PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

"R" Package for Computation of Earthquake Ground Motion Response Spectra

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ABSTRACT

Earthquake ground motions are typically recorded with one vertical and two horizontal components. It has become standard practice to represent the horizontal component of ground shaking in a manner that recognizes a range of amplitudes with changing azimuths. These variable amplitudes can be generically denoted RotDxx, where xx indicates the percentile of the horizontal amplitude range. RotDxx representations of ground motion are used with amplitude parameters (peak acceleration and velocity) as well as response spectral ordinates for a range of oscillator periods. The use of RotDxx ground motions was introduced in the NGA-West2 project, and analysis procedures for their computation were originally developed in Fortran by the fourth author of this report. Here we describe the implementation of these analysis procedures in R, resulting in an "R" package referred to as *Rotated Combination of Two-Component* ground motions (RCTC). We describe related algorithms for recovering accurate peak quantities from digital data (i.e., Sinc-interpolation and subset selection), which are also implemented in RCTC. We verify the code outputs by comparing them with a prior Fortran code. RCTC takes as input two horizontal components of ground motion, their azimuths, and their time step, and returns various types of variables, including pseudo spectral acceleration for each horizontal component, RotDxx for xx=0, 50, 100% as well as earlier, orientation-independent, geometric mean parameter GMRotI50. Other period-independent variables are also computed and outputted. We document here the code verification and provide instructions for its use.

ACKNOWLEDGMENTS

The original Fortran code, which was used to verify RCTC code, was provided by the fourth author (Dr. David M. Boore). This work also benefited from the opinion and advice of Dr. Dong Youp Kwak. This study was supported by the California Department of Transportation and the Pacific Gas & Electric Company.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the California Department of Transportation and the Pacific Gas & Electric Company, Pacific Earthquake Engineering Research Center, or the University of California.

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1 Introduction

Earthquake ground motions are typically recorded with triaxial accelerometers or seismometers having one vertical and two horizontal components. Prior to the NGA-West1 project [Power et al. 2008], the geometric mean was typically used to represent horizontal component ground motions. The geometric mean is computed as:

$$IM_{gm} = \sqrt{IM_x IM_y} \tag{1.1}$$

where IM_x and IM_y are the as-recorded intensity measures in the horizontal plane. Equation (1.1) can also be viewed as the exponent of the mean of the natural logs of IM_x and IM_y. Figure 1.1 shows the 5% damped pseudo-acceleration response spectra based on the two individual horizontal component ground motions and the geometric mean recorded at the LA–Pico and Sentous site (RSN1000) during the 1994 Northridge, California, earthquake.

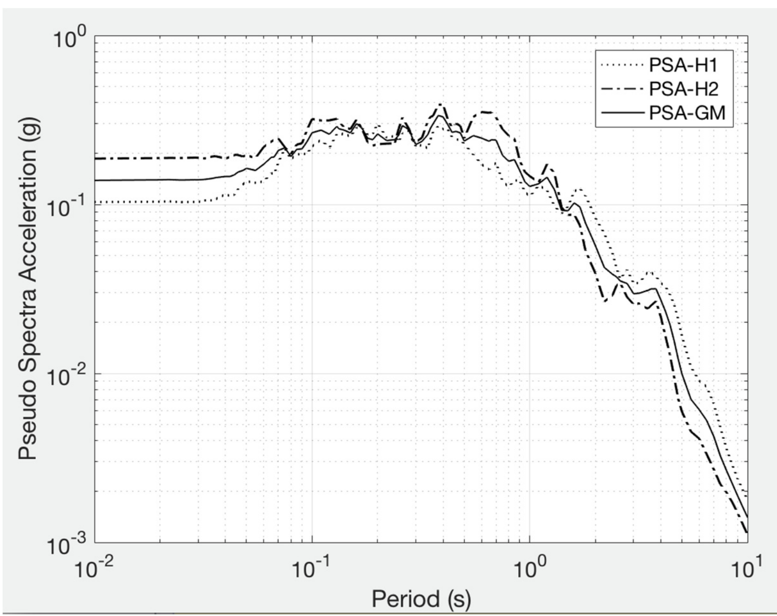

Figure 1.1 5% damped pseudo spectra accelerations of two horizontal components and their geometric mean. Ground motions from LA–Pico and Sentous station, 1994 Northridge, California, earthquake.

During the NGA-West1 project, there was concern that the geometric mean has an arbitrary dependence on the azimuths of the two horizontal components of the recording instrument. As a result of this, an azimuth-independent geometric mean intensity measure was proposed and denoted GMRotI50 [Boore et al. 2006]. Alternate definitions for other percentiles (e.g., GMRotI100) can also be readily computed, but the median was used in NGA-West1. Figure 1.2

compares the geometric mean spectra with the range of GMRotIxx spectra (0, 50, and 100 percentile). Note that GMRotI100 is not necessary larger than GMRotI00 and GMRotI50 at all periods, because GMRotI100 is not selected as a maximum value but is an outcome of a particular choice of penalty function, as described in Boore et al. [2006, Section 2.3].

Following NGA-West1, the maximum component replaced the geometric mean as the seismic design requirement in U.S. building codes. Although this is widely recognized as a poorly conceived definition of ground motion that introduces bias to risk analysis of structures [Stewart et al. 2011], the maximum component shifted the representation of horizontal ground motions away from geometric mean to a single-azimuth combination of the two components. Partially in response to that change in the ground-motion definition used in a large fraction of earthquake engineering practice, NGA-West2 [Bozorgnia et al. 2014] adopted the median-component ground motion, denoted RotD50 [Boore 2010]. RotDxx representations of ground motion are used with amplitude parameters (peak acceleration and velocity) as well as response spectral ordinates for a range of oscillator periods. Analysis procedures to compute RotDxx were originally produced in Fortran by the fourth author.

In this report, we describe the *Rotated Combination of Two-Component* (RCTC) code for computing RotDxx in R (statistical computing software). The RCTC code computes RotDxx for xx=0, 50, and 100%, as well as the earlier, orientation-independent, geometric mean parameter GMRotI50. We verify RCTC against the original Fortran code and provide instructions for its installation and usage.

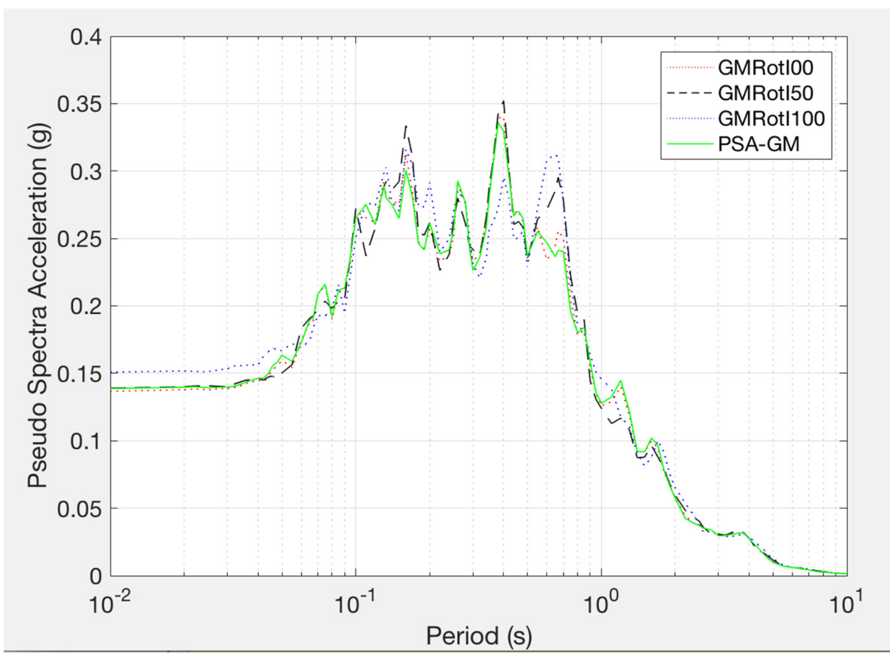

Figure 1.2 **Comparison between GMRotIxx spectra and geometric mean spectra. Ground motions from LA-Pico and Sentous, 1994 Northridge, California, earthquake.**

2 Intensity Measure Computation

This chapter describes the procedures used to compute GMRotI50 and RotDxx ground-motion intensity measures. The procedures are intended for use with two-component records from the PEER ground-motion database, which has already been instrument-corrected (as needed), and low- and high-pass filtered. Sections in this chapter describe required signal processing, the intensity measure computations, and verification.

2.1 SIGNAL PROCESSING

Because acceleration time series in the NGA-West2 database are instrument-corrected and filtered, the only required signal processing pertains to accurate identification of peak oscillator response given the signal time step.

Figure 2.1(a) illustrates the problem with peak identification; the figure shows a short window in time of an acceleration time series at its native resolution with time step dt = 0.01 sec (100 samples per sec, sps) and a decimated version of the record with dt = 0.05 sec (20 sps). There are two notable differences between the 100 and 20 sps records: (1) the peak of the decimated version is lower than that of the native record, which demonstrates that had the resolution of the data acquisition unit been 0.05 sec or higher, the peaks would be mis-identified with simple linear-interpolation between observations; and (2) some high-frequency features of the record, like the undulation in the negative peak near 12.9 sec, are lost in the decimation.

To address the peak identification problem, Sinc interpolation is applied [Shannon 1998; Wikipedia, 2017]. Sinc interpolation is a method of obtaining an acceleration time series at a higher sample rate than the input time series by resampling the input acceleration under the condition that the resampled time series has no energy above the Nyquist frequency (f_{Nyq}) of the original record. The interpolation factor (IF) is defined as the factor by which the original time step is divided to provide the desired level of resolution. Sinc interpolation requires that IF is a power of 2. Figure 2.1(a) shows a Sinc-interpolated version of the 20 sps record with IF = 8. It captures the majority of peaks better than the decimated version of record with 20 sps, but it does not capture the high-frequency features of the record seen in the 100 sps signal.

