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# QUAKEMANAGER: A COMPREHENSIVE SOFTWARE TOOL FOR GROUND MOTION SELECTION, MODIFICATION AND ANALYSIS

**Mahmoud M. Hachem[1], Bashar M. Abdo[2], Hamza A. Al-Jundi[2], Sohaib A. Al-Jundi[2], Bahaa T. Tayba[2], Bahaa S. Ghieh[2], Yousra A. Hachem, and Khaled A. Chandab[2]**

[1] Earthquake Solutions
Tripoli, Lebanon
e-mail: mahmoud@eqsols.com

[2] Earthquake Solutions
Tripoli, Lebanon
{bashar,hamza,sohaib,bahaa,bghieh,yousra,kchandab}@eqsols.com

**Abstract**

*Given the increasing usage of Response-History Analysis in the analysis and design of existing and new structures and infrastructure, ground motion records must be selected properly and adjusted to attain the best possible fit to the site-specific response spectrum. QuakeManager addresses many of the limitations of existing tools by integrating various functionalities into a single, powerful, yet simple-to-use program, allowing the selection, analysis and adjustment of ground motions to be conducted more accurately and effectively. It includes state-of-the-art methods in the ground motion science and earthquake engineering fields, as well as the two primary methods used in engineering application: Amplitude Scaling and Spectral Matching. In addition, it can perform nonlinear site response analysis and generate simulated artificial bidirectional near-fault ground motion records that can be used in earthquake simulations. QuakeManager features a customizable searchable database that allows the storage, search and analysis of records of various file formats from global databases. Additional tools allow record rotation of records to fault-normal/parallel or other orientations, computation of intensity measures, and generation of engineering reports of the ground motion selection and scaling or spectral matching of suites.*

**Keywords:** Baseline correction, Ground Motion Selection and Scaling, Spectral Matching, Site Response Analysis, Artificial Ground Motion Simulation


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## 1 INTRODUCTION

The usage of ground motion data is increasing due to the continuous rise in the use of Response-History Analysis in the design and analysis of new and existing structures and infrastructure. The ground motions are required to be properly selected and modified to acquire an appropriate suite of records that provide the best possible fit to the site-specific response spectrum.

Engineers routinely expend substantial efforts in building and refining finite element models in order to ensure the highest possible accuracy, but usually pay significantly less attention to the selection, scaling and modification of the ground motion records, which can have an equal if not larger effect on the accuracy of the analysis. The selection of an appropriate suite of ground motions with the proper characteristics, that possesses the correct seismological characteristics, and mean and dispersion statistics can have a substantial impact on the accuracy and validity of the analysis results.

The QuakeManager software addresses many of the shortcomings of current software tools by integrating several functionalities in one easy-to-use program and allowing the process of ground motion selection, analysis and modification to be performed more effectively and accurately.

QuakeManager is an integrated software for the management, analysis, selection and modification of earthquake ground motions and related waveforms. The software incorporates the latest state-of-the-art techniques in the earthquake engineering field and ground motion science. QuakeManager incorporates the two primary methods used in engineering practice: Amplitude Scaling and Spectral Matching. The software consists of multiple modules that are tightly integrated within a common user-interface which allows data to flow seamlessly between modules: *QuakeSelect*, *QuakeMatch*, *QuakeSim, QuakeLibrary*, *QuakeSignal* (under development), and *QuakeSpec*, with other modules that are under development**.**

## 2 USER-INTERFACE

The software has a highly interactive and configurable user interface that is intuitive and easy to learn. These interactive features combined with the advanced capabilities of QuakeManager will make it easier for earthquake engineering professionals, students and researchers to search and utilize ground motion data.

Significant effort was invested in designing a graphical user interface that is modern, powerful, efficient, intuitive and easy to use. This enhanced the software capability and maximized the user productivity [1]. The user interface (Figure 1) draws on the latest developments in user-interface design, such as using moveable and resizable panes, providing the ability to browse record database information and display record histories, as well as the ability to instantly compute record properties including spectral values and intensity measures.

The workspace is fully configurable, and the various panes can be arranged and sized in a multitude of ways. Panes can be docked, floated or hidden, which maximizes space use and allows the use of multiple screens if desired (Figure 2). An emphasis was placed on visual output and immediate feedback from the user interface.

QuakeManager's ribbon guides users to browse, find and use commands efficiently. QuakeManager's ribbon allows users to discover the software features and functions faster and quickly enables learning of the software as a whole. The project pane (project tree) includes the list of commands that can be performed in QuakeManager (defining Target Spectra, Selection & Scaling, Spectral Matching…). The Ground Motion Database Library includes all the stored records in the libraries. History charts panes display the time-history charts (AVD, Acceleration, Velocity and Displacement) of one or multiple records, in addition to the Arias, Polar chart and the geographical Mapping of the selected records. The spectra chart pane shows the various spectral quantities in various formats, or other types of spectra such as Fourier spectra and Power Spectral Density. The records view pane is at the center of the QuakeManager user interface. It displays a list of records, which can be all the records belonging to a given database collection, a filtered set of records, or the result of a selection or spectral matching. The view can be customized to remove or add columns (fields). Up to 147 different fields can be shown. This allows the user to show the fields of interest and hide all other fields in order to preserve screen space. The record properties (metadata) pane includes the properties and stored parameters of the ground motions. More than 160 fields are currently supported including a large number of automatically computed intensity measures. The "GM Search & Select" pane (Auto-Hidden by default) enables manually selecting as-recorded ground motions from the database for scaling, matching, modification and/or rotation. QuakeManager provides users a wide range of filtering criteria in which users may define, and GM Search Panel will generate all records that satisfy these criteria.

