Package ‘nga’

December 8, 2011

Description This package implements the earthquake ground motion prediction equations developed as part of the Next Generation Attenuation of Ground Motions (NGA) project coordinated by the Pacific Earthquake Engineering Research Center (PEER) in 2008. The models implemented in this package are AS08 (Abrahamson & Silva,2008), BA08 (Boore & Atkinson, 2008), CB08 (Campbell & Bozorgnia,2008), and CY08 (Chiou & Youngs, 2008). This numerical implementation has been validated by comparing the results for 128,000 test cases against the results obtained using the Fortran implementation composed by David M. Boore and Kenneth W. Campbell. Users are encouraged to view U.S. Geological Survey Open-File Report 1296, entitled ‘‘Implementation of the Next Generation Attenuation (NGA) Ground-Motion Prediction Equations in Fortran and R,’’ by J. Kaklamanos, D. M. Boore, E. M. Thompson, and K. W. Campbell (2010) for further details on these programs. More details (including a change log) are available at <http://geohazards.cee.tufts.edu/people/jkakla01>.

Title NGA Earthquake Ground Motion Prediction Equations

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R topics documented:

`Distance Calculations` *Calculation of Source-to-Site Distance Measures*

Description

Calculates the values of the rupture distance (`Rrup`) and site coordinate (`Rx`) from the other distance parameters and the geometric source characteristics of the fault rupture. The equations for `Rx` and `Rrup` are derived and explained in Kaklamanos et al. (2011).

Usage

```
Rx.calc(Rjb, Ztor, W, dip, azimuth, Rrup = NA)
Rrup.calc(Rx, Ztor, W, dip, azimuth, Rjb = NA)
```

Arguments

`Rjb`	Horizontal distance to the surface projection of the rupture plane; Joyner-Boore distance (km).
`Rrup`	Closest distance to the rupture plane; rupture distance (km).
`Rx`	Horizontal distance to the surface projection of the top edge of the rupture plane, measured perpendicular to the strike; site coordinate (km).
`Ztor`	Depth to top of rupture (km).
`W`	Down-dip rupture width (km).
`dip`	Fault dip angle (deg).
`azimuth`	source-to-site azimuth (deg); see Kaklamanos et al. (2011) for a description.

Details

The distance functions for Rx and Rrup require that the Joyner-Boore distance (Rjb) be known. The source-to-site azimuth is also a necessary argument; if the exact azimuth is unknown, assume a generic value of 50 degrees for sites on the hanging wall side of the fault and -50 degrees for sites on the footwall side of the fault. An analysis of the database used to derive the NGA relations suggests that these values are reasonable. The geometric source parameters Ztor, W, and dip are also required; for methods of estimating these source parameters when they are not known beforehand, see Ztor.calc, W.calc, and dip.calc, respectively.

A general strategy for calculating distances is to first calculate Rx, and then calculate Rrup using Rx. In order to calculate Rx using the function Rx.calc, the argument Rrup is only necessary when the site is located directly over the ruptured area (Rjb = 0). If Rrup is unknown in this case, then the function assumes that the site is located in the middle of the surface projection of the ruptured area. In the function Rrup.calc, the argument Rjb is only necessary in the rare case that the site is located directly on the surface projection of fault strike (azimuth = 0, 180, or -180).

Value

Rx.calc outputs Rx (the "site coordinate"), the horizontal distance to the surface projection of the top edge of the rupture plane, measured perpendicular to the strike (km).

Rrup.calc outputs Rrup (the "rupture distance"), the closest distance to the rupture plane (km).

Author(s)

James Kaklamanos <james.kaklamanos@tufts.edu> and Eric M. Thompson <eric.thompson@tufts.edu>

References

Kaklamanos, J., L. G. Baise, and D. M. Boore (2011). Estimating Unknown Input Parameters when Implementing the NGA Ground-Motion Prediction Equations in Engineering Practice. *Earthquake Spectra* **27,** 1219–1235.

See Also

Ztor.calc, W.calc, dip.calc, trig, Sa, Sa.nga.

Examples

```
###########################################################################
# Example 1:  Calculate the distance measures for a synthetic example,
#             with Rjb = 5

# Assumed source and location parameters
M <- 6
Rjb <- 5
azimuth <- 15
rake <- 90   # Reverse fault

# Estimate Ztor, W, and dip, using the respective functions
```

```
W <- W.calc(M = M, rake = rake)
W

dip <- dip.calc(rake = rake)
dip

Zhyp <- Zhyp.calc(M = M, rake = rake)
Zhyp
# Zhyp is needed in order to estimate Ztor

Ztor <- Ztor.calc(W = W, dip = dip, Zhyp = Zhyp)
Ztor


# Estimate Rx and Rrup
Rx <- Rx.calc(Rjb = Rjb, Ztor = Ztor, W = W, dip = dip,
              azimuth = azimuth, Rrup = NA)
Rx

Rrup <- Rrup.calc(Rx = Rx, Ztor = Ztor, W = W, dip = dip,
                  azimuth = azimuth, Rjb = Rjb)
Rrup



##########################################################################
# Example 2:  Calculate and plot the distance measures for a synthetic
#             example, for values of Rjb ranging from 0 to 100

# Redefine Rjb as a vector
Rjb <- seq(from = 0, to = 20, by = 0.5)

# Calculate Rx; vectorize the calculation using the intrinsic
# R "sapply" function
Rx <- sapply(Rjb, Rx.calc, Ztor = Ztor, W = W, dip = dip,
             azimuth = azimuth, Rrup = NA)

# Calculate Rrup, again using the "sapply" function
Rrup <- sapply(Rx, Rrup.calc, Ztor = Ztor, W = W, dip = dip,
               azimuth = azimuth, Rjb = NA)
# Note: Rjb is not needed as an input parameter because the site is
#       not located directly on the surface projection of the fault
#       strike.


# Plot the results against Rjb
# Make basic plot
plot(Rjb, Rjb, type = "l", xaxs = "i", yaxs = "i", xlab = "Rjb (km)",
     ylab = "Rjb, Rrup, and Rx (km)", main = "Comparison of Distance Measures",
     col = "black", lwd = 2)

# Add line for Rrup
lines(Rjb, Rrup, col = "red", lwd = 2)
```

```
# Add line for Rx
lines(Rjb, Rx, col = "blue", lwd = 2)

# Add legend
legend(x = "topleft", inset = 0.02, lwd = 2, bty = "n",
       col = c("black", "red", "blue"),
       legend = c("Rjb", "Rrup", "Rx"))
```