One of the principal benefits of Sinc interpolation is for the computation of oscillator responses. Figure 2.1(b) shows the response for a 0.1-sec oscillator with 5% of critical damping near the time of its peak response. Responses are shown for the 20 sps signal with IF = 1, 2, 4, 8, and 16. Not only do the responses obtained with the sinc-interpolated records with IF $\geq$ 4 capture the peak reasonably consistently, they provide a result nearly matching the PSA that would have been obtained using the 100 sps record. This demonstrates that Sinc-interpolation improves the resolution of oscillator responses relative to the original 20 sps records, and that there is a saturation effect whereby beyond some limiting value of IF, further interpolation is not helpful.

Because an acceleration time series cannot have energy above f_{Nyq}, the time series of oscillator responses for oscillators with natural frequencies above f_{Nyq} should be very similar to one with an oscillator frequency of f_{Nyq}.(The only reason for differences would be the effect of energy at lower frequencies than oscillator frequency on the responses.) As a result of these considerations, when selecting IF, it is sensible to seek to resolve oscillator responses only up to a maximum frequency of f_{Nyq}.

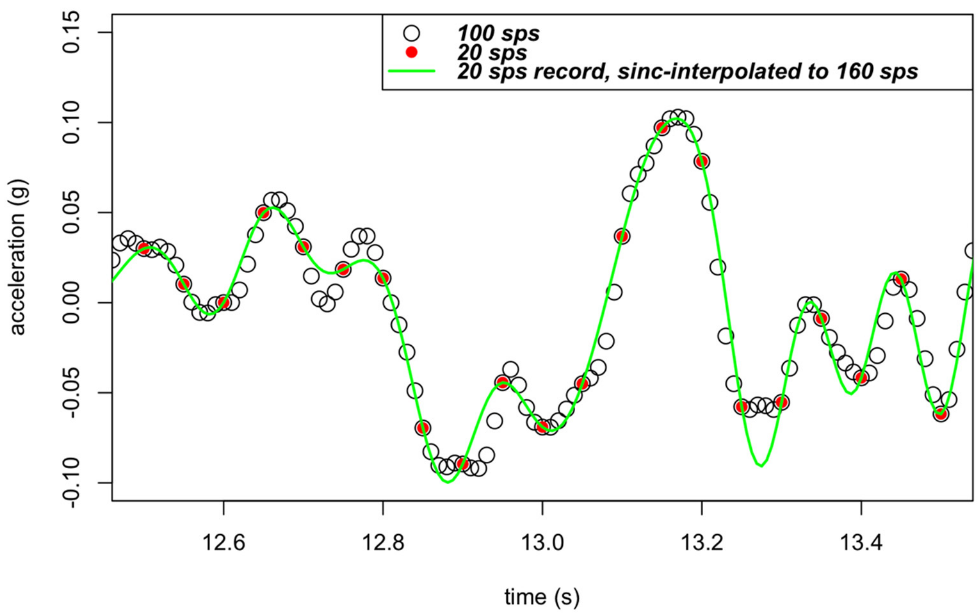

Figure 2.1(a) Original time series with 100 samples per sec (sps), decimated version of original with 20 sps, and Sinc-interpolated time series of 20 sps record using IF = 8. All time series are shown over a narrow time interval encompassing the peak acceleration. Original acceleration time series is the first horizontal component recorded at LA–Pico and Sentous in the 1994 Northridge, California, earthquake (NGA-West2 RSN 1000).

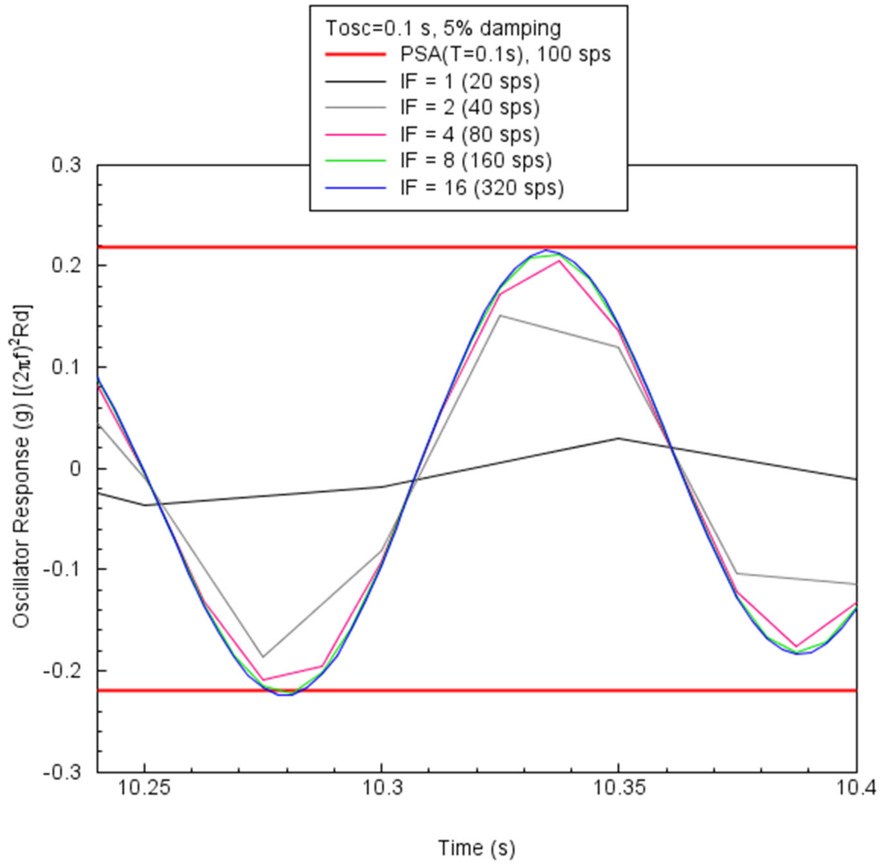

Figure 2.1(b) **Oscillator responses at 0.1 s for 20 sps record sinc-interpolated with IF = 1, 2, 4, 8, and 16. PSA shown for the original 100 sps record. Rd = relative displacement of oscillator.**

A common rule of thumb is to use 10 sample points for the response of an oscillator of period T (e.g., Nigam and Jennings [1969]; Alford, et al. [1974]; and Ebeling, et al. [1997]). To resolve oscillator responses to the maximum frequency of f_{Nyq} would then require a new sample rate dt' of

$$dt' = \frac{T_{Nyq}}{10} = \frac{1}{10 f_{Nyq}} \tag{2.1}$$

Because $f_{Nyq} = 1/(2dt)$, the time step becomes

$$dt' = \frac{dt}{5} \tag{2.2}$$

and the interpolation factor is then,

$$\text{IF} = \frac{dt}{dt'} = 5 \tag{2.3}$$

However, because IF must be a power of two, the next highest power of two beyond 5 is recommended, which is 8.

The influence of IF on oscillator responses for a wide period range was evaluated using the example time series from Figure 2.1. Figure 2.2 shows the resulting pseudo-spectral accelerations (PSA) obtained using the 20 sps record with IF varied from 1 to 64. The plot shows no clear difference in PSA. Figure 2.3 magnifies the results from Figure 2.2 for a period range of 0.01 sec to 0.2 sec, and shows no clear difference in PSA when IF is greater than 4. Figure 2.4 shows the ratio of PSA for different IF values relative to PSA for IF = 8. Figure 2.4 shows that sensitivity of PSA to IF disappears for IF ≥ 8. This confirms the hypothesis presented earlier: that the maximum frequency that can be reasonably resolved is f_{Nyq}, which in turn justifies no greater level of interpolation than 8.

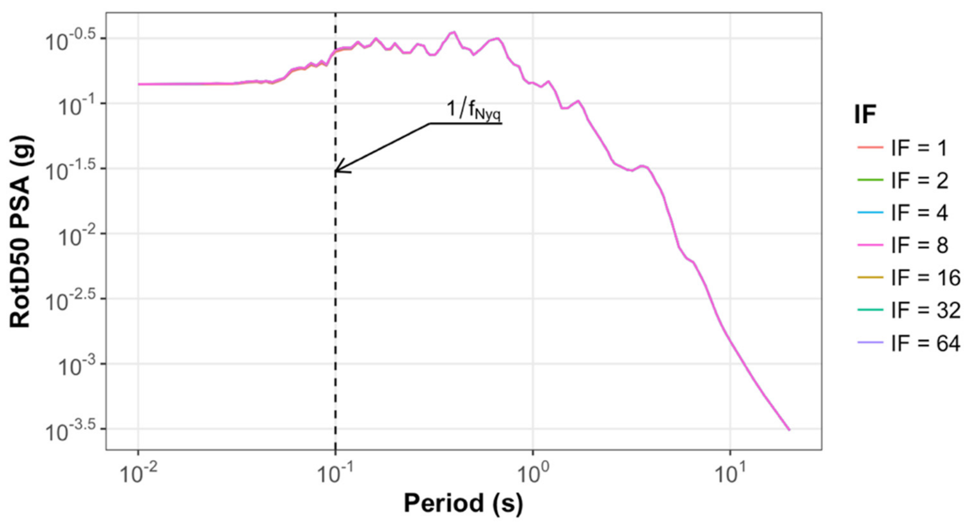

Figure 2.2 RotD50 PSA using decimated record in Figure 2.1 at time step 0.05 sec with different interpolation factors.

