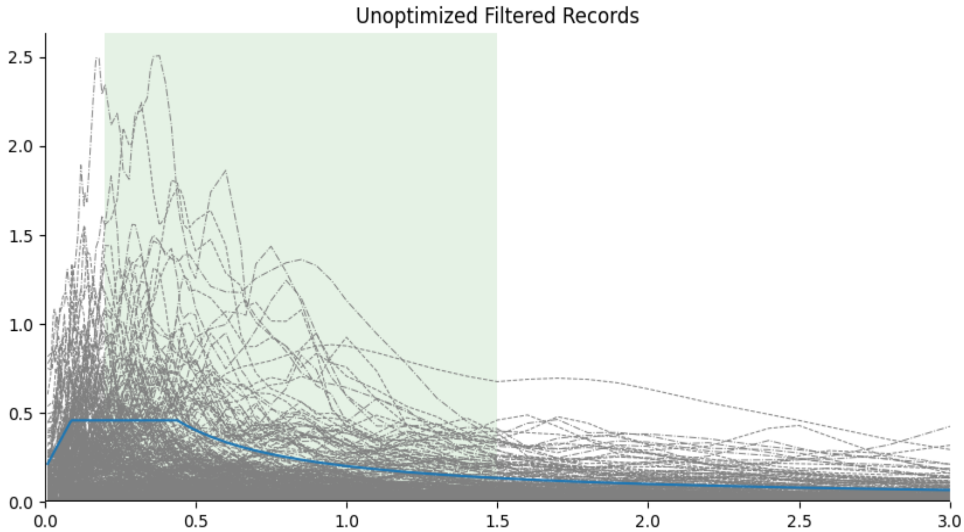

Figure 56. Test Case 32 Data Set 4 Unoptimized Filtered Records

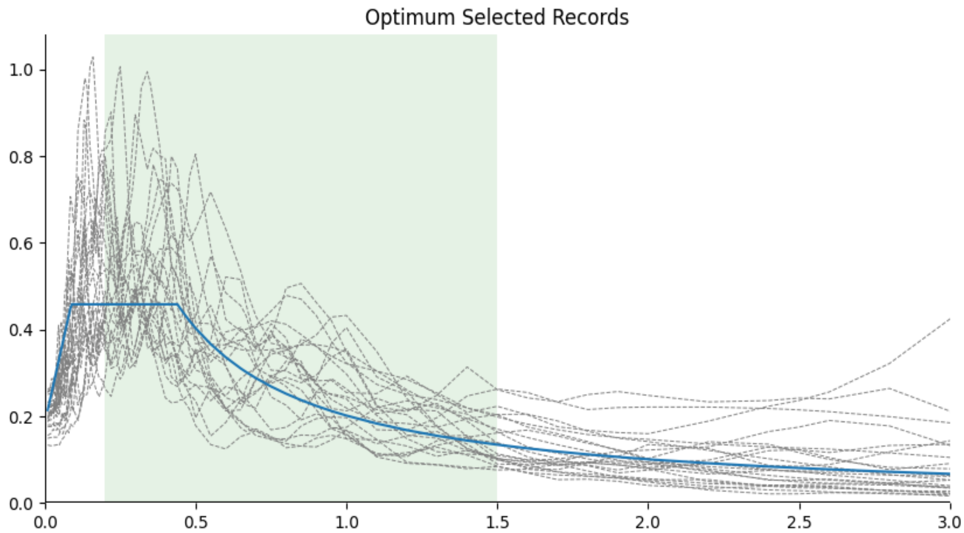

Figure 57. Test Case 32 Data Set 4 Optimum Selected Records

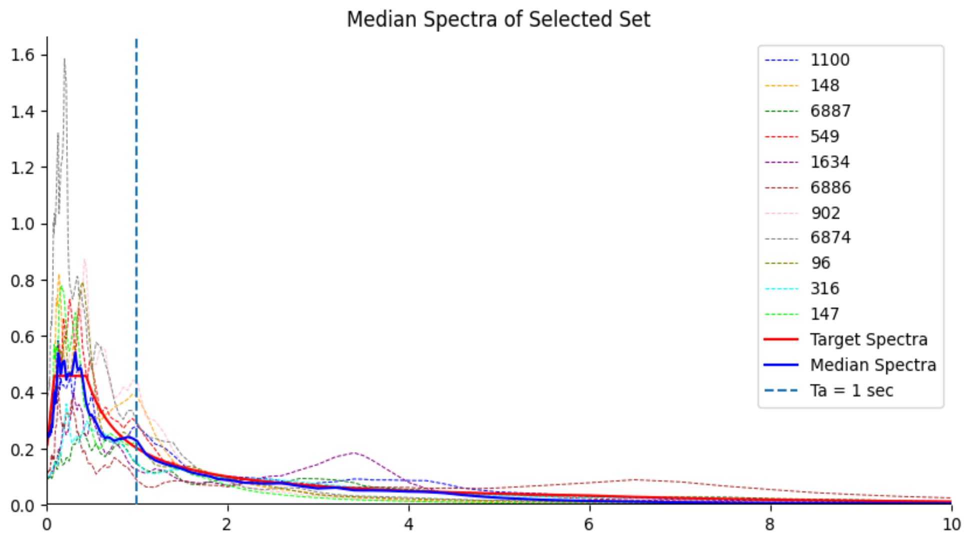

Figure 58. Test Case 32 Data Set 4 Median Spectra of Selected Set

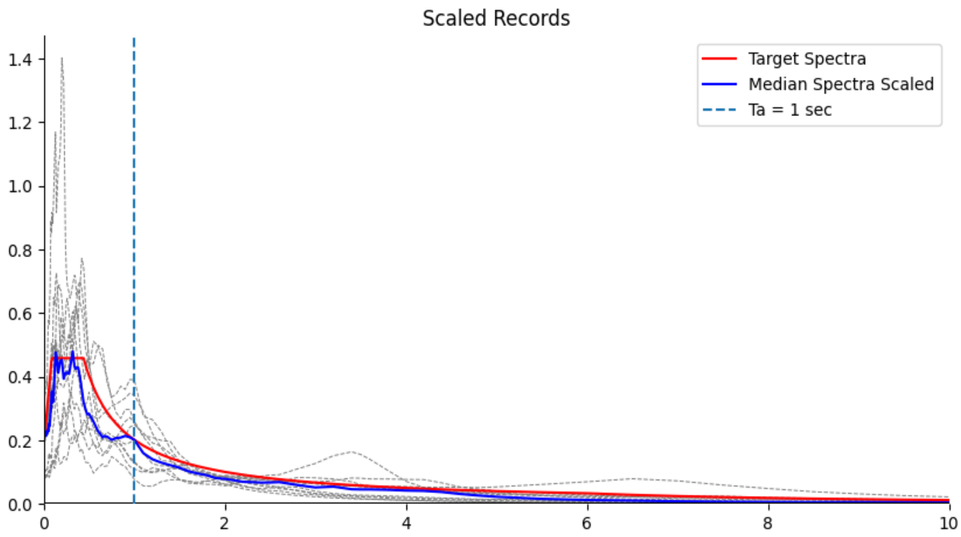

Figure 59. Test Case 32 Data Set 4 Scaled Records

- Numerical Example 3 Comparison Tables

	PEER	Scalepy - SRSS	Scalepy - RotD100	Scalepy - P695
	1.086	1.197	1.499	0.885
	2.567	1.029	1.290	0.885
	1.497	1.021	1.280	0.885
	1.254	0.976	1.223	0.885
	1.485	0.948	1.188	0.885
	1.617	0.954	1.195	0.885
	2.324	0.935	1.172	0.885
	3.455	0.944	1.183	0.885
	1.816	0.928	1.163	0.885
	1.891	0.918	1.150	0.885
	2.484	0.912	1.143	0.885
Average	***1.952***	***0.978***	***1.226***	***0.885***
Standard Deviation	***0.664***	***0.078***	***0.098***	**-**