Estimation of Depth Parameter, Z1.0

Estimation of Depth Parameter, Z1.0

Description

Estimates the depth parameter `Z1.0` from the average shear wave velocity (`Vs30`), using Equation 17 in Abrahamson and Silva (2008) and Equation 1 in Chiou and Youngs (2008) for `Z1.calc.as` and `Z1.calc.cy`, respectively.

Usage

```
Z1.calc.as(Vs30)
Z1.calc.cy(Vs30)
```

Arguments

`Vs30`	Time-averaged shear wave velocity over a subsurface depth of 30 meters (m/s).

Value

Estimated value of `Z1.0`, the depth to a shear wave velocity horizon of Vs = 1.0 km/s (m).

Author(s)

James Kaklamanos <james.kaklamanos@tufts.edu> and Eric M. Thompson <eric.thompson@tufts.edu>

References

Abrahamson, N., and W. Silva (2008). Summary of the Abrahamson & Silva NGA Ground-Motion Relations. *Earthquake Spectra* **24,** 67–97.

Chiou, B. S.-J., and R. R. Youngs (2008). An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthquake Spectra* **24,** 173–215.

See Also

`Sa`, `Sa.nga`, `Z2.5.calc`.

Examples

```
# Estimated depth to Vs = 1.0 km/s using the AS08 and CY08 correlations

# AS08 model, Vs30 = 500 m/s
Z1.calc.as(Vs30 = 500)

# CY08 model, Vs30 = 500 m/s
Z1.calc.cy(Vs30 = 500)

# The CY08 relation generates smaller values of Z1.0 than the
# AS08 relation generates.
```

Estimation of Depth Parameter, Z2.5

Estimation of Depth Parameter, Z2.5

Description

Estimates the depth parameter `Z2.5` from either `Z1.5`, `Z1.0`, or `Vs30`, in decreasing order of preference, using the guidelines by Campbell and Bozorgina (2007).

Usage

```
Z2.5.calc(Vs30 = NA, Z1.0 = NA, Z1.5 = NA)
```

Arguments

`Vs30`	Time-averaged shear wave velocity over a subsurface depth of 30 meters (m/s).
`Z1.0`	Depth to Vs = 1.0 km/s (m).
`Z1.5`	Depth to Vs = 1.5 km/s (m).

Value

Estimated value of `Z2.5`, the depth to a shear wave velocity horizon of Vs = 2.5 km/s (m).

Author(s)

James Kaklamanos <james.kaklamanos@tufts.edu> and Eric M. Thompson <eric.thompson@tufts.edu>

References

Campbell, K. W., and Y. Bozorgnia (2007). Campbell-Bozorgnia NGA Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters, *PEER Report No. 2007/02*, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

See Also

Sa, Sa.nga, Z1.calc.

Examples

```
# Estimated depth to Vs = 2.5 km/s

# Example if Z1.5 is known
Z2.5.calc(Z1.5 = 1000)

# Example if Z1.0 is known
Z2.5.calc(Z1.0 = 800)

# Example if only Vs30 is known
Z2.5.calc(Vs30 = 400)
```

Estimation of Depth to Top of Rupture, Ztor
Estimation of Depth to Top of Rupture, Ztor

Description

Estimates the depth to top of rupture, `Ztor`.

Usage

```
Ztor.calc(W, dip, Zhyp)
```

Arguments

`W`	Down-dip rupture width (km).
`dip`	Fault dip angle (deg).
`Zhyp`	Hypocentral depth of the earthquake (km).

Details

To implement this function, `W`, `dip`, and `Zhyp` must be specified. Estimates of `W`, `dip`, and `Zhyp` may be obtained using the functions `W.calc`, `dip.calc`, and `Zhyp.calc`, respectively. The resulting calculation for `Ztor` assumes that the hypocenter is located 60% down the fault width, as suggested by Mai et al. (2005).

Value

Estimated value of the depth to top of rupture, Ztor (km).

Author(s)

James Kaklamanos <james.kaklamanos@tufts.edu> and Eric M. Thompson <eric.thompson@tufts.edu>

References

Mai, P. M., P. Spudich, and J. Boatwright (2005). Hypocenter Locations in Finite-Source Rupture Models. *Bulletin of the Seismological Society of America* **95,** 965–980.

See Also

W.calc, dip.calc, Zhyp.calc, Sa, Sa.nga.