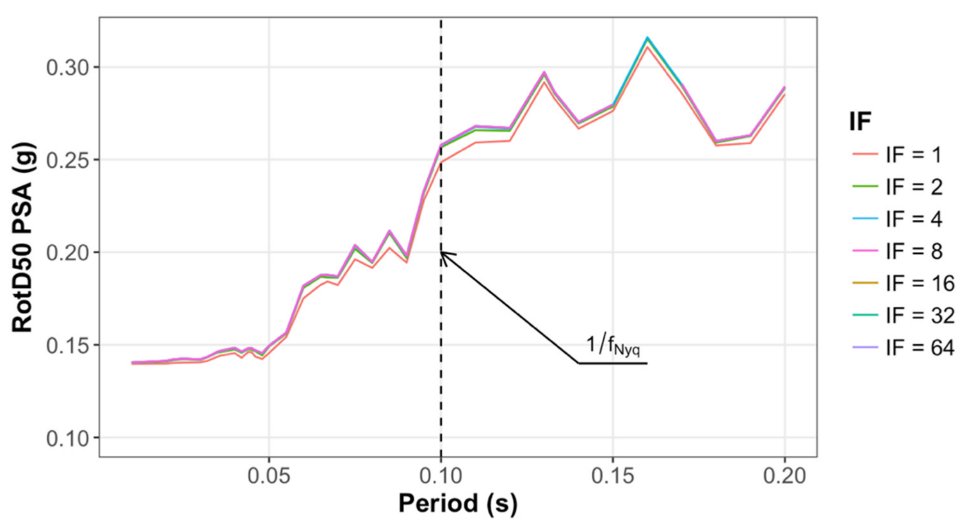

Figure 2.3 Magnified plot of Figure 2.2 from 0.01 to 0.2 sec.

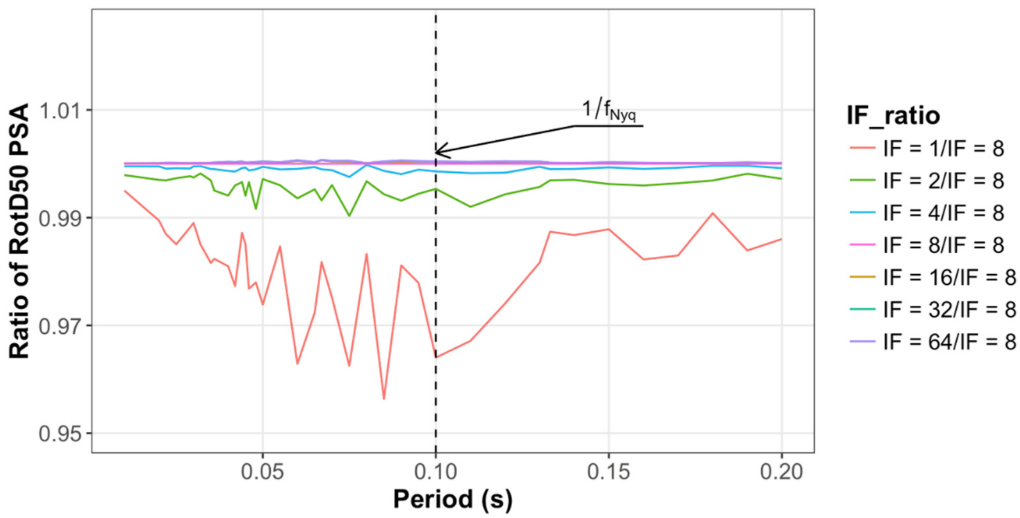

Figure 2.4 Ratio of RotD50 PSA referenced to the results with interpolation factor IF = 8.

Returning now to the notation of the RCTC code, following application of the Sinc-interpolation procedures, the modified time series (with time step dt' are denoted $a_{1_{in}}$ and $a_{2_{in}}$). The interpolation scheme greatly increases the number of data points in both the ground accelerations used to compute oscillator responses and the oscillator displacement time series (denoted $Rd_{1_{in}}$ and $Rd_{2_{in}}$). To save memory and speed up calculation, a subset selection function is applied to oscillator displacement time series $Rd_{1_{in}}$ and $Rd_{2_{in}}$, where only data points with amplitudes greater than or equal to a threshold value are retained. The threshold is defined by:

$$\text{level} = c \times \min\left\{\max\left[\left|Rd_{1_{in}}(t)\right|\right], \max\left[\left|Rd_{2_{in}}(t)\right|\right]\right\} \tag{2.4}$$

where c is a fraction that defaults to 0.7, and $\max\left[\left|Rd_{1_{in}}(t)\right|\right]$ and $\max\left[\left|Rd_{2_{in}}(t)\right|\right]$ are the peak or trough values for the two components of oscillator response. The portions of the oscillator response time series that are retained for the computations are then identified as:

$$\begin{cases} Rd_{1out}(j) = Rd_{1_{in}}, Rd_{2out}(j) = Rd_{2_{in}} \text{ if } \sqrt{Rd_{1_{in}}{}^2(i) + Rd_{2_{in}}{}^2(i)} \geq \text{level}; \\ \text{skip, otherwise;} \end{cases} \tag{2.5}$$

where $Rd_{1_{out}}$ and $Rd_{2_{out}}$ are the output time series after subset selection.

2.2 DEFINITIONS OF GMROTIxx AND ROTDxx

GMRotIxx is an orientation-independent geometric mean ground motion intensity measure [Boore, et al, 2006], where xx denotes the percentile within the set of geometric means for a given period. NGA-West1 uses GMRotI50. The procedure to compute GMRotI50 is as follows:

1. Apply Sinc interpolation with IF = 64 to obtain $a_{1_{in}}(t)$ and $a_{2_{in}}(t)$;

2. Using $a_{1_{in}}(t)$ and $a_{2_{in}}(t)$, compute 5%-damped oscillator displacements within the usable range of oscillator periods T_i, to obtain $Rd_{1_{in}}\left(T_i;t\right)$ and $Rd_{2_{in}}\left(T_i;t\right)$;

3. Utilize the subset selection function to obtain a subset of oscillator response time series for the subsequent calculations, $Rd_{1_{out}}\left(T_i;t\right)$ and $Rd_{2_{out}}\left(T_i;t\right)$;

4. For applicable time intervals in which both $Rd_{1_{out}}\left(T_i;t\right)$ and $Rd_{2_{out}}\left(T_i;t\right)$ are defined, multiply the two oscillator time series by the rotation matrix,

$$R_k = \begin{bmatrix} \cos\theta_k & \sin\theta_k \\ -\sin\theta_k & \cos\theta_k \end{bmatrix} \tag{2.6}$$

where θ_k, is an angle of rotation relative to the as-recorded accelerometer azimuth of the first horizontal component, taken from 1° to 90° in 1° increments (the 1° increment is fixed in RCTC).

The rotated components can be expressed as:

$$Rd_{ROT1}\left(\theta_k;T_i;t\right) = Rd_{1_{out}}\left(T_i;t\right)\cos(\theta_k) + Rd_{2_{out}}\left(T_i;t\right)\sin(\theta_k) \tag{2.7a}$$

$$Rd_{ROT2}\left(\theta_k;T_i;t\right) = -Rd_{1_{out}}\left(T_i;t\right)\sin(\theta_k) + Rd_{2_{out}}\left(T_i;t\right)\cos(\theta_k) \tag{2.7b}$$

5. Find the maximum amplitude for each rotated oscillator time series for different periods T_i. The two components corresponding to the response spectral acceleration $RotPSA1$ and $RotPSA2$ with rotated angle θ_k can be obtained by multiplying the maximum amplitude of displacement by $\omega_i^2 = 2\pi/T_i$ below:

$$RotPSA1\left(\theta_k;T_i\right) = \omega_i^2 \max\left[Rd_{ROT1}\left(\theta_k;T_i;t\right)\right] \tag{2.8a}$$

$$RotPSA2\left(\theta_k;T_i\right) = \omega_i^2 \max\left[Rd_{ROT2}\left(\theta_k;T_i;t\right)\right] \tag{2.8b}$$

6. Calculate the geometric mean of two components of response spectral acceleration $RotPSA1$ and $RotPSA2$ using Equation (1.1) for the different periods T_i and rotation angles θ_k so that the $GMRotD\left(\theta_k;T_i\right)$ matrix is obtained. The $GMRotD\left(\theta_k;T_i\right)$ matrix has a length (number of rows) to accommodate the realizations of θ_k and a width (number of columns) to accommodate the number of periods T_i. In the TCTC code, there are 90 rows and 111 columns;

7. Compute the penalty function for each rotation angle by the equation:

$$\text{penalty}\left(\theta_k\right) = \frac{1}{N_{per}}\sum_{i=1}^{h}\left(\frac{GMRotD\left(\theta_k;T_i\right)}{GMRotD50\left(T_i\right)} - 1\right)^2 \tag{2.9}$$

where N_{per} is the number of usable oscillator periods and $GMRotD50\left(T_i\right)$ is the median value of $GMRotD\left(\theta_k;T_i\right)$ for each specific oscillator period T_i; [Note that the penalty function in Equation (2.9) is set up for median response, but alternative percentiles could in principal be used];

8. Find the rotation angle $\theta_{\min}$ that minimizes the penalty function; and
9. GMRotI50 is taken as the row of $GMRotD\left(\theta_k;T_i\right)$ for which $\theta = \theta_{\min}$.

RotDxx is a period-dependent, component-based (not geometric mean) measure of ground motion [Boore 2010], which was used in the NGA-West2 project. RotDxx uses the two orthogonal-component horizontal time series to compute ground motions for a range of azimuths. Beginning with the Sinc-interpolated ground motions, the component of ground motion rotated by angle θ_k from two as-recorded azimuths is calculated as:

$$a_{ROT}\left(\theta_k;t\right) = a_{1_{in}}(t)\cos\left(\theta_k\right) + a_{2_{in}}(t)\sin\left(\theta_k\right) \tag{2.10}$$

We consider θ_k from 1° to 180° in 1° increments.