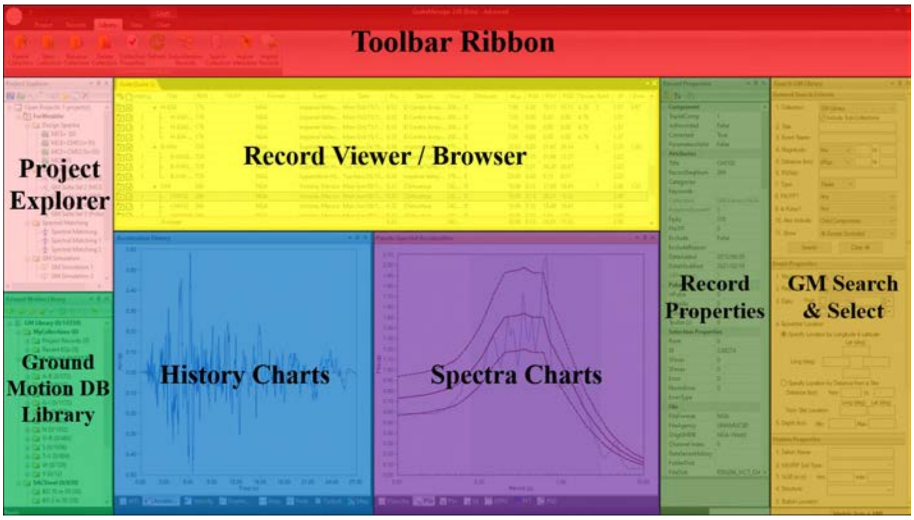


Figure 1: QuakeManager user interface

Figure 2 : Dockable user interface

QuakeManager can plot a wide range of time histories charts. The supported history charts are: AVD (Figure 3), Acceleration (Figure 4), Velocity (Figure 5), Displacement, Polar chart (Figure 6) and Arias (Figure 7). The Arias (Figure 7) chart plot the Husid plot of the recorded ground motion which reflects the variation of the cumulative ground motion input energy as a function of time. QuakeManager is also able of showing the locations of the selected records on a Google Map (Figure 8); the records can be viewed as clusters or individual markers representing the event and station of the record.

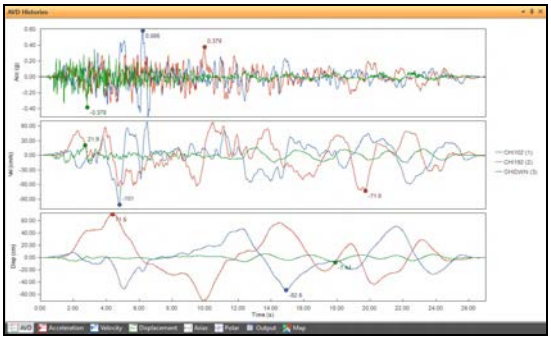

Figure 3: Acceleration-velocity-displacement time histories

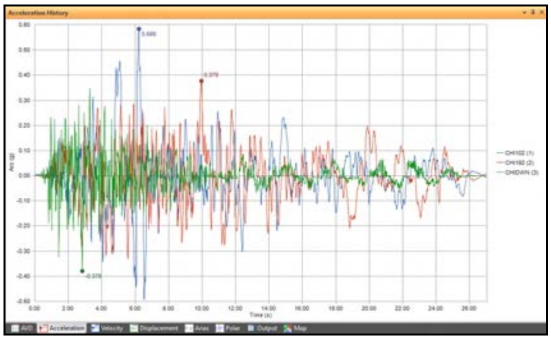

Figure 4 : Acceleration time history

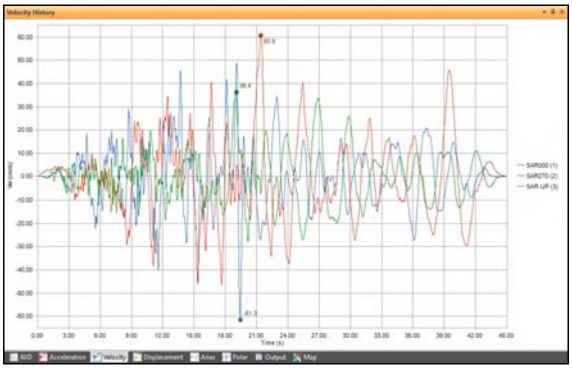

Figure 5 : Velocity time history

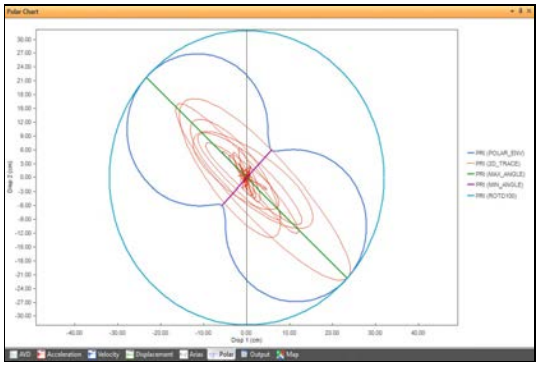

Figure 6 : Polar interaction 2D trace and Envelope

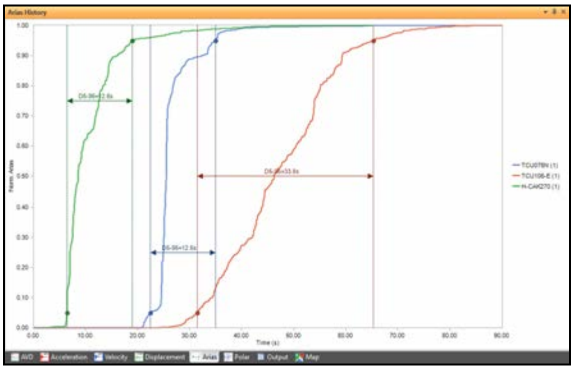

Figure 7: Husid plot (Arias Intensity) with D5-95 duration

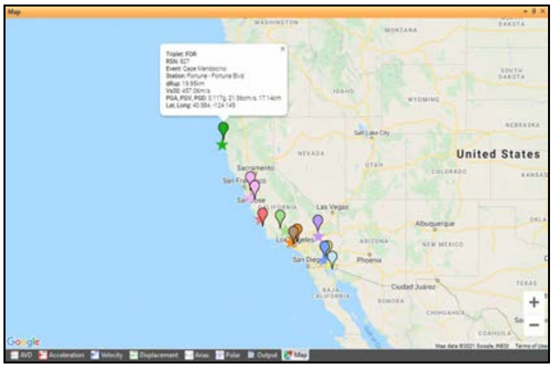


Figure 8 : Map of selected records

## 3 CODE AND USER-DEFINED DESIGN SPECTRA

The Design response spectra can be defined by the user and are typically used as Target Response Spectra for several operations within QuakeManager including selection and scaling and spectral matching of ground motions. Design spectra are used while performing ground motion search and ranking by spectral shape and when performing ground motion selection and scaling or spectral matching for suites of records or individual records.