Examples

```
# Assumed earthquake parameters for this example:
M <- 6
rake <- 180   # Strike-slip fault

# First, estimate W using W.calc
W <- W.calc(M = M, rake = rake)
W

# Second, estimate dip using dip.calc
dip <- dip.calc(rake = rake)
dip

# Third, estimate Zhyp using Zhyp.calc
Zhyp <- Zhyp.calc(M = M, rake = rake)
Zhyp

# Third, estimate Ztor (now that we have estimates of W, dip, and Zhyp)
Ztor <- Ztor.calc(W = W, dip = dip, Zhyp = Zhyp)
Ztor
```

Estimation of Down-Dip Rupture Width, W

Estimation of Down-Dip Rupture Width, W

Description

Estimates the down-dip rupture width (W) from the moment magnitude of the earthquake (M) using the empirical correlations published in Wells and Coppersmith (1994), for strike-slip, normal, and reverse faulting mechanisms.

Usage

```
W.calc(M, rake)
```

Arguments

`M`	Moment magnitude of the earthquake.
`rake`	Rake angle of fault movement (deg).

Value

Estimated down-dip width of the rupture plane, `W` (km).

Author(s)

James Kaklamanos <james.kaklamanos@tufts.edu> and Eric M. Thompson <eric.thompson@tufts.edu>

References

Wells, D. L., and K. J. Coppersmith (1994). New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. *Bulletin of the Seismological Society of America* **84,** 974–1002.

See Also

`Ztor.calc`, `dip.calc`, `Sa`, `Sa.nga`.

Examples

```
# Estimate the down-dip rupture widths for some various scenarios

# Small earthquake, reverse fault
W.calc(M = 5, rake = 90)

# Small earthquake, normal fault
W.calc(M = 5, rake = -90)

# Small earthquake, strike-slip fault
W.calc(M = 5, rake = 180)

# Large earthquake, reverse fault
W.calc(M = 7, rake = 90)

# Large earthquake, strike-slip fault
W.calc(M = 7, rake = 0)

# Large earthquake, normal fault
W.calc(M = 7, rake = 90)
```

`Estimation of Fault Dip` *Estimation of Fault Dip*

Description

Estimates the fault dip angle from the style of faulting (using the rake angle), following the explanation in Kaklamanos et al. (2011). These recommendations are a modification of the guidelines Chiou and Youngs (2008) utilized in developing their NGA model.

Usage

```
dip.calc(rake)
```

Arguments

`rake`	Rake angle of fault movement (deg).

Value

Estimated fault dip angle (deg).

Author(s)

James Kaklamanos <james.kaklamanos@tufts.edu> and Eric M. Thompson <eric.thompson@tufts.edu>

References

Chiou, B. S.-J., and R. R. Youngs (2008). NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra, *PEER Report No. 2008/09*, Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Kaklamanos, J., L. G. Baise, and D. M. Boore (2011). Estimating Unknown Input Parameters when Implementing the NGA Ground-Motion Prediction Equations in Engineering Practice. *Earthquake Spectra* **27,** 1219–1235.

See Also

`Ztor.calc`, `W.calc`, `Sa`, `Sa.nga`.

Examples

```
# Estimated dip angle for a strike-slip fault
dip.calc(rake = 180)

# Estimated dip angle for a reverse fault
dip.calc(rake = 90)

# Estimated dip angle for a normal fault
dip.calc(rake = -90)
```

Estimation of Hypocentral Depth, Zhyp

Estimation of Hypocentral Depth, Zhyp

Description

Provides an estimate of the hypocentral depth (Zhyp), which in turn may be used to estimate the depth to top of rupture (Ztor), if Ztor is unknown.

Usage

```
Zhyp.calc(M, rake)
```

Arguments

M	Moment magnitude of earthquake.
rake	Rake angle of fault movement (deg).

Details

The value of Zhyp is estimated using correlations presented in Table 1 of Scherbaum et al. (2004).

Value

Estimated value of the hypocentral depth, Zhyp (km).

Author(s)

James Kaklamanos <james.kaklamanos@tufts.edu> and Eric M. Thompson <eric.thompson@tufts.edu>

References

Scherbaum, F., J. Schmedes, and F. Cotton (2004). On the Conversion of Source-to-Site Distance Measures for Extended Earthquake Source Models. *Bulletin of the Seismological Society of America* **94,** 1053–1069.

See Also

Ztor.calc, Sa, Sa.nga.

Examples

```
# Estimate the hypocentral depths for some various scenarios:

# Small earthquake, shallow-dipping fault (not strike-slip)
Zhyp.calc(M = 5, rake = 90)

# Small earthquake, strike-slip fault
```

```
Zhyp.calc(M = 5, rake = 180)

# Large earthquake, shallow-dipping fault (not strike-slip)
Zhyp.calc(M = 7, rake = -90)

# Large earthquake, strike-slip fault
Zhyp.calc(M = 7, rake = 0)
```

`Example Data Analysis Using the nga Package: KB Flatfile Data`
Example Earthquake Records from Recent California Earthquakes

---

Description

This data set contains 1060 ground motion records from seven recent earthquakes recorded in California: the (1) 2003 **M** 6.5 San Simeon, (2) 2004 **M** 6.0 Parkfield, (3) 2005 **M** 5.2 Anza, (4) 2007 **M** 5.4 Alum Rock, (5) 2008 **M** 5.4 Chino Hills, (6) 2010 **M** 7.2 Baja, and (7) 2010 **M** 5.7 Ocotillo earthquakes. None of these earthquakes were present in the database used to develop the NGA models (the NGA flatfile), and thus these records were used in a blind comparison test of the models in Kaklamanos and Baise (2011). The headers of this data frame are designed to be similar to those in the NGA flatfile; this data frame is termed the "KB flatfile" ("KB" stands for "Kaklamanos and Baise"). For further details on this dataset, please refer to Kaklamanos and Baise (2011) and the electronic supplement available at http://www.seismosoc.org/publications/BSSA_html/bssa_101-1/2010038-esupp/index.html.