Traditionally, response spectra would be computed from time series $a_{ROT}\left(\theta_k;t\right)$. Instead, we compute response spectral displacements for the $a_{1_{in}}$ and $a_{2_{in}}$ time series, apply subset selection, and then compute oscillator displacements for rotation angle θ_k using the following modified form of Equation (2.10):

$$Rd_{ROT}\left(\theta_k;T_i;t\right) = Rd_{1_{out}}\left(T_i;t\right)\cos(\theta_k) + Rd_{2_{out}}\left(T_i;t\right)\sin(\theta_k) \tag{2.11}$$

Pseudo spectral accelerations are then taken as:

$$RotPSA\left(\theta_k;T_i\right) = \omega_i^2 \max\left[Rd_{ROT}\left(\theta_k;T_i;t\right)\right] \tag{2.12}$$

This operation produces the same result as directly computing spectral displacements from $a_{ROT}\left(\theta_k;t\right)$ because the oscillator response operation is linear[1].

The steps in the computations, as implemented in RCTC are as follow:

1. Apply the same procedure as in steps 1 to 3 of the GMRotI50 calculation to obtain $Rd_{1_{out}}\left(T_i;t\right)$ and $Rd_{2_{out}}\left(T_i;t\right)$;
2. Apply Equation (2.11) to obtain oscillator displacements $Rd_{ROT}\left(\theta_k;T_i;t\right)$ for θ_k = 1° to 180° in 1° increments., as well as pseudo-spectral accelerations $RotPSA\left(\theta_k;T_i\right)$;
3. Form a *RotPSA* matrix with a length (number of rows) to accommodate the realizations of θ_k and a width (number of columns) to accommodate the number of periods T_i. The RCTC code uses 180 rows and 111 columns;
4. Take RotD00, RotD50, and RotD100 as the minimum, median, and maximum values in the *RotPSA* matrix for each oscillator period T_i.

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[1] *http://www.daveboore.com/daves_notes/notes_on_revisions_to_smc2psa_rot_gmrot_v1.0.pdf.*

Note the Step 2 in this procedure is similar to Step 4 in the GMRotI50 calculation. In particular, the first 90 rows of *RotPSA* are the same as *RotPSA*1, and rows 91–180 in *RotPSA* are the same as *RotPSA*2. This occurs because for 90° < θ_k < 180°, $Rd_{1_{out}}\left(T_i;t\right)\cos(\theta_k)+Rd_{2_{out}}\left(T_i;t\right)\sin(\theta_k) = -Rd_{1_{out}}\left(T_i;t\right)\sin(\theta_k-\pi/2)+Rd_{2_{out}}\left(T_i;t\right)\cos(\theta_k-\pi/2)$, where the left side is from Equation (2.11), and the right side is what would be provided by Equation (2.7b) for 90° < θ_k < 180°. In RCTC, we take advantage of this result and use the intermediate values from the calculation of GMRotI50 to compute RotDxx.

2.3 VERIFICATION

We verified the RCTC code against a Fortran code prepared by the fourth author using 500 pairs of horizontal ground motions for 111 different oscillator periods from 0.01–20 sec. We used c = 0.7 for these computations; see Equation (2.4). The ground motions were randomly selected from the NGA-West2 database. The misfit between the two codes was quantified by the relative difference, which is calculated as:

$$\varepsilon=\left|\frac{V_{\mathrm{ref}}-V_{\mathrm{trial}}}{V_{\mathrm{ref}}}\right|\times 100\% \qquad (2.13)$$

where V_{ref} is the reference value (for the present calculation, this is the result returned by the Fortran code), and V_{trial} is the trail value from RCTC being assessed in the verification exercise. The median and maximum relative differences for both GMRotI50 and RotDxx are shown in Table 2.1. The differences are small, and we consider the RCTC implementation to be verified.

Next, we investigate the sensitivity of results to scalar c, which is used in Equation (2.4) to set subset size. If c were set to zero, the entire time series will be used in the component combination calculations. This is computationally intensive due to the large number of time steps introduced by Sinc interpolation but provides the most rigorous point of comparison. We consider scalars c = 0, 0.5, and 0.7. Table 2.2 shows error terms computed taking the reference as 0.5 and the trial as 0.7, and the reference as 0 and trial as 0.5. We use 496 pairs of randomly selected time series for the 0.5 to 0.7 comparison and 190 pairs of time series for the 0 to 0.5 comparison.

The use of c = 0.5 produces error only for RotD00 and exact results otherwise. Use of c = 0.7 gives very small errors for RotD50 and RotD100 but larger errors otherwise. Fraction c = 0.7 (default value in RCTC) is recommended if the user is mainly interested in RotD50 and RotD100, while fraction c = 0.5 is recommended if GMRotI50 is also of interest. Calculation of RotD00 requires setting fraction c = 0.

Table 2.1 Relative differences between Fortran and R codes for intensity measured computations using 500 randomly selected ground motions.

	GMRotI50	RotD00	RotD50	RotD100
Maximum ε (500 motions, 111 periods)	2.2×10^{-3}%	4.1×10^{-3}%	1.8×10^{-3}%	2.0×10^{-5}%
Median ε (500 motions, 111 periods)	8.2×10^{-6}%	1.0×10^{-5}%	9.0×10^{-6}%	9.3×10^{-8}%
Maximum ε (500 motions, usable periods)	7.2×10^{-5}%	1.1×10^{-4}%	8.5×10^{-5}%	7.9×10^{-7}%
Median ε (500 motions, usable periods)	0%	0%	0%	0%

Table 2.2 Comparison of results in the form of error terms for alternate values of scaling parameter c = 0, 0.5, and 0.7

	GMRotI50	RotD00	RotD50	RotD100
Maximum ε (0.5 vs 0.7; 496 motions, 111 periods)	47.2%	69.6%	1.65×10^{-11}%	1.66×10^{-13}%
Median ε (0.5 vs 0.7; 496 motions, 111 periods)	0%	0%	0%	0%
Maximum ε (0 vs 0.5; 190 motions, 111 periods)	0%	51%	0%	0%
Median ε (0 vs 0.5; 190 motions, 111 periods)	0%	0%	0%	0%

3 Input and Output files of RCTC

3.1 INPUT FILES

RCTC can accept input time series formatted in different ways. The default is the PEER-formatted paired horizontal-component acceleration time series data downloaded from the NGA-West2 database, each component of which has an ".AT2" extension. As shown in Table 3.1, other available input data formats include COSMOS, SMC, and a simple single column of data with a time step provided in the first row of the file (the examples of each format are showed by screenshots in Appendix A). PEER-formatted data matches that of NGA-West2 data, but is given its own column in Table 3.1 due to the present lack of a flatfile implemented into RCTC for non-NGA-West2 PEER data.

To use RCTC, a folder named *Inputdata* needs to be created. All data should be placed into this folder. Any number of time series pairs can be used. An example is showed by screen shot in Figure 3.1. In the case of PEER-formatted data for the NGA-West2 project (for which a flatfile is currently available), the file naming protocol is RSNxxx_textstring1_textstring2.AT2 (or RSNxxx_textstring1.AT2), with two files per recording (one for each horizontal component). RSN indicates record sequence number, where xxx is the number. RCTC reads the RSN, which allows the record to be located in a flatfile (e.g., from NGA-West2) and to obtain usable frequencies. RCTC then cross-checks the subsequent text strings (separated by underscores _) against azimuths in the flatfile, allowing the azimuth associated with the file to be identified.

Ground-motion data generated as part of the NGA-Sub and NGA-East projects also follows the PEER format. Accordingly, the RSN in the file names are used to pair two horizontal-component ground motions. However, because flatfiles for these data are not implemented in RCTC, azimuths and usable frequencies cannot be recognized automatically. We expect to add these flatfiles to RCTC in the future when they become public; in the meantime, ground motions from these projects can be analyzed with some additional data entry in the same manner as non-PEER data, which is described below.

Table 3.1 The summary information for each of the input data formats.

	NGA-West2	PEER formatted	COSMOS	SMC	Single column data
Resource	NGA-West2 database	NGA-Sub, NGA-East	Strong-Motion Virtual Data Center	USGS	Users collected
Need to change filenames?	No, two separate files, one for each horizontal component	No, two separate files, one for each horizontal component	Yes, one file contains all components	Yes, two separate files, one for each horizontal component	Yes, two separate files, one for each horizontal component
Time step	Read from headers	Read from headers	Read from headers	Read from headers	Read from data
Azimuth angle	Read from flatfile	Users defined, Otherwise zero	User defined, Otherwise zero	User defined, Otherwise zero	User defined, Otherwise zero
Usable periods	Read from flatfile	Users defined, otherwise 0(min) and 10s(max) are used	Users defined, otherwise 0(min) and 10s(max) are used	Users defined, otherwise 0(min) and 10s(max) are used	Users defined, otherwise 0(min) and 10s(max) are used
Unit of input acceleration	*g*	*g*	cm/sec^2	cm/sec^2	*g*

For non-PEER data, the file names uploaded to the *Inputdata* folder should contain station identifiers so that the code can identify paired components from the filenames. This will generally require the re-naming of files. These station identifiers can be text or numerical strings. This file re-naming enables RCTC to identify paired horizontal component files (two per recording, except for COSMOS format). This can be undertaken for individual files by renaming filenames as xx_xx_xx, where xx represents station name, sensor number, and component index, respectively, with text strings separated by underscores. For instance, LA-BH_1_H1 and LA-BH_2_H1 are two recordings by the first horizontal component from station LA-BH. The former was recorded by sensor 1 and the later by sensor 2. This occurs when two sensors are installed at the same station in a vertical array. For the more typical case of a single sensor at a given station, no sensor number need be specified. For COSMOS format in which all components of ground motions are included in one file, then RCTC will only read one file for all calculations instead of two paired files. In this situation, the filenames can be LA-BH_1_H12 and LA-BH_1_H12 for two recordings from station LA-BH. Component index "H12" indicates that both horizontal components are contained in the file.