Prior to defining the target spectrum, the user can use the Site dialog to define the site location (Street Address or Latitude/Longitude) and soil condition by site class (A, B, C…) or shear wave velocity (Vs30). QuakeManager supports two methods to define the target spectrum: Code Design Spectrum or User-Defined Spectrum.

Using the Code Design Spectrum dialog (Figure 9), the design spectrum parameters can be automatically retrieved from the USGS webs services [2] based on the defined site conditions and QuakeManager will calculate and plot the spectrum. The tool supports all codes supported by USGS including: ASCE 7-16, ASCE 7-10, ASCE 41-17, ASCE 41-13, NEHRP 2020, NEHRP 2015, NEHRP 2009 IBC 2015, IBC 2012, CBC 2019, CBC 2015, CBC 2010 and AASHTO 2009, with support for ASCE 7-22 becoming available once officially released. In addition to that, QuakeManager can develop the two-period and multi-period (NEHRP 2020 and ASCE 7-22) of MCE and DBE horizontal and vertical spectra. Spectra parameters that are downloaded include $S_S$, $S_1$, $T_L$, Fa, Fv, $S_{MS}$, $S_{M1}$, $S_{DS}$ and $S_{D1}$. QuakeManager also reads additional hazard parameters such as: risk category, PGA, seismic design category, $S_{suh}$ and others.

When the design spectrum is obtained from a site-specific probabilistic seismic hazard analysis, the User-Defined Spectrum dialog may be used in which the user can enter data directly in the table (T vs Sa), or by pasting the data which is copied from another software such as Excel. The user-defined spectrum allows the design spectral values and dispersion logSigma (optional) to be defined for each period independently. The data table and spectrum curve will update automatically when input parameters are defined or modified. Users may also select to plot to the **Standard Deviation** and **Target Mean +/- Standard Deviation** in a **Linear** or **Logarithmic** scale on the same plot (Figure 10).

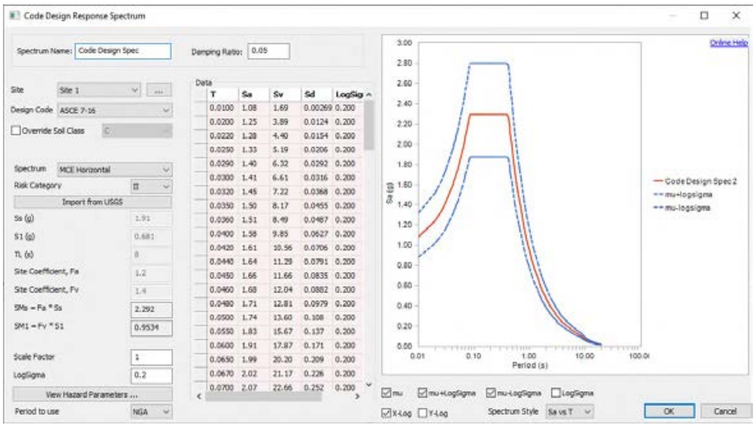


Figure 9 : Code design spectrum dialog

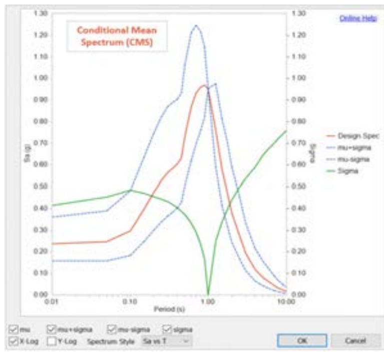


Figure 10: User-defined spectrum

## 4 QUAKEMANAGER MODULES

QuakeManager was designed as a framework that supports common functions and operations needed for the management and analysis of ground motion records. The software was fully developed in C++ under Microsoft Visual C++ [1]. The software incorporates the latest state-of-the-art techniques in the earthquake engineering field and ground motion science. The design of the framework was conceptually and functionally separated into several modules. This has several benefits in conceptual design as well as actual software development. The software consists of multiple modules that are tightly integrated within a common user-interface which allows data to flow seamlessly between modules: QuakeSelect, QuakeMatch, QuakeSim, QuakeLibrary, QuakeSignal (under development), and QuakeSpec, with additional modules that are planned or under development.

### 4.1 QuakeSelect

The QuakeSelect module (Figure 11) provides enhanced record selection and scaling by selecting suites with optimal spectral shapes and statistics matching those of the target spectrum, while satisfying a variety of seismological, statistical, and code constraints. QuakeManager has the full capability (advanced and basic options) for ground motion selection and scaling to match the target spectrum.

The software allows scaling the records to the target-spectrum over a user-specified period range. It enables the user to define and control how the error between the records and the target spectrum is defined over the specified period range.

QuakeManager supports multiple types of selection targets including: Components (H1 component, H2 component and vertical), Bidirectional (SRSS, Geomean, RotD100, RotD50, RotD00, H1 component, H2 component, vertical component, FN component, FN component and the maximum of H1 component and H2 component) and a Custom Match. With Custom Match, QuakeManager enable defining up to three different target spectra with different matching types (RotD100, FN/FP Comp…) and fitting criteria.

The GM fitting criteria (Figure 12) allow the user to define parameters for selecting and optimizing the record selection and scale factors. In the dialog, minimum and maximum allowed scale factors may be defined. QuakeManager supports three different period range options including: Uniform Weight, Weighted Period and Weighted Frequency. The advanced options enable controlling the error types by specifying the evaluation method as Linear or Logarithmic and setting the desired error measure techniques of different spectral parameters as follows: Absolute Difference Sum, Absolute Difference Integral, Square Sum (SSE) or Square Integral. QuakeManager is capable of matching suite mean (Figure 13), suite dispersion (Standard Deviation (Figure 14) or Logarithmic Sigma) or individual records. The suite mean can be calculated arithmetically or using the geometric mean. Using the individual records feature, top records (records with smallest error) will be matched individually to the target spectrum, which is usually desired when the records will be subsequently spectrally matched. The suite scaling constraint is an additional adjustment in which the selected suite does not fall below the specified factor compared to the target spectrum. For example, if the average of the records generated in a suite may be specified to not fall below 90% of the target spectrum, which is used to satisfy the scaling requirements of some codes (e.g., ASCE 7-16 [3]).