Usage

```
data(KBflatfile)
```

Format

A dataframe containing 1060 rows and 45 columns. For further details about these columns, see the documentation for the electronic supplement of Kaklamanos and Baise (2011). The ground motion parameters at the bottom of the list are comprised of the geometric mean of the as-recorded horizontal components, and are presented in units of g.

1. `RecNum` Record sequence number in the KB flatfile

2. `EQID` Earthquake identification number in the KB flatfile

3. `EQName` Earthquake name

4. `Month` Month of the earthquake

5. `Day` Day of the earthquake

6. `Year` Year of the earthquake

7. `StationName` Name of the strong-motion station

8. `StaID` Identification number of the strong-motion station

9. `StaNetwork` Network code of the strong-motion station

10. `StaSeqNum` Sequence number of the strong-motion station in the KB flatfile
11. `StaLat` Latitude of the strong-motion station (deg)
12. `StaLong` Longitude of the strong-motion station (deg)
13. `M` Moment magnitude of earthquake
14. `Strike` Strike of the rupture plane (deg)
15. `Dip` Dip angle of the rupture plane (deg)
16. `Rake` Rake angle of fault movement (deg)
17. `EQmechanism` Earthquake mechanism defined by rake angle
18. `HypocenterLat` Hypocenter latitude (deg)
19. `HypocenterLong` Hypocenter longitude (deg)
20. `Zhyp` Depth of hypocenter (km)
21. `FiniteFaultModelFlag` Flag variable indicating if a finite fault model was used (1 = Yes, 0 = No)
22. `Source_of_SourceParameters` Reference for source parameters (finite fault model / moment tensor soln.)
23. `Ztor` Depth to top of rupture (km)
24. `L` Length of rupture plane (km)
25. `W` Down-dip width of rupture plane (km)
26. `Repi` Epicentral distance (km)
27. `Rhyp` Hypocentral distance (km)
28. `Rjb` Joyner-Boore distance (km)
29. `Rrup` Rupture distance (km)
30. `Rseis` Seismogenic distance (km)
31. `Rx` Site coordinate (km)
32. `Azimuth` Source-to-site azimuth (deg)
33. `Geology` Surficial geologic unit
34. `Vs30` Time-averaged shear wave velocity over a subsurface depth of 30 meters (m/s)
35. `VsFlag` Vs flag variable: 1 for measured Vs, 0 for inferred Vs
36. `VsSource` Source of Vs / geology data
37. `VsReference` Reference for Vs / geology data
38. `GroundMotionDataSource` Source of ground motion data
39. `PGA` Observed peak ground acceleration
40. `T0.1S` Observed spectral acceleration (Sa) at T = 0.1 sec
41. `T0.2S` Observed Sa at T = 0.2 sec
42. `T0.3S` Observed Sa at T = 0.3 sec
43. `T0.5S` Observed Sa at T = 0.5 sec
44. `T1.0S` Observed Sa at T = 1.0 sec
45. `T2.0S` Observed Sa at T = 2.0 sec

Author(s)

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Source

Electronic supplement of Kaklamanos and Baise (2011), available at http://www.seismosoc.org/publications/BSSA_html/bssa_101-1/2010038-esupp/index.html

References

Abrahamson, N., and W. Silva (2008). Summary of the Abrahamson & Silva NGA Ground-Motion Relations. *Earthquake Spectra* **24,** 67–97.

Boore, D. M., and G. M. Atkinson (2008). Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s. *Earthquake Spectra* **24,** 99–138.

Campbell, K. W., and Y. Bozorgnia (2008). NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD, and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10 s. *Earthquake Spectra* **24,** 139–171.

Chiou, B. S.-J., and R. R. Youngs (2008). An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthquake Spectra* **24,** 173–215.

Kaklamanos, J., and L. G. Baise (2011). Model Validations and Comparisons of the Next Generation Attenuation of Ground Motions (NGA-West) Project. *Bulletin of the Seismological Society of America*, **101,** 160–175.

Kaklamanos, J., L. G. Baise, and D. M. Boore (2011). Estimating Unknown Input Parameters when Implementing the NGA Ground-Motion Prediction Equations in Engineering Practice. *Earthquake Spectra* **27,** 1219–1235.