For non-NGA-West2 data, including NGA-East and NGA-Sub data, azimuths and usable periods are specified as arguments in the *IMplot* function in RCTC. This function is described further in Section 4.2. Time steps of all these data can be read from headers or data of the data file; see Table 3.1. Except for COSMOS (since it contains everything in one file), vertical motion data files should not be loaded into the *Inputdata* folder.

For relatively automated processing of large amounts of files, native file names can be converted to standardized file names using the *nametransfer* function in the RCTC package, as described further in Section 4.2.

Figure 3.1 shows an example of *Inputdata* folder, which is created and placed in the folder of *test* on the desktop. There are three pairs of horizontal component ground motions downloaded from NGA-West2 database are saved in *Inputdata* folder.

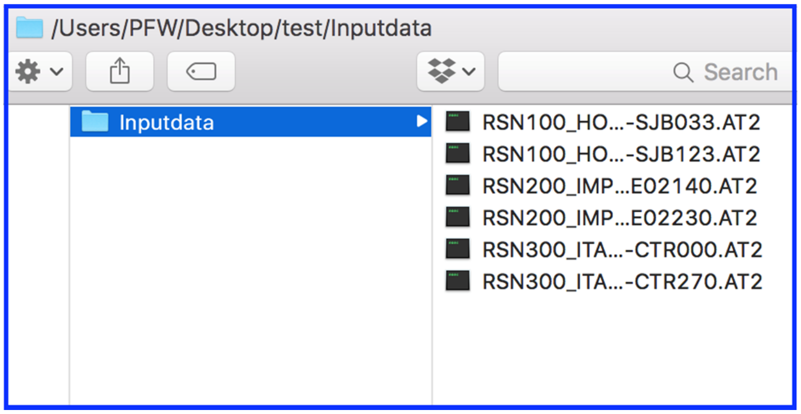

Figure 3.1 Screen shot showing *Inputdata* folder.

3.2 OUTPUT FILES

RCTC has two folders containing output files: *Outputdata* and *Outputplot*. These two folders will be generated in the same directory as the *Inputdata* folder when running the function *IMplot* in the RCTC package. The *Outputdata* folder contains two csv files for each horizontal ground motion pair and a summary file. One csv file is named as "xx_dep.csv", and another is named as "xx_indep.csv" (xx stands for RSN for NGA-West2 data or station name and sensor number for others). The parameters in these two files are explained in Table A.1 of the Appendix B. Figure 3.2 shows the resultant files after running the function of *IMplot.*

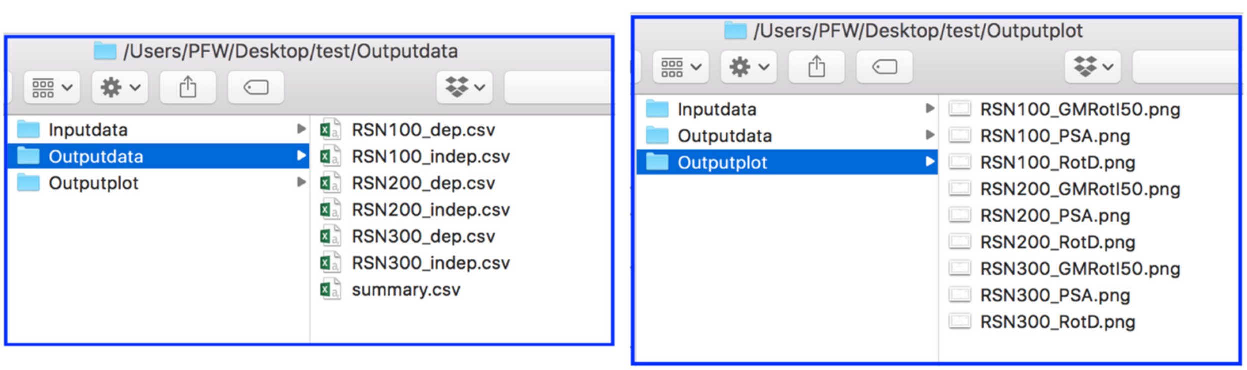

Figure 3.2 Screen shot showing generated *Outputdata* and *Outputplot* folders. The spreadsheets in the *Outputdata* folder and the figures in the *Outputplot* folder are obtained by running the *IMplot* function.

The summary file includes RSN, EQID, maximum and minimum usable frequencies, and RotD50 values for PGA, PGV, PGD, and pseudo spectral ordinates. These median outputs can be changed to other percentiles (00 or 100) by changing the input argument *combine_index* in the function *IMplot*. This function is also illustrated in Section 4.2.

Outputplot also contains pseudo-spectral acceleration versus periods plots using GMRotI50, PSA for two as-recorded horizontal components, and RotDxx for xx = 00, 50, and 100.

4 Installing and Using RCTC

4.1 INSTALLATION

The required steps to install RCTC are presented below and are accompanied by screen shots.

Mac users:

1. Make sure the required packages, *Rcpp* and *pracma*, are installed. They can be installed by executing the following command in R:

   install.packages(c('Rcpp', 'pracma'))

2. Download and install *Xcode* in App Store.
3. Change directory in Terminal to the folder where the main RCTC file was saved following download (RCTC_0.1.0.tar.gz file). Execute the following command:

   R CMD INSTALL RCTC_0.1.0.tar.gz

   This will install the RCTC package. Then users can type and run the following command to load and use RCTC library:

   library(RCTC)

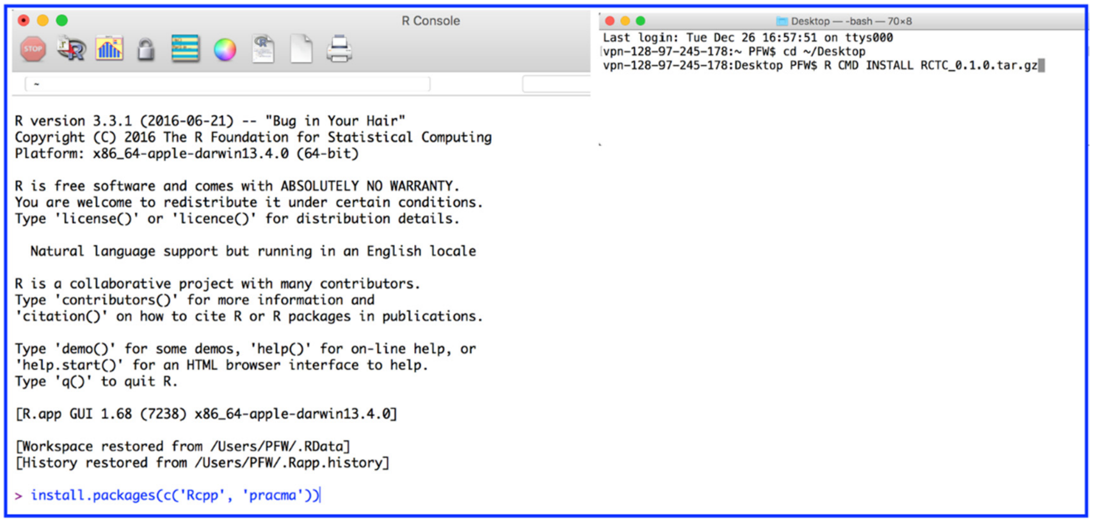

Figure 4.1 **Screen shot showing installing Rcpp and pracma packages in R console, and navigating directory and installing RCTC in Terminal.**

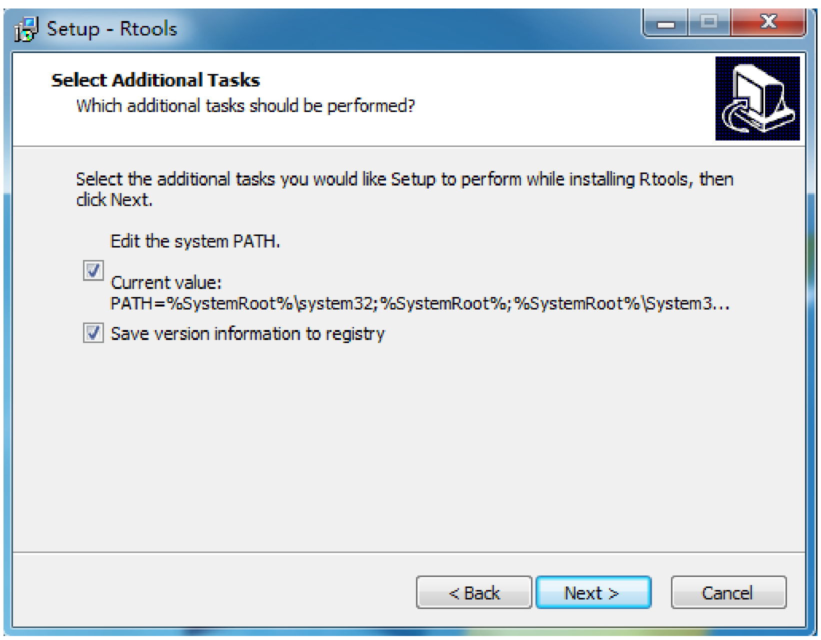

Figure 4.2 **Screen shot showing adding path of Rtools into system environment path during installation by selecting checkbox.**

In Figure 4.1, the left side of the screen shows the R console, and the right side shows the Terminal. In the Terminal, the first command navigates to the directory containing the RCTC file (the desktop in this case). Subsequent lines in the Terminal execute the command to install RCTC.