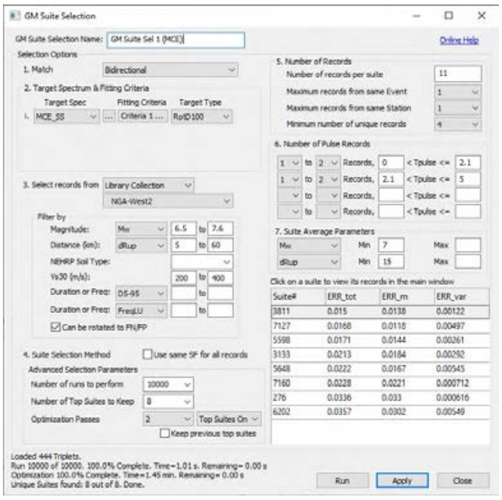

Figure 11: Ground motion selection

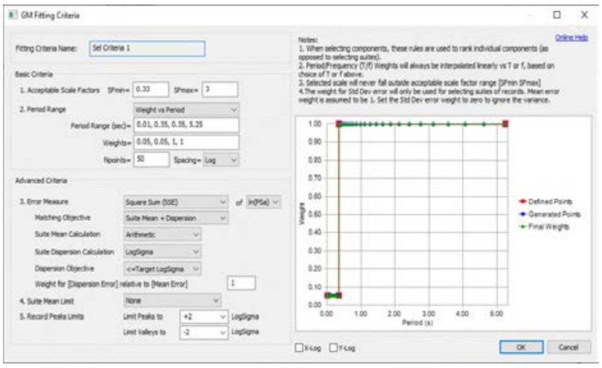

Figure 12 : Fitting criteria dialog

QuakeManager supports several record filtering options while performing ground motion selection. Filtering helps to select records that are a subset of the ground motion database that match the desirable tectonic and hazard properties of the site. Filter options include magnitude ($M_W$, $M_L$, or $M_S$, etc.), distance ($d_{epicenteral}$, $d_{hypocentral}$, $d_{rupture}$, $d_{Joyner\text{-}Boore}$…), frequency & duration ($D_{5\text{-}95}$, $D_{5\text{-}75}$, High-Pass Frequency, Low-Pass Frequency and Lowest-Usable Frequency), NEHRP Soil Class, Shear Wave Velocity (Vs30) and whether records can be rotated to FN/FP. The FN/FP rotation option will only select records that can be rotated to the fault axes. Finally, two suite target ranges can be set: Average Magnitude and Average Distance. When used, the magnitude and distance averages of the selected suite records will fall within the defined ranges.

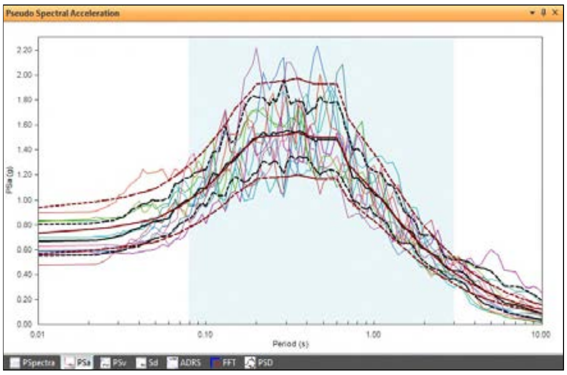

Figure 13: Ground motion selection and scaling

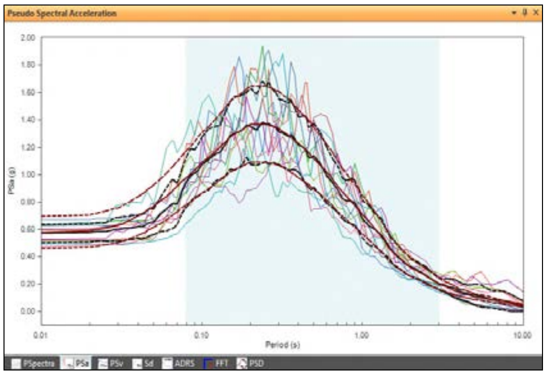

Figure 14: Ground motion selection and scaling

## 4.2 QuakeMatch

The Spectral Matching module provides the ability to modify a suite of records in order to achieve an ideal fit to the target spectrum, beyond what can be achieved by scaling alone.

QuakeMatch can perform both tight and mean spectral matching to further adjust ground motion suites for an improved fit to the target. Furthermore, the implemented mean spectral matching technique helps in maintaining record characteristics and controlling variability while meeting code requirements.

1. **Tight Matching:** This is the conventional spectral matching typically performed, where each ground motion is modified such that its spectrum perfectly matches the

target. This minimizes the potential amplification of higher modes and significantly reduces the variability in spectral ordinates (Figure 15)

2. **Mean Matching**: Is a hybrid spectral matching method, where records in the suite are each slightly modified such that the average (and optionally the dispersion) of the suite perfectly matches the target. Mean Matching preserves the peaks and valleys, characteristic period and energy content of the records (Figure 16). This method reduces the peak values of the individual spectra and hence, minimizes the amplification effects on higher modes, and is also better at preserving the natural characteristics of the records [4].

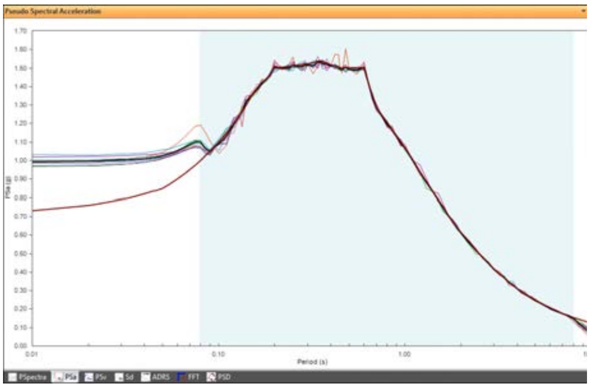


Figure 15: Tight spectral matching

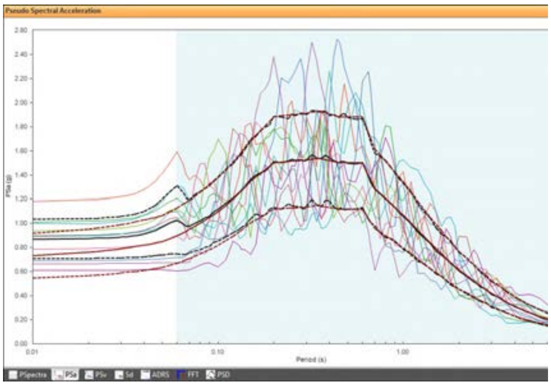


Figure 16: Mean spectral matching

The spectral matching dialog (Figure 17) is the main tool for performing spectral matching. Despite its simplicity, it offers a large number of possibilities for spectrally matching records. For example, it can match individual components as well as pairs and triplets of records. And it can be used to directly match record resultants such as SRSS, Geomean, RotD100 [5], RotD100 (approximate and exact), RotD50 (approximate and exact), and RotD100/RotD00 simultaneously, and can match all 3 components of a record including the vertical component.