See Also

Sa, Sa.nga

Examples

```
# Load dataset (this command MUST be typed prior to using the dataset)
data(KBflatfile)

# See the column names of the dataset
names(KBflatfile)


########################################################################
# Example 1:  Generate a plot of observed versus predicted response
#             spectrum for a ground motion record in the database

# Use Rec No. 824, the first ground motion record for the Baja
# earthquake of 2010 listed in the dataset.
```

```
# Read data from the 824th row
# Only read columns that are necessary for ground motion calculations

# Input variables:
n <- 824
M <- KBflatfile$M[n]
dip <- KBflatfile$Dip[n]
rake <- KBflatfile$Rake[n]
Ztor <- KBflatfile$Ztor[n]
W <- KBflatfile$W[n]
Rjb <- KBflatfile$Rjb[n]
Rrup <- KBflatfile$Rrup[n]
Rx <- KBflatfile$Rx[n]
azimuth <- KBflatfile$Azimuth[n]
Vs30 <- KBflatfile$Vs30[n]
# VsFlag is not read, because it is only necessary for standard
# deviation calculations (i.e., epsilon != 0)

# Observed response spectral values:
PGA <- KBflatfile$PGA[n]
Sa0.1 <- KBflatfile$T0.1S[n]
Sa0.2 <- KBflatfile$T0.2S[n]
Sa0.3 <- KBflatfile$T0.3S[n]
Sa0.5 <- KBflatfile$T0.5S[n]
Sa1.0 <- KBflatfile$T1.0S[n]
Sa2.0 <- KBflatfile$T2.0S[n]

# Vectorize the observed spectral acceleration and corresponding periods
# NOTE: Observed PGA is assumed to have a spectral period of T = 0.01 sec
T.obs <- c(0.01, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0)
Sa.obs <- c(PGA, Sa0.1, Sa0.2, Sa0.3, Sa0.5, Sa1.0, Sa2.0)

# Define the periods at which ground motion calculations will be performed
# NOTE: the same could be achieved by using the function call
# modelPeriods(model = "AS08", positive = TRUE).
T.list <- c(0.01, 0.02, 0.03, 0.04, 0.05, 0.075, 0.10, 0.15, 0.20,
            0.25, 0.30, 0.40, 0.50, 0.75, 1.0, 1.5, 2.0, 3.0, 4.0,
            5.0, 7.5, 10.0)

# Compute ground motion predictions
ResultsMatrix <- Sa.nga(M = M, dip = dip, rake = rake, Ztor = Ztor,
                        W = W, Rjb = Rjb, Rrup = Rrup, Rx = Rx,
                        azimuth = azimuth, Vs30 = Vs30,
                        epsilon = 1, T = T.list)

# Access individual columns of the data frame using the "$" operator:
SaAS08 <- ResultsMatrix$Y50.as
SaBA08 <- ResultsMatrix$Y50.ba
SaCB08 <- ResultsMatrix$Y50.cb
SaCY08 <- ResultsMatrix$Y50.cy

# Plot the results
plot(T.obs, Sa.obs, type = "p", log = "xy", col = "black", pch = 19, lwd = 4,
```

```
     xlim = c(0.01, 10), ylim = c(0.001, 1), xaxs = "i", yaxs = "i",
     xlab = "Spectral Period, T [sec]", ylab = "Spectral Acceleration, Sa [g]",
     main = paste("Comparison of NGA Ground Motion Predictions:", "\n",
                  "Record No. 824; Baja Earthquake of 2010"))
lines(T.list, SaAS08, lwd = 2, col = "blue")
lines(T.list, SaBA08, lwd = 2, col = "red")
lines(T.list, SaCB08, lwd = 2, col = "darkgreen")
lines(T.list, SaCY08, lwd = 2, col = "purple")
legend(x = "bottomleft", inset = 0.02, lwd = c(-1,2,2,2,2),
       lty = c(-1,1,1,1,1), pch = c(19,-1,-1,-1,-1), bty = "n",
       col = c("black", "blue", "red", "darkgreen", "purple"),
       legend = c("Observed", "AS08", "BA08", "CB08", "CY08"))



############################################################################
# Example 2:  Generate a plot of peak ground acceleration versus distance
#             for the Chino Hills earthquake of 2008

# The relevant ground motion records are present in rows 447 to 823 of
# the KB flatfile.  Note that because a finite fault model was not
# developed for this earthquake, some of the source and distance
# parameters are unknown and must be estimated by the program.

# Read data
start <- 447
end <- 823
n <- seq(from = start, to = end, by = 1)
M <- KBflatfile$M[n]
rake <- KBflatfile$Rake[n]
dip <- KBflatfile$Dip[n]
Zhyp <- KBflatfile$Zhyp[n]
Repi <- KBflatfile$Repi[n]
Vs30 <- KBflatfile$Vs30[n]
PGA <- KBflatfile$PGA[n]


# Generate NGA ground motion predictions versus distance

# Extract source parameters from the vectors.
# These are constants for each of the 337 ground motion records in the
# subset, so it does not matter which row we extract.
M.value <- M[1]
rake.value <- rake[1]
dip.value <- dip[1]
Zhyp.value <- Zhyp[1]

# Assume an average Vs30 for the purpose of drawing the graphs
Vs30.value <- mean(Vs30)

# Assume site is on footwall (since the earthquake is low-magnitude,
# the hanging wall effects are not likely to be significant).
Fhw <- 0
```

```
# First, illustrate the calculation for one point:
ResultsMatrix1 <- Sa.nga(M = M.value, dip = dip.value, rake = rake.value,
                         Rjb = 0, Fhw = 0, Vs30 = Vs30.value, epsilon = 0, T = 0)

# Generate a vector of Rjb values from 0 to 200 to be used for
# plotting and for generating ground motion predictions
Rjb.plot <- seq(from = 0, to = 200, by = 4)

# Perform ground motion calculations for all points.
# Define ResultsMatrix2; use the column names of ResultsMatrix1
ResultsMatrix2 <- matrix(nrow = length(Rjb.plot), ncol = length(ResultsMatrix1))
ResultsMatrix2 <- as.data.frame(ResultsMatrix2)
names(ResultsMatrix2) <- names(ResultsMatrix1)
# It is necessary to place the calculation in a loop since we are varying Rjb.
for(i in 1:length(Rjb.plot)){
  ResultsMatrix2[i,] <- Sa.nga(M = M.value, dip = dip.value, rake = rake.value,
                               Rjb = Rjb.plot[i], Fhw = 0, Vs30 = Vs30.value,
                               epsilon = 0, T = 0)
}

# Access individual columns of the data frame using the "$" operator:
pgaAS08 <- ResultsMatrix2$Y50.as
pgaBA08 <- ResultsMatrix2$Y50.ba
pgaCB08 <- ResultsMatrix2$Y50.cb
pgaCY08 <- ResultsMatrix2$Y50.cy