Table 16. Numerical Example 3 Comparison Table

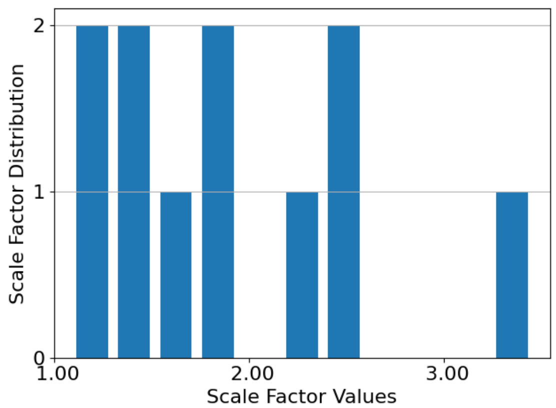

Figure 60. Numerical Example 3 Scale Factor Distribution PEER

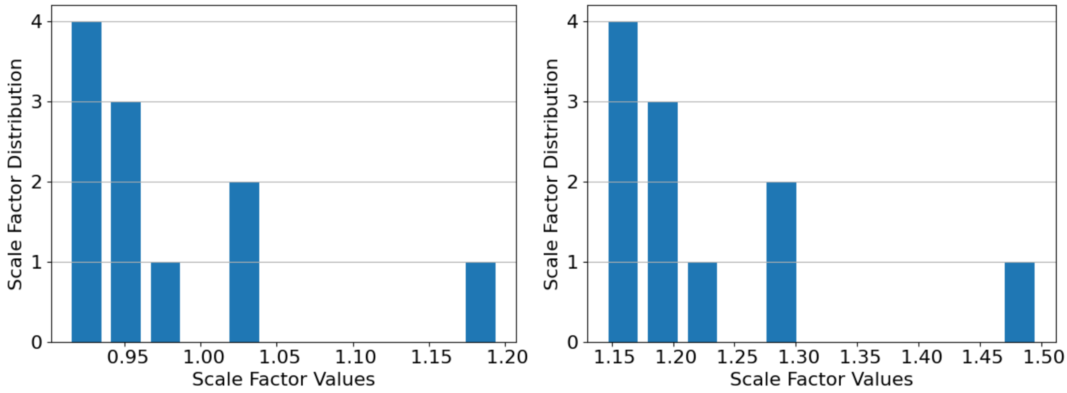

Figure 61. Numerical Example 3 Scale Factor Distribution Scalepy SRSS and RotD100

5. Summary and Conclusion

5.1. Summary

This dissertation proposed a record selection and scaling methodology with the aim of finding the optimum set of real earthquake records to be used in the performance verification or design of structural systems. The academic and practical studies showed that, spectrally matched records are more compatible with the response spectrum than the records matched with amplitude scaling method. However, there is concerns about frequency matching method because the frequency content of real earthquake records is manipulated, among earthquake engineering community.

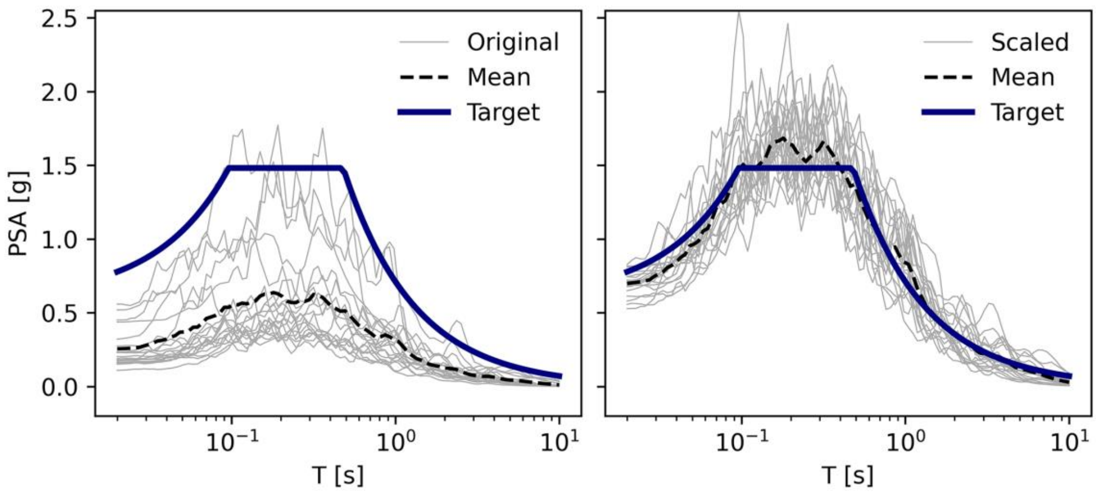

Figure 62. Scaled Earthquake Records using Frequency Scaling Method [20]

Because of these concerns, tendency to use amplitude scaling method is increased among the researchers and analysts. However, there is no consensus on record selection process and how to reduce the dispersion of the acceleration content from the design spectrum. In this approach, a framework is programmed to reduce spectral variation within the ground motion suite with an iteration algorithm. The framework has four basic functions. First function is generating a target spectrum according to TSC – 2018.

Second function is selecting the set of records which correlates best with the target spectrum generated from the first function.

There are 19554 earthquake records in database which is cloned from PEER NGA database. This function has multiple selection filtering stages:

- First stage is filtering the database according to the user input (magnitude range, soil type, RJB range, fault mechanism, duration, arias intensity).
- Second stage is filtering the selected records with an iterative algorithm which is measuring the similarities of the acceleration curves to find the record set with minimum dispersion from the target spectrum.
- Third stage is checking the set if there are 3 or more records from the same event which is not recommended.
- Last stage is sorting all selected records in terms of scaling factors and select 11 records with minimum scale factors.