The Matching Criteria (Figure 18) allows the user to control the parameters of the spectral matching including the definition of wavelet model to produce better solutions. QuakeManager enables defining period or frequency ranges that could be split into multiple matching steps, pre-scaling records at specific periods, applying additional factors and baseline correction. QuakeManager also supports different wavelet models including: Reverse Acceleration Impulse Response Function, Tapered Cosine Function and Improved Tapered Cosine Function [6].

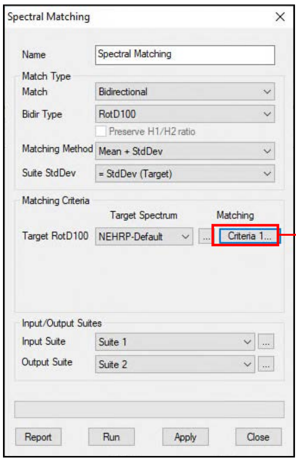


Figure 17: Spectral matching dialog

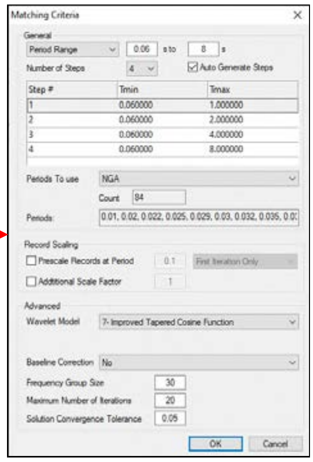


Figure 18: Matching criteria

## 4.3 QuakeSim

The QuakeSim module (Figure 19) can be used to generate simulated artificial bidirectional near-fault ground motion records that can be used in earthquake simulations (Figure 20), using a published algorithm for artificial ground motion simulation [7].

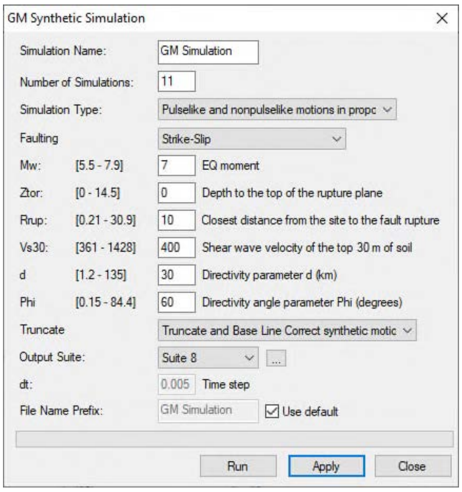


Figure 19: GM simulation Dialog

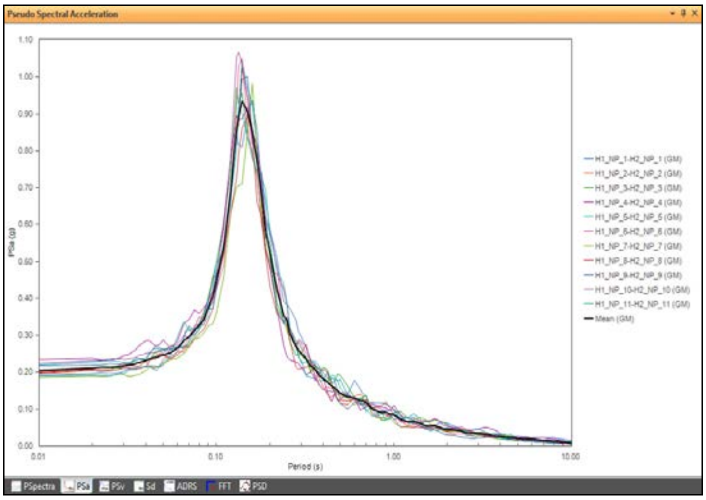


Figure 20 : GM record simulation

## 4.4 QuakeSpec

The QuakeSpec can calculate and plot a wide range of spectra including: PSa, PSv and Sd (Figure 21), Maximum and Minimum components, SRSS, Geomean, RotD100, RotD50, RotD00 (Figure 22) and FN/FP components. The spectra chart pane shows the various spectral quantities in various formats, or other analytical quantities such as Power Spectral Density and Fourier spectra (Figure 23). In addition to that, the software calculates and plots the Acceleration-Displacement Response Spectum (ADRS) as shown in Figure 24. The charts are organized in a tabbed interface to provide quick and easy switching between different chart types. They also allow comparison of multiple records. It is possible to export chart data as an image or to text format (to be pasted in spreadsheets or other software).