# Plot the results.
# For the purpose of generating the plot, Repi is used in place of
# Rjb. For small-magnitude events, the area of fault rupture is
# small, and the assumption Repi = Rjb is not unreasonable.
plot(Repi, PGA, type = "p", log = "y", pch = 1,
     xlab = "Joyner-Boore Distance, Rjb [km]",
     ylab = "Peak Ground Acceleration, PGA [g]",
     main = paste("Comparison of NGA Ground Motion Predictions:", "\n",
     "PGA versus Rjb for the Chino Hills Earthquake of 2008"))
lines(Rjb.plot, pgaAS08, lwd = 2, col = "blue")
lines(Rjb.plot, pgaBA08, lwd = 2, col = "red")
lines(Rjb.plot, pgaCB08, lwd = 2, col = "darkgreen")
lines(Rjb.plot, pgaCY08, lwd = 2, col = "purple")
legend(x = "bottomleft", inset = 0.02, pch = c(1,-1,-1,-1,-1),
       lwd = c(-1,2,2,2,2), lty = c(-1,1,1,1,1), bty = "n",
       col = c("black", "blue", "red", "darkgreen", "purple"),
       legend = c("Observed", "AS08", "BA08", "CB08", "CY08"))



########################################################################
# Example 3:  Tabulate predicted versus observed peak ground acceleration
#             for the ground motion records of the San Simeon earthquake
#             of 2003
```

```
# The relevant ground motion records are present in rows 1 to 30 of
# the KB flatfile:

# Read data
start <- 1
end <- 30
n <- seq(from = start, to = end, by = 1)
M <- KBflatfile$M[n]
dip <- KBflatfile$Dip[n]
rake <- KBflatfile$Rake[n]
Ztor <- KBflatfile$Ztor[n]
W <- KBflatfile$W[n]
Rjb <- KBflatfile$Rjb[n]
Rrup <- KBflatfile$Rrup[n]
Rx <- KBflatfile$Rx[n]
azimuth <- KBflatfile$Azimuth[n]
Vs30 <- KBflatfile$Vs30[n]
PGA.obs <- KBflatfile$PGA[n]

# Create matrices to store the calculated values
pgaAS08 <- matrix(nrow = length(n), ncol = 1)
pgaBA08 <- matrix(nrow = length(n), ncol = 1)
pgaCB08 <- matrix(nrow = length(n), ncol = 1)
pgaCY08 <- matrix(nrow = length(n), ncol = 1)

# Perform ground motion predictions
for(i in 1:length(n)){
  ResultsMatrix <- Sa.nga(M = M[i], dip = dip[i], rake = rake[i],
                          Ztor = Ztor[i], W = W[i], Rjb = Rjb[i],
                          Rrup = Rrup[i], Rx = Rx[i],
                          azimuth = azimuth[i], Vs30 = Vs30[i],
                          epsilon = 0, T = 0)
  pgaAS08[i] <- ResultsMatrix$Y50.as
  pgaBA08[i] <- ResultsMatrix$Y50.ba
  pgaCB08[i] <- ResultsMatrix$Y50.cb
  pgaCY08[i] <- ResultsMatrix$Y50.cy
}

# Combine the results into a data frame
Ex3 <- cbind(PGA.obs, pgaAS08, pgaBA08, pgaCB08, pgaCY08)
colnames(Ex3) <- c("pgaObs", "pgaAS08", "pgaBA08", "pgaCB08", "pgaCY08")

# Display results
Ex3

# You could now use a function such as "write.csv" or "write.table" to export Ex3



########################################################################
# Example 4:  Generate matrices of median predicted response spectra
#             for the San Simeon earthquake of 2003
```

```
# The relevant ground motion records are present in rows 1 to 30 of
# the KB flatfile (same as example 3)

# Read data
start <- 1
end <- 30
n <- seq(from = start, to = end, by = 1)
M <- KBflatfile$M[n]
dip <- KBflatfile$Dip[n]
rake <- KBflatfile$Rake[n]
Ztor <- KBflatfile$Ztor[n]
W <- KBflatfile$W[n]
Rjb <- KBflatfile$Rjb[n]
Rrup <- KBflatfile$Rrup[n]
Rx <- KBflatfile$Rx[n]
azimuth <- KBflatfile$Azimuth[n]
Vs30 <- KBflatfile$Vs30[n]
VsFlag <- KBflatfile$VsFlag[n]

# Create matrix of observed response spectra

# Read observed data as vectors
PGA <- KBflatfile$PGA[n]
Sa0.1 <- KBflatfile$T0.1S[n]
Sa0.2 <- KBflatfile$T0.2S[n]
Sa0.3 <- KBflatfile$T0.3S[n]
Sa0.5 <- KBflatfile$T0.5S[n]
Sa1.0 <- KBflatfile$T1.0S[n]
Sa2.0 <- KBflatfile$T2.0S[n]

# Combine the individual vectors into a matrix using the
# "cbind" function
Obs <- cbind(PGA, Sa0.1, Sa0.2, Sa0.3, Sa0.5, Sa1.0, Sa2.0)

# Periods for analysis
T.list <- c(0, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0)


# Create matrices to store the calculated values
PredAS08 <- matrix(nrow = length(n), ncol = length(T.list))
PredBA08 <- matrix(nrow = length(n), ncol = length(T.list))
PredCB08 <- matrix(nrow = length(n), ncol = length(T.list))
PredCY08 <- matrix(nrow = length(n), ncol = length(T.list))
colnames(PredAS08) <- colnames(Obs)
colnames(PredBA08) <- colnames(Obs)
colnames(PredCB08) <- colnames(Obs)
colnames(PredCY08) <- colnames(Obs)


# Perform ground motion predictions (this example illustrates the
# use of the individual functions Sa.as, Sa.ba, Sa.cb, and Sa.cy,
# which are faster and generate less output than Sa.nga)
```

```
# Ground motion calculations
for(i in 1:length(n)){
  PredAS08[i,] <- Sa.as(M = M[i], dip = dip[i], rake = rake[i],
                        Ztor = Ztor[i], W = W[i], Rjb = Rjb[i],
                        Rrup = Rrup[i], Rx = Rx[i],
                        azimuth = azimuth[i], Vs30 = Vs30[i],
                        VsFlag = VsFlag[i], Fas = 0, epsilon = 0,
                        T = T.list)
  PredBA08[i,] <- Sa.ba(M = M[i], rake = rake[i], Rjb = Rjb[i],
                        Vs30 = Vs30[i], epsilon = 0, T = T.list)
  PredCB08[i,] <- Sa.cb(M = M[i], dip = dip[i], rake = rake[i],
                        Ztor = Ztor[i], Rjb = Rjb[i], Rrup = Rrup[i],
                        Vs30 = Vs30[i], epsilon = 0, T = T.list)
  PredCY08[i,] <- Sa.cy(M = M[i], dip = dip[i], rake = rake[i],
                        Ztor = Ztor[i], W = W[i], Rjb = Rjb[i],
                        Rrup = Rrup[i], Rx = Rx[i],
                        azimuth = azimuth[i], Vs30 = Vs30[i],
                        VsFlag = VsFlag[i], AS = 0, epsilon = 0,
                        T = T.list)
}

# Display results
Obs
PredAS08
PredBA08
PredCB08
PredCY08

# Now each of the matrices may be used in later calculations, or
# written to a text or csv file.
```