The third function is performing amplitude scaling for 11 selected records according to the generated target spectrum with the spectrum creation possibilities with SRSS, RotD50 and RotD100.

The selection and scaling applications of the proposed methodology to select ground motions for matching target spectrum are presented in Chapter 4. To assess the efficiency of the developed framework for this study, selection and scaling procedure has applied to 19 different locations with two different earthquake intensity levels. 3 of the 38 numerical example cases has shown with the results in the dissertation.

To compare the effectiveness of the proposed framework, widely used PEER selection and scaling tool is used as comparison tool. The comparative studies are performed to examine the sensitivity of the scale factors to different ground motion selection and scaling approaches.

The main comparison parameters in the study are the dispersion of the scale factors of selected ground motions. Histograms are showing the distribution of the calculated scale factors for different selection and scaling procedures. The developed tool named "ScalePy", and the PEER NGA selection and scaling tool is named as "PEER". Also, SRSS and RotD100 spectrum creation functions in the ScalePy tool has an internal quality check.

5.2. Conclusion

The main conclusions derived from this dissertation are given below.

i. In general, obtaining a sufficient number of ground motion records that fully satisfy with the target earthquake scenario's related target hazard level (e.g., magnitude, distance, fault mechanism, soil class) is challenging. This study makes use of the computational capability of searching through a large database, which takes about 9 seconds to discover the best matched record set. The probability of discovering an adequate set of accelerograms may increase as the database grows. This attribute also allows the analyst to simply alter inputs to loosen limits for candidate records.

ii. The case studies in this dissertation show that the proposed procedure prevents large dispersion of scale factors. The scale factors have a significantly low standard deviation in every case which is important to avoid uncertainties in engineering demand parameters. These results indicate that the proposed method avoids potential bias resulting from scaling the ground motions.

iii. The numerical test cases show that, soil type is the main determinant factor in the scale factor distribution. In the real ground motion database, there is limited number of locations which has ZA and ZE type of soil. This lack of records is causing a significant incensement for scale factors. Nevertheless, proposed methodology is still calculating a set of scale factors which is low and has less dispersion, when it is compared with the PEER

NGA selection and scaling tool. The real ground motion records which have recorded a location with a ZB, ZC and ZD has better results, because there is a sufficient number of real ground motion records.

iv. In this study, orientation-independent spectrum concept has shown, which is probably will be a mandatory concept in the future seismic code in Turkey. RotD100 spectrum is resulting slightly higher scale factors in comparison with the SRSS spectrum as expected.

v. In general, the average scale factor is significantly lower, and the scale factor have a lower, nearly 0, standard deviation with developed framework, in comparison with conventional PEER NGA selection and scaling tool. In addition, PEER NGA tool is not consistent in every application. It is returning different results with the same inputs time to time. Developed framework is consistent and open-source, to make the theory behind transparent. For example, a comparison table for numerical example 2 has shown below.

	Average Scale Factor	Standard Deviation of Scale Factor Set
PEER NGA	2,123	1,075
Scalepy SRSS	1,186	0,044
Scalepy RotD100	1,417	0,052

Table 17. Result Comparison for Case 2

A comparison table for numerical example 3 has shown below.

	Average Scale Factor	Standard Deviation of Scale Factor Set
PEER NGA	1,952	0,664
Scalepy SRSS	0,978	0,078
Scalepy RotD100	1,226	0,098

Table 18. Result Comparison for Case 3

vi. A different scaling procedure, FEMA P695, has implemented in the developed framework to verify the results of the studies. P695 scaling procedure is resulting higher scaling factors in most of the numerical examples, in comparison with the proposed methodology. Nevertheless, since the P695 method is scaling all the records with a single scalar, the acceleration content maybe resulting more engineering demand parameters. As a result, the most efficient way of selection and scaling of real ground motions is to use the proposed methodology in this study.

5.3. Future Work

The main objective of this dissertation is to propose a new methodology for selection and scaling of ground motion records. In terms of that, an open-source framework is developed in python programming language. This means, the source-code of this study is stored in Github site.

Since this study is based on an iterative method, the expansion of the ground motion record database may increase the success of this framework. Currently, there is 19554 ground motion records is stored in the public repository.

Due to complexity of the earthquake engineering problems, obtaining sufficient results is only possible with the power of computer programming. Source code can be also found in the Appendix A. Also, the repository can be found in the link below.

https://github.com/dogukankaratas/scalepy

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