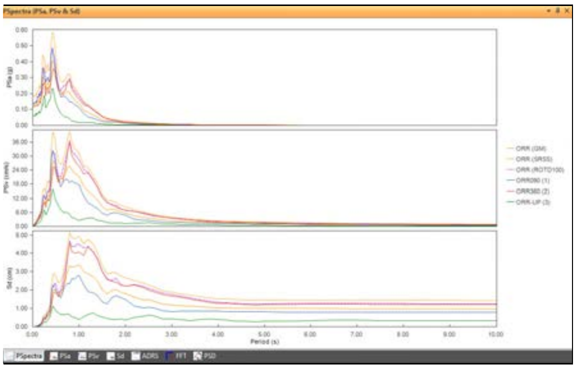

Figure 21: Pseudo spectra

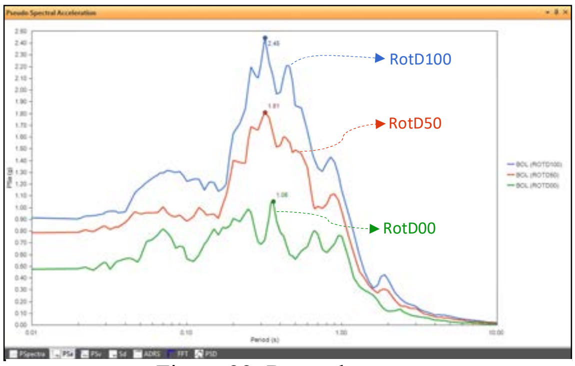


Figure 22: Rotated spectra

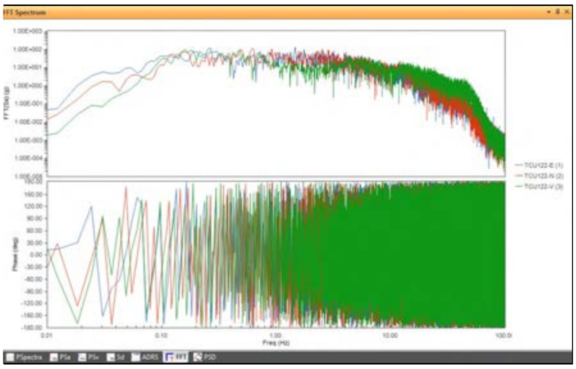

Figure 23: Fast fourier transform

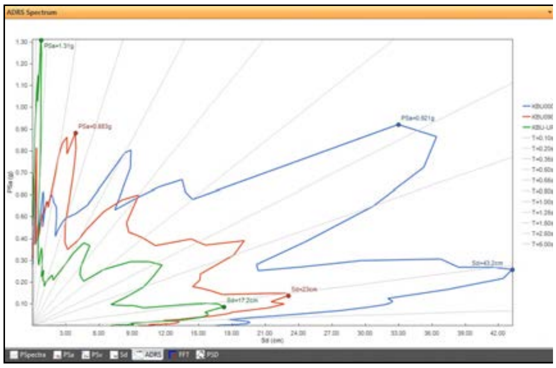

Figure 24: Acceleration-displacement response spectrum (ADRS)

### 4.5 QuakeLibrary

The QuakeLibrary module includes a massive searchable database enabling storing, searching and analyzing records with different file formats from worldwide libraries.

The Ground Motion Library is a ground motion database record manager within the user interface that provides the capability to organize, browse, and search a large number of ground motion records, both individual Components and Triplets. QuakeManager comes with pre-loaded and fully searchable ground motion databases including the metadata of NGA-West2 [8] database metadata and the SAC Steel ground motion set. The software allows users to add additional data, which can be obtained from multiple sources:

- Online ground motion databases
- Published sets of ground motions
- Simulated, user-generated, or proprietary ground motion records

The QuakeManager ground motion database includes multifaceted data as follows:

- Record metadata: which includes all the information about the event, station, time, place, etc. There could hundreds of metadata field values for each record that need to be saved, browsed, searched and imported from and to files and databases.
- The record file: this is usually a file on disk, but it could be located on a network.
- The data series (or time history): recorded data, which includes acceleration, velocity, and/or displacement. This represents the bulk of the recorded data and is extremely valuable for engineering and seismological analysis.

- Response spectra (Sa, Sv, Sd, PSa, PSv, etc): needed to perform useful engineering search, scaling, matching and other operations using the records.
- Intensity Measures: includes numerous types of intensity measures and indices intended to provide simple representations of the records damaging or shaking potential.

The software supports worldwide file formats including: USGS (SMC), PEER NGA, NRC, SAC Steel, K-Net and Kik-net, CSMIP/CGS, Chile, New Zealand, RSP Match, Generic File Format, COSMOS, NBCC, Multi-Column Format, Costa Rica and a User-Defined File Format

### 4.6 QuakeSite

The QuakeSite Module (Figure 25) is a one-dimensional site response analysis tool that can perform: nonlinear time domain analyses with and without pore water pressure generation, equivalent linear frequency domain analyses including convolution and deconvolution, linear time and frequency domain analyses convolution and deconvolution, and linear time and frequency domain analyses.

The module allows users to define the properties of the soil layers (Figure 26), including their density, stiffness, and damping characteristics. It can model nonlinear soil behavior, including hysteretic damping and strain softening, and can simulate the effects of soil liquefaction.

Below are some of the capabilities of QuakeSite Module:

1. One-dimensional (1D) site response analysis using linear and nonlinear soil models.
2. Time-domain and frequency-domain analyses to simulate seismic response.
3. Supports multiple Soil Models including GQ/H, MKZ, Yee, Linear and Points.
4. Incorporation of pore water pressure effects in the soil.
5. Visualization of results through various plots and graphs (Figure 27).

QuakeSite relies on DEEPSOIL [11] to perform analysis.