Ground Motion Predictions for all NGA Models

Ground Motion Predictions for all NGA Models

Description

Comprehensive function that estimates ground motion parameters using the AS08, BA08, CB08, and CY08 models from the Next Generation Attenuation of Ground Motions (NGA) project in 2008. The function `Sa.nga` is designed to mimic the output from Boore and Campbell's Fortran output files.

Usage

```
Sa.nga(M, Rjb, Vs30, T, Rrup = NA, Rx = NA, dip = NA, W = NA,
       Ztor = NA, Z1.0 = NA, Z1.5 = NA, Z2.5 = NA, rake = NA,
       Frv = NA, Fnm = NA, Fhw = NA, azimuth = NA, Zhyp = NA,
       Fas = 0, epsilon = 1)
```

Arguments

`M`	Moment magnitude of earthquake.
`Rjb`	Joyner-Boore distance (km): the horizontal distance to the surface projection of the rupture plane.
`Vs30`	Time-averaged shear wave velocity over a subsurface depth of 30 meters (m/s).
`T`	Spectral period (sec). Use 0 for PGA and -1 for PGV. For spectral acceleration, `T` must be in the range `0.01 <= T <= 10 sec`. If the specified period is within the allowable range and does not have defined equations, the program uses log-log interpolation (using `interpolate`) between the next-highest and next-lowest spectral periods with defined equations.
`Rrup`	Rupture distance (km): the closest distance to the rupture plane; if left empty, `Rrup` is calculated from `Rx`, the source-to-site azimuth, and the geometric rupture parameters (`Ztor`, `W`, and `dip`) using `Rrup.calc`.
`Rx`	Site coordinate (km): The horizontal distance to the surface projection of the top edge of the rupture plane, measured perpendicular to the strike. If left empty, `Rx` is calculated from `Rjb`, the source-to-site azimuth, and the geometric rupture parameters (`Ztor`, `W`, and `dip`) using `Rx.calc`. When only `Rjb` and the azimuth are assumed, `Rjb` is used to calculate `Rx`, which is then used to calculate `Rrup`.
`dip`	Dip angle of the rupture plane (deg). If left empty, the dip is estimated using `dip.calc`.
`W`	Down-dip width of rupture plane (km). If left empty, `W` is estimated using `W.calc`.
`Ztor`	Depth to top of rupture (km). If left empty, `Ztor` is estimated using `Ztor.calc`.
`Z1.0`	Depth to Vs = 1.0 km/s (m). If left empty, `Z1.0` is estimated using `Z1.calc.as` for the AS08 model and `Z1.calc.cy` for the CY08 model.
`Z1.5`	Depth to Vs = 1.5 km/s (m). `Z1.5` is not utilized in ground motion calculations, but if available, it may be used to estimate `Z2.5` for the CB08 model.
`Z2.5`	Depth to Vs = 2.5 km/s (m; **note the units**). If left empty, `Z2.5` is estimated from `Z1.5` or `Z1.0` if available, using the recommendations in Campbell and Bozorgnia (2007); see `Z2.5.calc`. If neither `Z1.5` nor `Z1.0` is available, then `Vs30` is used to estimate `Z1.0` using `Z1.calc.as`, which is in turn used to estimate `Z2.5`.
`rake`	Rake angle of fault movement (deg). Either the rake angle or the style-of-faulting flag variables (`Frv` and `Fnm`) must be specified.
`Frv`	Reverse style-of-faulting flag (1 for reverse faulting, 0 otherwise). Either (a) the rake angle, or (b) both `Frv` and `Fnm`, must be specified. Reverse faulting is characterized by rake angles in the range `30 <= rake <= 150 deg` for the AS08, BA08, and CY08 models; and in the range `30 < rake < 150 deg` for the CB08 model.
`Fnm`	Normal style-of-faulting flag (1 for normal faulting, 0 otherwise). Either (a) the rake angle, or (b) both `Frv` and `Fnm`, must be specified. Normal faulting is characterized by rake angles in the range `-120 <= rake <= -60 deg` for the AS08 and CY08 models, `-150 <= rake <= -30 deg` for the BA08 model, and `-150 < rake < -30 deg` for the CB08 model.