Windows users:

1. Make sure the required packages, *Rcpp* and *pracma*, are installed. The procedure to install these packages is the same as that in Mac.
2. Download and install *Rtools*. The link to download *Rtools* is here: *https://cran.r-project.org/bin/windows/Rtools/*. Select the version compatible with the local version of R. For example, download Rtools34.exe if you are using R 3.4.x. Select the checkbox for adding the path into the system; see Figure 4.2.
3. Add the file path for R into the system environment path, which can be done using Windows CMD. An example for adding the R path is shown in Figure 4.3. Note the actual path of R will vary and is user-specified. For instance, the path of R in Figure 4.3 is C:\Program Files\R\R-3.4.3\bin.

   If the path for *Rtools* was not established during step 2 showing in Figure 4.2, this path can be added using the same procedure shown in Figure 4.3. The applicable paths from the root directory are: C:\Rtools\bin; C:\Rtools\perl\bin; C:\Rtools\MinGW\bin. Actual paths should be modified to reflect the location of *Rtools*.
4. Go to Windows CMD, and navigate to the folder where the main RCTC file was saved following download (RCTC_0.1.0.tar.gz). Execute the following command:

   R CMD INSTALL RCTC_0.1.0.tar.gz

   This will install the RCTC package so that it can be used by issuing the following command:

   library(RCTC)

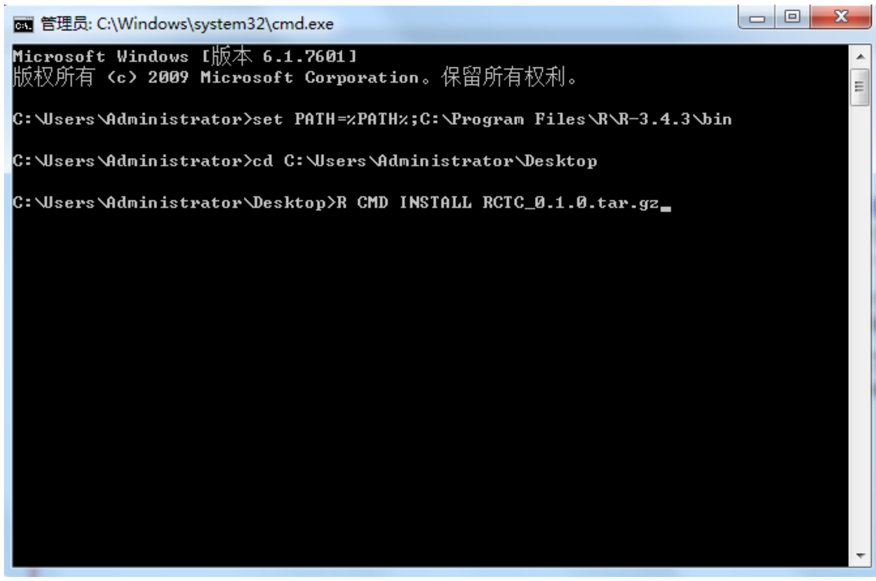

Figure 4.3 Screen shot showing Windows CMD and three commands for installing RCTC.

Figure 4.3 shows three commands. The first command adds R into the system environment. The second command navigates to the directory where the RCTC downloaded file is saved. The last command installs the RCTC package.

4.2 IMPLEMENTATION

There are seven functions in the RCTC package. If data are PEER formatted, only the *IMplot* function is needed. For other formats, if only response spectra are needed, the required functions are *IMplot* and, if files re-naming is to be automated, *nametransfer*. An additional two functions are provided for users interested in outputting Sinc-interpolated acceleration time series and/or spectral displacements. Details of the four functions are given below.

IMplot: This is the main function to compute response spectra and generate spreadsheets and plots. There are nine input arguments, as follows:

1. inputpath specifies the location of the *Inputdata* folder where all data are saved;
2. datatype is a string, containing options "ngaw2", "nga", "cosmos", "smc", or "timeseries". "ngaw2" represents the downloaded data from NGA-West2 database, while "nga" stands for the PEER formatted NGA-Sub and NGA-East data. The reason we distinguish them is that flatfiles for NGA-Sub and NGA-East data are not presently included in the RCTC package, and their azimuths and usable frequencies cannot be recognized by RCTC automatically. "cosmos" and "smc" are data formats from Strong-Motion Virtual Data Center and USGS, respectively. "timeseries" consists of a one column array. The array has the time step in the first row of the column and acceleration values below. The units of each data format are

summarized in Table 3.1. Data not in the right units should be converted before using RCTC. Data that are not downloaded from PEER should have files names adjusted as described in Section 3.1, which can be automated by using the *nametransfer* function. The operation of this function is described further below. If an error occurs that is related to data format, the easiest remedy is to format the data as a column vector ("timeseries" option);

3. tmax4penalty_in and tmin4penalty_in are the maximum and minimum periods used for calculation of the penalty function [Equation (2.9)] (default values are 10 and 0, respectively). The specification of these variables is only needed if the maximum and minimum usable frequencies for the ground motion are not available from NGA-West2 flatfile. Their values will be obtained from NGA-West2 flatfile automatically if the input data are from NGA-West2 database;
4. combine_index is used to specify the value of xx for RotDxx. 00 is used for RotD00, 50 is for RotD50, and 100 is for RotD100. The default is 50;
5. ang1 is the as-recorded azimuth angle of the first horizontal component. It can be obtained automatically from NGA-West2 flatfile if the input data are downloaded from NGA-West2 database. Otherwise, users need to provide this angle. The second component is assumed to be 90° clockwise from ang1. If ang1 is not specified, a default value of zero is used;
6. damping is the fraction of critical damping for which the oscillator response is computed (expressed as decimal). The default is 0.05;
7. fraction is the scalar c (Section 2.1) used to select the subset size. The default is 0.7 and guidance on selection is provided in Section 2.3; and
8. Interpolation_factor specifies the degree of interpolation, as described in Section 2.1. The default is "auto", meaning the desired value of interpolation factor will be computed automatically. Users can also specify a value, which should be a power of 2.

An example script could be:

IMplot(inputpath = "/Users/PFW/Desktop/test/Inputdata", datatype = "ngaw2", tmax4penalty_in = 10, tmin4penalty_in = 0, combine_index = 50, ang1 = 0, damping = 0.05, fraction = 0.7, Interpolation_factor = "auto")

nametransfer: This function changes filenames into standard forms that can be read by RCTC. This operation is not required for the "ngaw2" and "nga" data type (data downloaded from PEER) or if users manually rename data files as instructed in Section 3.1. There are five input arguments:

1. filedir1 and filedir2 are file paths (directory + filenames) of the first and the second horizontal component of ground motions;
2. stationname is the station name;
3. sn is the sensor number. If there is more than one sensor at the station, users should enter separate sns for each;

4. <u>outputdir</u> is the directory where renamed files are saved. It can be the *Inputdata* folder.

An example application of the *nametransfer* function is illustrated in Figure 4.4. In this example, there two sets of three-component time series, from one event and two different sensors at the same station. There are two horizontal components and one vertical component for each sensor. They are placed in *'/Users/PFW/Desktop/RCTC'* directory. The file *20160101231556A1* and *20160101231556A2* are paired horizontal ground motions for the first sensor, *20160101231556A4* and *20160101231556A5* are paired horizontal ground motions for the second sensor. File *20160101231556A3* and *20160101231556A6* are their corresponding vertical ground motions. *Inputdata* folder is the destination directory for renamed files. The scripts in R for using *nametransfer* to change filenames and place the renamed files into *Inputdata* are as follows:

nametransfer(filedir1 = '/Users/PFW/Desktop/RCTC/20160101231556A1', filedir2 = '/Users/PFW/Desktop/RCTC/20160101231556A2', stationname = 'LA-BH', sn = 1, outputdir = '/Users/PFW/Desktop/RCTC/Inputdata')

nametransfer(filedir1 = '/Users/PFW/Desktop/RCTC/20160101231556A4', filedir2 = '/Users/PFW/Desktop/RCTC/20160101231556A5', stationname = 'LA-BH', sn = 2, outputdir = '/Users/PFW/Desktop/RCTC/Inputdata')

Figure 4.5 shows the files in the *Inputdata* folder after execution of the above commands.

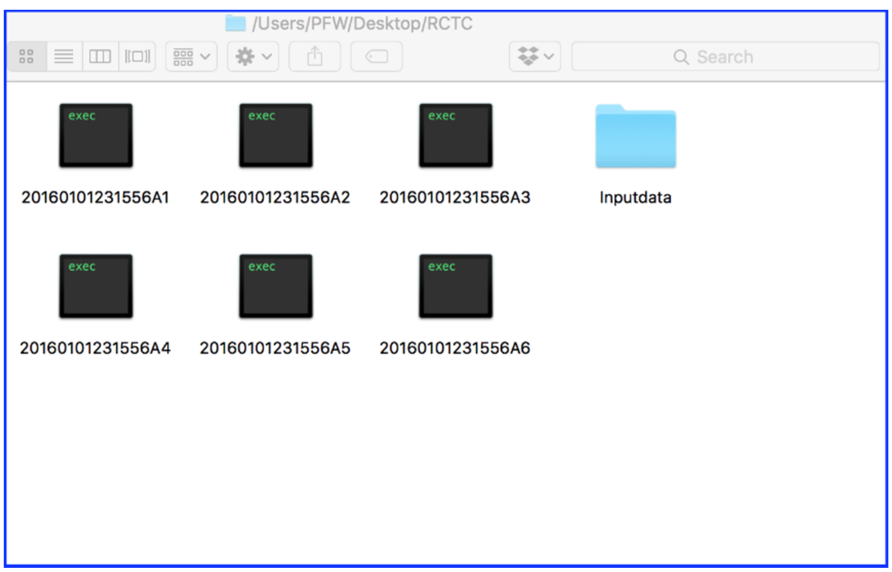

Figure 4.4 Screen shot showing time series files that will be renamed and moved to the *Inputdata* folder.