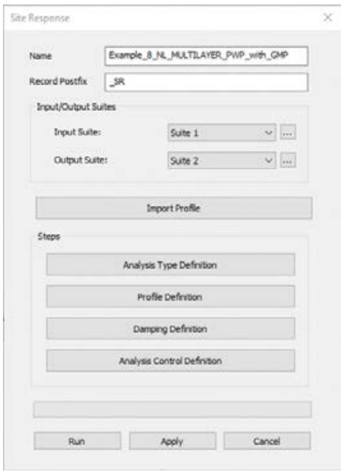


Figure 25: QuakeSite user interface

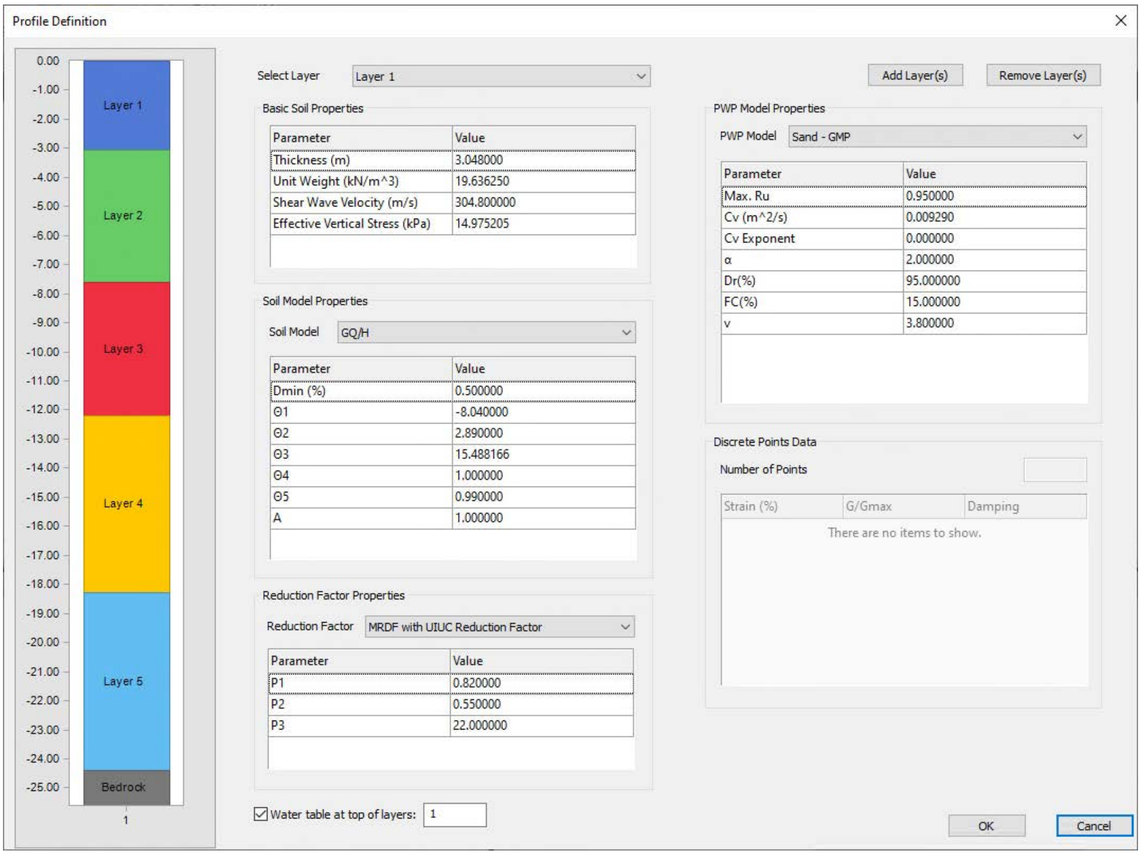


Figure 26: QuaeSite profile definition

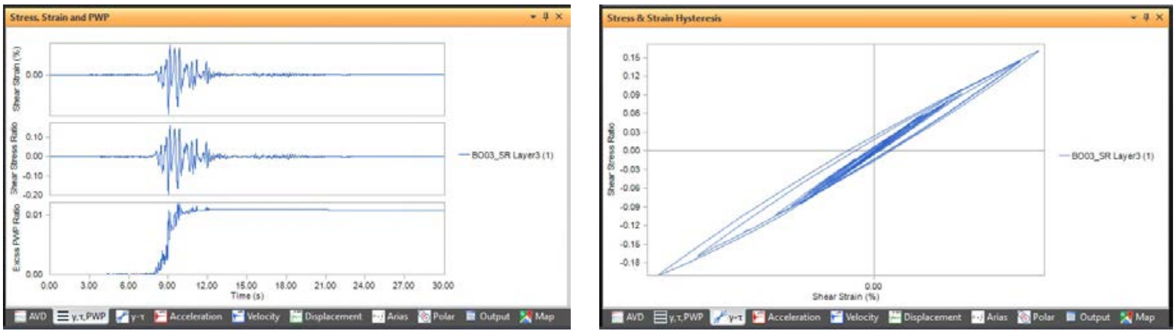


Figure 27: QuakeSite results charts

## 5 QUAKEMANAGER TOOLS

### 5.1 Ground Motion Rotation Tool

In general, it is assumed that the angle corresponding to the FN/FP directions will lead to the most critical structural response. Hence, some codes require that records be rotated to their FP/FN orientations (Figure 28) before being applied to a building, if the building is within the near-fault zone of a significant seismic fault.

Near-fault records are also likely to exhibit a pulse effect. Near-source effects cause most of the seismic energy from the rupture to arrive in a short coherent long-period pulse of motion in the FN (and/or FP) direction(s).

The Ground Motion Rotation Tool allows records to be rotated from their original as-recorded orientation to any desired orientation. Some records may also be rotated to their fault-normal (FN) and fault-parallel (FP) components, often without further input from the user. QuakeManager provides Basic and Advanced options and parameters for defining very specifically how the rotation should be performed and allows for scale the records. This feature guides users to search and compute the near-fault and pulse records. The software enables rotating a record or multiple records in a suite. The basic options allow scaling and rotating the records by a specific angle, rotate to FN, rotate to FP, rotate to FN plus an additional angle to account for building orientation or rotate to the record Azimuth.


Figure 28: Ground motion rotation example to FN/FP

## 5.2 Intensity Measures

There are numerous intensity measures that can be used to represent the shaking intensity and damage potential of a ground motion record. The variation of these values depends mainly on the distance of the fault rupture area, due to the distribution across the geographical area from the epicenter. Other parameters that contribute to the variation of the Intensity Measure is the rupture direction and surface geology. QuakeManager has the capability of computing various ground motion parameters (intensity measures). These measures are usually computed from the acceleration, velocity or displacement history, but some are related to the ground motion spectrum (acceleration, velocity, displacement), or other related quantities such as the PSD (Power Spectral Density), etc. QuakeManager can compute a large number (30+) of intensity measures like PGA (peak ground acceleration), PGV, PGD, RMSa (Root-Mean-Square Acceleration), EPA (effective peak acceleration - average spectral acceleration over the period range 0.1 to 0.5 sec divided by 2.5), SPA (sustained peak acceleration - third highest absolute value of the acceleration in the time history) [9], IV (Incremental Velocity), CAV (cumulative absolute velocity), Arias intensity, duration measures, cross-correlations of acceleration components, etc. Duration measures include $D_{5-75}$ and $D_{5-95}$ representing the Arias duration and $D_{b5PcG}$ corresponding to the bracketed duration of accelerations over 5%g [9].

## 5.3 Report Generator

The Report Generator tool generates engineering reports of the ground motion selection and scaling or spectral matching of suites. The Report Generator extracts all the output data and automatically generates a complete MS-Word report for the selected records. Users can easily navigate through the report, make adjustments and save the report. Users may also select and define the data tables and figures to retrieve and have the ability to choose various display options. This is a tremendous time saver when generating long reports (Figure 29).