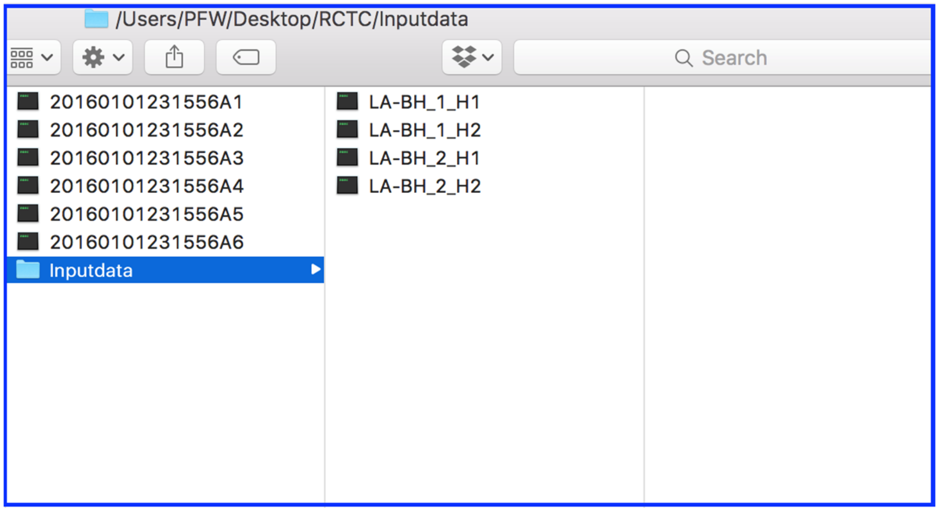

Figure 4.5 **Screen shot showing the files that have been renamed and placed into the *Inputdata* folder by the *nametransfer* function**

Note that if the file names of COSMOS format data need to be renamed (one file contains all ground-motion components), just set *filedir1* and *filedir2* the same file path, then RCTC will standardize their file names.

The following functions are subroutines called by the main function *IMplot*. Users do not need to use these directly unless spectral displacements or Sinc-interpolation acceleration time series are desired as outputs.

PS_cal_cpp: This function computes pseudo-spectral accelerations and spectral displacements. There are five input arguments:

1. data is an acceleration time series array;
2. period_t is an array of oscillator periods;
3. damping is damping ratio, expressed as a decimal (default value is 0.05);
4. time_dt is the time step in seconds; and
5. type_return is a dummy variable controlling output type, set to either 1 or 2. If 1 is selected, it returns a two-row matrix with actual spectral acceleration in the first row and PSA in the second row. If 2 is selected, it returns a row vector of spectral displacements.

Interpft: This function applies Sinc interpolation to reduce the time step and returns a time series with more data points than in data. This function has two inputs:

1. data is as defined above; and
2. interpolation_factor specifies the degree of interpolation and should be a power of two.

Please contact github (*https://github.com/wltcwpf/RCTC/issues*) with any issues or suggestions.

5 Summary and Conclusions

The standard of practice for representing the horizontal amplitude of ground motions recognizes the range that occurs with changing azimuths. These variable amplitudes can be generically denoted as RotDxx, where xx represents a percentile ranging from null to 100%. This definition was introduced by Boore [2010] and adopted by the NGA-West2 project [Bozorgnia et al. 2014]. Software for computing RotDxx was originally developed by the fourth author as a Fortran code. The purpose of the work described in this report was to summarize in one document the complete analysis procedure, including the computation of response spectral ordinates using Sinc-interpolation and the RotDxx ordinates, and to introduce an open-source package presented in R and referred to as *Rotated Combination of Two-Component* ground motions (RCTC).

RCTC computes pseudo-spectral acceleration for each horizontal component, RotDxx for xx = 0, 50, 100%, GMRotI50, and other period-independent variables by inputting two horizontal components of ground motion, their azimuths, and their time step. It implements the Sinc-interpolation and subset selection algorithms to recover accurate peak quantities from digital data. The code was verified with the original Fortran code for RotDxx calculation developed by the fourth author. The instructions for installation and usage of RCTC are given in Chapter 4 of this report.

The package and report can be downloaded from PEER website. Updates of RCTC in the future are planned when flatfiles for the NGA-East and NGA-Sub projects are publically released.

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Available at: https://en.wikipedia.org/wiki/Lanczos_resampling

Appendix A Screenshots of each Data Format

```
PEER NGA STRONG MOTION DATABASE RECORD
Hollister-03, 11/28/1974, San Juan Bautista 24 Polk St, 33
ACCELERATION TIME SERIES IN UNITS OF G
NPTS=   4151, DT=   .0050 SEC,
  -.1309151E-03  -.1313470E-03  -.1309291E-03  -.1280221E-03  -.1218626E-03
  -.1112233E-03  -.9688324E-04  -.8040297E-04  -.6584598E-04  -.5769174E-04
  -.6125633E-04  -.7773564E-04  -.1058095E-03  -.1411642E-03  -.1795012E-03
  -.2131026E-03  -.2334854E-03  -.2318410E-03  -.2051317E-03  -.1532015E-03
  -.8439767E-04  -.1332989E-04   .4384745E-04   .7082000E-04   .5116798E-04
  -.2087277E-04  -.1305838E-03  -.2578329E-03  -.3914530E-03  -.5187097E-03
  -.6301037E-03  -.7180235E-03  -.7763969E-03  -.7955394E-03  -.7701292E-03
  -.6967446E-03  -.5735030E-03  -.4077535E-03  -.2020855E-03   .3899609E-04
   .3051981E-03   .6026969E-03   .9448701E-03   .1327290E-02   .1713638E-02
   .2032483E-02   .2178580E-02   .2064897E-02   .1704283E-02   .1208138E-02
   .6541764E-03   .1045330E-03  -.4061120E-03  -.8334591E-03  -.1106582E-02
  -.1162690E-02  -.1013148E-02  -.7448757E-03  -.4238086E-03  -.9708800E-04
   .1881556E-03   .3973265E-03   .5123768E-03   .5183891E-03   .4001477E-03
   .1549795E-03  -.1984953E-03  -.6477999E-03  -.1159147E-02  -.1673189E-02
  -.2113738E-02  -.2387298E-02  -.2439285E-02  -.2232108E-02  -.1721121E-02
  -.9204231E-03   .1094053E-03   .1211748E-02   .2254512E-02   .3107221E-02
```

Figure A.1 Screen shot of acceleration time series in PEER format.

```
0.005
-0.0001309151
-0.000131347
-0.0001309291
-0.0001280221
-0.0001218626
-0.0001112233
-9.688324e-05
-8.040297e-05
-6.584598e-05
-5.769174e-05
-6.125633e-05
-7.773564e-05
-0.0001058095
-0.0001411642
-0.0001795012
-0.0002131026
```

Figure A.2 Screen shot of acceleration time series formatted as a vector with time step in first row ('timeseries' option). Units are in *g*.

```
CORRECTED ACCELEROGRAM   24207-S2485-94021.02       CHAN  1: 194 DEG     FROM
UNCORRECTED ACCELEROGRAM DATA             PROCESSED: 02/04/94, CDMG QN94A207 TT
NORTHRIDGE EARTHQUAKE
JANUARY 17, 1994 04:31 PST            (ORIGIN(CIT): 01/17/94, 12:30:55.4 GMT)
24207-S2485-94021.02             TRIGGER TIME: 01/17/94, 12:31:00.5 UTC
STATION NO. 24207   34.334N, 118.396W     SMA-1  S/N 2485
PACOIMA DAM - UPPER LEFT ABUTMENT
CHAN  1: 194 DEG
NORTHRIDGE EARTHQUAKE     JANUARY 17, 1994 04:31 PST
HYPOCENTER(CIT): 34.215N, 118.538W, H=18KM. ML=6.6, MW=6.7(CIT); MS=6.7(NEIC)
INSTR PERIOD =  .0380 SEC,  DAMPING =  .593,  SENSITIVITY = 1.69 CM/G.
                        RECORD LENGTH = 59.980 SEC.
                                     UNCOR MAX  = -1.492 G, AT   4.558 SEC.
RMS ACCEL OF (UNCOR) RECORD  =  .098 G.
ACCELEROGRAM BANDPASS FILTERED WITH RAMPS AT  .080- .160 AND 23.00-25.00 CYC/SEC
  3000 POINTS OF INSTRUMENT- AND BASELINE-CORRECTED ACCEL, VELOC AND DISPL DATA
AT EQUALLY-SPACED INTERVALS OF    .020  SEC.
PEAK ACCELERATION = -1259.910    CM/SEC/SEC  AT    4.540   SEC.
PEAK   VELOCITY   =   104.536      CM/SEC    AT    3.820   SEC.
PEAK DISPLACEMENT =    21.755        CM      AT    3.980   SEC.
INITIAL VELOCITY  =    -1.905   CM/SEC;   INITIAL DISPLACEMENT =    -.242   CM
NORTHRIDGE EARTHQUAKE     JANUARY 17, 1994 04:31 PST

24207-S2485-94021.02      PACOIMA DAM - UPPER LEFT ABUTMENT   CHAN  1: 194 DEG

    1    1    1    3    3    0    1    1    1 2048    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0 19412175   21   33   52    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    01217512175 3000    4   10   10    0    0   52   78   10   10    0 3000
    0 3000    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0
      .038      .593    59.996      .098     1.000     1.690    -1.469     4.558
    26.300    50.000     2.959    50.000     4.928      .092     3.255     9.758
      .000      .000      .000      .000      .000      .000      .000      .000
      .000      .000      .000      .000      .000      .000      .000      .000
      .000      .000      .000      .000      .000      .000      .000      .000
      .000      .000      .000      .000      .000      .000      .000      .000
      .000      .000      .000    98.066      .005    59.996   165.248      .000
      .000    25.000     2.000    59.980      .020      .160      .080      .000
     4.540 -1259.910     3.820   104.536     3.980    21.755    -1.905      .160
    23.000      .020      .020     -.242      .000      .000      .000      .000
      .000      .000      .000      .000      .000      .000      .000      .000
      .000      .000      .000      .000      .000      .000      .000      .000
      .000      .000      .000      .000
 3000 POINTS OF ACCEL DATA EQUALLY SPACED AT  .020 SEC.  (UNITS: CM/SEC/SEC)
    -6.071    -4.268     -.187     2.191     4.308     6.868     4.266    -7.805
   -17.485   -15.148      .235    32.561    53.324    43.635    -1.233   -43.778
   -49.196   -22.468    10.966    36.680    64.949    60.652    12.391   -48.926
   -67.410   -88.817   -93.000   -59.277    37.242    99.735   159.947   207.809
   146.766    25.491  -247.404  -282.731  -169.126   -80.394    62.706   104.051
   125.016   124.566    62.208   -32.097   -63.025   -26.507   -21.342    59.655
```

Figure A.3 **Screen shot of acceleration time series in COSMOS data format as described here[2]. Data downloaded from Strong-Motion Virtual Data Center is formatted in this manner and contains three components of acceleration. Units are cm/sec^2. Data in this format should use files renamed manually or with *nametransfer* function.**

[2] *https://www.strongmotioncenter.org/vdc/cosmos_format_1_20.pdf.*

```
2 CORRECTED ACCELEROGRAM
*
2001
     2016  12  28    0913 SW OF HAWTHORNE, NV
Moment Mag=          Ms=          Ml= 5.50
station = NV:Hawthorne;Ammunition Depot  component= 90
epicentral dist =     28.1       pk acc =  1.02E+2
inst type=ETNA       data source = USGS
*
*
*
    -32768      2016       363         9        13        31       940      1992
         1    -32768    -32768      1108        90        90    -32768        10
     23317    -32768    -32768    -32768    -32768    -32768    -32768    -32768
    -32768    -32768    -32768    -32768    -32768      2001         1     23317
    -32768    -32768    -32768    -32768    -32768    -32768    -32768    -32768
    -32768    -32768    -32768    -32768    -32768    -32768    -32768    -32768
  1.7000000E+38  2.0000000E+02  3.8376999E+01 -1.1889600E+02  8.6000004E+00
  1.7000000E+38  1.7000000E+38  5.5000000E+00  1.7000000E+38  2.6299999E+24
  3.8545250E+01 -1.1865483E+02  1.2700000E+03  1.7000000E+38  1.7000000E+38
  1.7000000E+38  2.8140429E+01  2.2849278E+02  3.3554430E+06  1.7000000E+38
  1.7000000E+38  2.0000000E+02  6.9999999E-01  1.2766847E-03  1.7000000E+38
  1.7000000E+38  1.7000000E+38  1.7000000E+38  2.7225000E+01  1.0247371E+02
  2.7295000E+01 -9.8267296E+01  7.9999998E-02 -2.0000000E+00  4.0000000E+01
  5.0000000E+01  1.7000000E+38  1.7000000E+38  1.7000000E+38  1.7000000E+38
  1.7000000E+38  1.7000000E+38  1.7000000E+38  1.7000000E+38  1.7000000E+38
  1.7000000E+38  1.7000000E+38  1.7000000E+38  1.7000000E+38  1.7000000E+38
| Converted to SMC format using program sac2smc on 2016/12/28 18:04
| Input file: 2001.HNE.NP.0B
|<SCNL>2001.HNE.NP.0B
|
|<loclbl=>Basement<end>
|EventID: nn00570744
|Source Magnitude: NN
|Source Location: NN
|Source Seimic Moment: NN
| Digital counts re-scaled using the factor 2.3343527E-04 cm/s/s/count
-1.1162E-2-2.0166E-2-1.7681E-2-6.5300E-3 3.1689E-3 4.0421E-3-3.4761E-3-1.3227E-2
-1.8402E-2-1.6471E-2-1.1241E-2-8.9272E-3-1.0695E-2-1.0693E-2-3.3832E-3 8.8757E-3
 1.8492E-2 2.2018E-2 2.3482E-2 2.7809E-2 3.3807E-2 3.5312E-2 2.7868E-2 1.3209E-2
-1.7753E-3-9.9731E-3-9.5758E-3-5.8283E-3-6.1064E-3-1.2262E-2-1.8976E-2-2.0423E-2
-1.6609E-2-1.1344E-2-5.8661E-3 2.0356E-3 1.2539E-2 2.0888E-2 2.2107E-2 1.7084E-2
 1.1607E-2 9.3833E-3 7.9933E-3 3.0544E-3-4.6268E-3-8.6209E-3-4.8807E-3 1.9155E-3
 3.4432E-3-1.1318E-3-3.7309E-3 5.3945E-4 4.5076E-3-2.0590E-3-1.6688E-2-2.5152E-2
-1.9944E-2-1.0713E-2-1.1306E-2-2.1461E-2-2.8440E-2-2.4663E-2-1.5770E-2-9.8138E-3
-5.5516E-3 3.6368E-3 1.7613E-2 2.6740E-2 2.2073E-2 6.1617E-3-7.4713E-3-6.4523E-3
 7.6675E-3 1.9708E-2 1.6724E-2 3.0338E-3-5.2071E-3-1.2845E-3 2.9292E-3-5.8821E-3
-2.1971E-2-2.6552E-2-1.3223E-2 3.0130E-3 6.0540E-3-5.2334E-4-8.9840E-4 9.4736E-3
```

Figure A.4 **Screen shot of acceleration time series in SMC data format as described here[3]. Units are cm/sec^2. Data in this format should use files renamed manually or with *nametransfer* function.**

[3] *https://escweb.wr.usgs.gov/nsmp-data/smcfmt.html.*

Appendix B Parameters Explanations

Table A.1 Period dependent and period independent variables calculated by RCTC in spreadsheets.

Notations in spreadsheet	File name (xx stands for recording's name)	Descriptions
PSA_1, PSA_2	xx_dep.csv	Pseudo spectral acceleration of two ground motions; unit is in *g*.
Absoulte_acc_1, Absolute_acc_2	xx_dep.csv	Spectral acceleration of two ground motions; unit is in *g*.
PSA_gm_ar, PSA_larger_ar	xx_dep.csv	Geometric mean and the larger of two PSAs; unit is in *g*.
GMRotI50, RotD00, RotD50, RotD100	xx_dep.csv	The orientation-independent geometric mean, and the minimum, median, and maximum of orientation-dependent parameters; unit is in *g*.
RotD00_ang, RotD100_ang	xx_dep.csv	The azimuth angles of minimum and maximum orientation-dependent combinations of two ground motions; unit is in *g*.
Num_points	xx_dep.csv	The number of subset selected points in the response displacement time series
npts1, npts2	xx_indep.csv	The number of points in Sinc-interpolated acceleration time series
tmax4penalty, tmin4penalty	xx_indep.csv	The maximum and minimum periods used to calculation penalty function. They are from NGA-West2 Flatfile if available, otherwise, they are user defined; unit is in sec.
Damping, Lowest usable freq, Highest usable freq	xx_indep.csv	The damping ratio (in decimal), and the minimum and maximum usable frequencies (in Hz).
GMRotI50angle	xx_indep.csv	The azimuth angle which minimizes the penalty function (in degrees).
PGA_GMRotI50, PGV_GMRotI50, PGD_GMRotI50,	xx_indep.csv	The orientation-independent geometric mean of two ground motions for peak ground acceleration (*g*), peak ground velocity (cm/sec), and peak ground displacement (cm)

Notations in spreadsheet	File name (xx stands for recording's name)	Descriptions
PGA_GMRot50, PGV_GMRot50, PGA_GMRot100, PGV_GMRot100	xx_indep.csv	The median and maximum of orientation-dependent geometric mean of two ground motions for peak ground acceleration (*g*) and peak ground velocity (cm/sec).
PGA_GMRot100angle, PGV_GMRot100angle	xx_indep.csv	The azimuth angles for the maximum of orientation-dependent geometric mean of two ground motions of peak ground acceleration and velocity; unit are in degrees.
PGA_1, PGA_2, PGV_1, PGV_2, PGD_1, PGD_2	xx_indep.csv	The peak ground accelerations (*g*), peak ground velocities (cm/sec), and peak ground displacements (cm) of two ground motions.
n_a_subset, n_v_subset, n_d_subset	xx_indep.csv	The number of subset selected points in acceleration, velocity, and displacement time series.
PGA_Rot00, PGA_Rot50, PGA_Rot100, PGV_Rot00, PGV_Rot50, PGV_Rot100, PGD_Rot00, PGD_Rot50, PGD_Rot100	xx_indep.csv	The minimum, median, and maximum orientation-dependent parameters of two ground motions for peak ground accelerations (*g*), peak ground velocities (cm/sec), and peak ground displacements (cm)
PGA_Rot00angle, PGA_Rot100angle, PGV_Rot00angle, PGV_Rot100angle, PGD_Rot00angle, PGD_Rot100angle	xx_indep.csv	The azimuth angles of minimum and maximum of orientation-dependent parameters of two ground motions for peak ground accelerations, peak ground velocities, and peak ground displacements; units are in degrees.

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