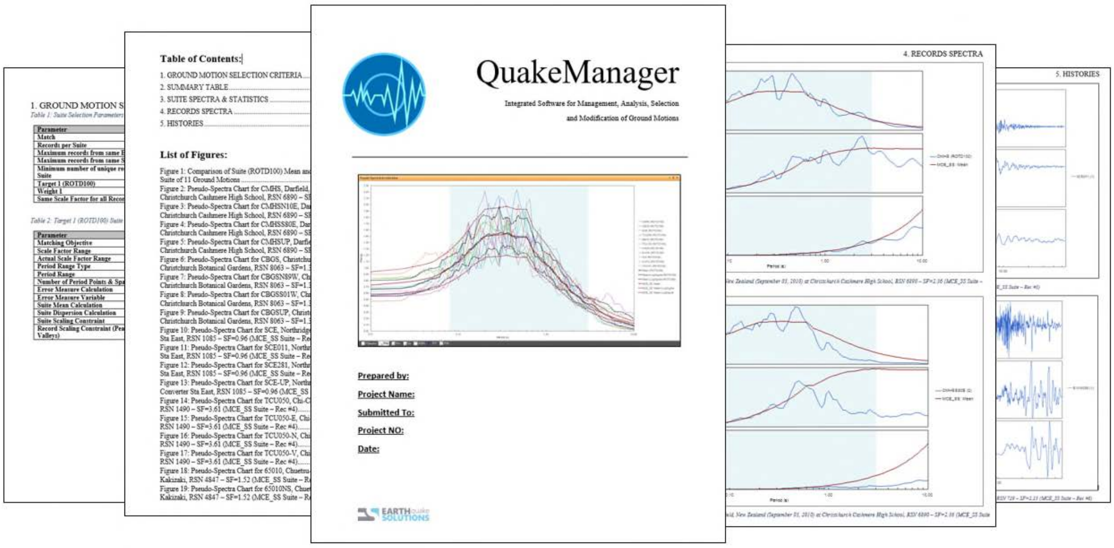


Figure 29: Sample generated report

## 5.4 Import Tool

The QuakeManager supports multiple methods to import records to the GM Library or the suite including:

- Drag and Drop
- Import from CSV
- QuakeManager Import Tool

The QuakeManager Import Tool enables importing records from a local source on the disk. The tool imports unlimited number of records and QuakeManager automatically detects the correct record file format if not specified. In case the record file format was not identified, QuakeManager, provides helpful debugging information for files that do not match the any of the file formats.

In the "Drag & Drop" method, the files are dragged from a folder on the computer disk into a collection in the Ground Motion Library. QuakeManager then checks all the files for a valid ground motion format and imports the valid ones to the database. If the record has header information, metadata is extracted and stored in the database.

In the "Import from csv" method, the user prepares a csv file that defines the metadata of each record and specifies the file disk location for each record (which contains the acceleration history data). This method can require more work but allows a large number of metadata to be imported for each record (e.g., from a flat file). Note that the acceleration history is not included in the csv, but only record properties.

## 5.5 Pulse Calculation Tool

Ground motions with significant velocity pulses are of particular importance to structural engineers because they can place greater demands on structures than non-pulse-like ground motions. The pulse calculation tool calculates up to 5 different pulses for a triplet and allows the user to select the most appropriate pulse. Once the desired pulse is selected, the user can plot the time histories and the spectra of 1) The pulse, 2) The record rotated to the pulse direction, and 3) The residual. The pulse calculation is based on the algorithm presented in Shahi and Baker [10].

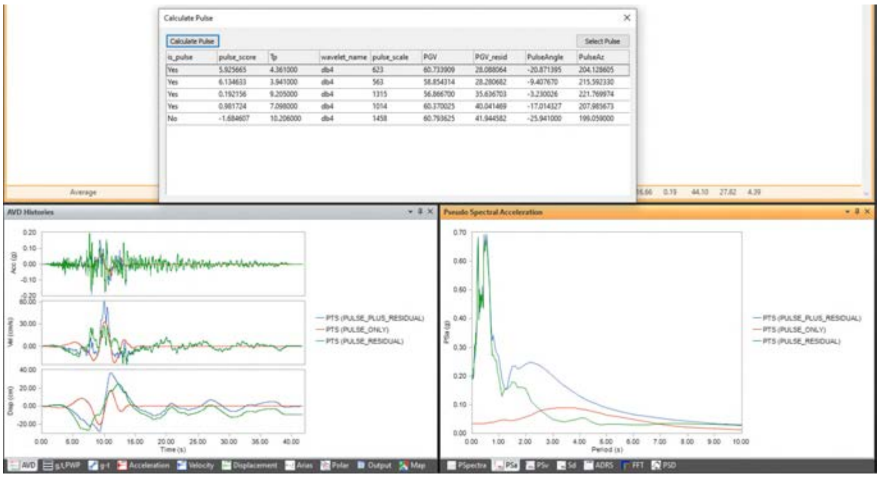

Figure 30: Time histories and spectra of the pulse, pulse direction and residual

### 5.6 Baseline Correction Tool

The baseline correction tool is required for some time series to correct the resulting drift in the velocity and displacement time series. This is done by doing a least square fitting of a polynomial of the specified order (from 0 to 15) on the acceleration time history and subtracting it from the original acceleration.

## 6 CONCLUSION

The QuakeManager is an integrated software for the management, selection, modification and analysis of ground motion records. The software incorporates the latest state-of-the-art techniques in the earthquake engineering field and ground motion science. QuakeManager incorporates the two primary methods used in engineering practice: Amplitude Scaling and Spectral Matching. The software consists of multiple modules that are tightly integrated within a common user-interface which allows data to flow seamlessly between modules: QuakeSelect, QuakeMatch, QuakeSim, QuakeLibrary, QuakeSignal (under development), and QuakeSpec, with other modules that are under development.

This software introduces an integrated and dynamic approach for using ground motion records that increases productivity and provides new capabilities that are not available in other ground motion analysis software. The major infrastructure and user interface components have been developed, and development is continuing on additional record modification and analysis features.

The usage of ground motion data is increasing due to the continuous rise in the use of Response-History Analysis in the design and analysis of new and existing structures and infrastructure. Engineers may expend efforts in the selection, scaling and modification of the ground motion records as they can largely affect the accuracy of the analyses and models. The selection of an appropriate suite of ground motions with the proper characteristics, that possesses the correct seismological characteristics, mean and dispersion statistics can have a substantial impact on the accuracy and validity of the analysis results.

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