`Fhw` Hanging wall flag; equal to 1 for sites on the hanging wall side of the fault (`Rx >= 0; azimuth >= 0`), and 0 otherwise. Either `Fhw`, `Rx`, or the azimuth must be specified.

`azimuth` Source-to-site azimuth (deg); see Kaklamanos et al. (2011) for details. Used by `Rx.calc` and `Rrup.calc` for distance calculations. Either `Fhw`, `Rx`, or the azimuth must be specified.

`Zhyp` Hypocentral depth of the earthquake (km). `Zhyp` is not utilized in ground motion calculations, but it may be used to estimate `Ztor`. See `Ztor.calc` for details.

`Fas` Aftershock flag; equal to 1 for aftershocks and 0 for mainshocks (the default)

`epsilon` Number of standard deviations to be considered in the calculations (default value is 1). The function `Sa.nga` automatically outputs the median estimates (corresponding to `epsilon = 0`) as well as the estimates corresponding to the median estimate plus and minus `epsilon * sigmaTotal`

Details

Note that T (spectral period) can be a vector, while all other arguments are scalars.

In the "Output Section" of this function, "Y" refers to the ground motion parameter of interest, which can be:

1. Sa = Spectral acceleration (g)
2. PGA = Peak ground acceleration (g), calculated by evaluating Sa at `T = 0`;
3. PGV = Peak ground velocity (cm/sec), calculated by evaluating Sa at `T = -1`.

Because only the CB08 model has coefficients for PGD (peak ground displacement), the CB08-specific function `Sa.cb` must be used to obtain predictions for PGD. In addition, "sd" refers to the standard deviation of the ground motion estimate, which is presented in natural log space.

The flag variables `VsFlag` and `arb` refer to:

`VsFlag` = Flag variable indicating how `Vs30` is obtained (AS08 and CY08 models only); equal to 1 if `Vs30` is measured, and 0 if `Vs30` is estimated or inferred.

`arb` = Flag variable indicating the method of determining aleatory uncertainty for the CB08 model; equal to 1 if the standard deviation should be calculated for the arbitrary horizontal component of ground motion, and 0 if the standard deviation should be calculated for the geometric mean horizontal ground motion.

These two indicator variables represent model-specific options for output: AS08 and CY08 have different standard deviation terms for measured and inferred Vs30 (specified by `VsFlag`), and CB08 is the only model that offers predictions for the arbitrary horizontal component of ground motion (`arb`). For each case (0 and 1) of each of these three indicator variables, `Sa.nga` provides the estimated ground motion. This output is consistent with that of the Fortran program described later in this report. The model-specific functions `Sa.as`, `Sa.ba`, `Sa.cb`, and `Sa.cy` allow the user to specify the values of the indicator variables in the arguments to the functions.

The median BA08 estimate is presented in terms of the original GMPE (Boore and Atkinson, 2008) as well as the modified GMPE given by Atkinson and Boore (2011). The small-magnitude modification affects ground motion estimates for `M <= 5.75`. The modified BA08 model corresponds to `AB11 = 1` in the `Sa.ba` function, and the original BA08 model corresponds to `AB11 = 0`.

Value

The function `Sa.nga` outputs a data frame composed of the following 62 columns:

Input Variables:

`T`	Spectral period, sec [input]
`M`	Moment magnitude [input]
`Rjb`	Joyner-Boore distance (km) [input]
`Rrup.in`	Rupture distance (km) [input]
`Rrup.out`	Rupture distance (km) [calculated if `Rrup.in` is not specified]
`Rx.in`	Site coordinate (km) [input]
`Rx.out`	Site coordinate (km) [calculated if `Rx.in` is not specified]
`azimuth.in`	source-to-site azimuth (deg) [input]
`azimuth.out`	source-to-site azimuth (deg) [calculated if `azimuth.in` is not specified]
`Fhw`	Hanging wall flag
`Zhyp.in`	hypocentral depth (km) [input]
`Zhyp.out`	hypocentral depth (km) [calculated if `Zhyp.in` is not specified]
`rake.in`	Rake angle of fault movement (deg) [input]
`rake.out`	Rake angle of fault movement (deg) [calculated if `rake.in` is not specified]
`Frv1`	Reverse style-of-faulting flag for AS08, BA08, and CY08 [input]
`Frv2.cb`	Reverse style-of-faulting flag for CB08
`Fnm1`	Normal style-of-faulting flag for AB08 and CY08
`Fnm2.ba`	Normal style-of-faulting flag for BA08
`Fnm3.cb`	Normal style-of-faulting flag for CB08
`dip.in`	Fault dip angle (deg) [input]
`dip.out`	Fault dip angle (deg) [calculated if `dip.in` is not specified]
`W.in`	Down-dip rupture width (km) [input]
`W.out`	Down-dip rupture width (km) [calculated if `W.in` is not specified]
`Ztor.in`	Depth to top of rupture (km) [input]
`Ztor.out`	Depth to top of rupture (km) [calculated if `Ztor.in` is not specified]
`Vs30`	Time-averaged shear wave velocity over 30 m subsurface depth (m/sec) [input]
`Z1.0in`	Depth to Vs of 1.0 km/sec (m) [input]
`Z1.0as`	Depth to Vs of 1.0 km/sec (m) [calculated for use in AS08 model
`Z1.0cy`	Depth to Vs of 1.0 km/sec (m) [calculated for use in CY08 model]
`Z1.5in`	Depth to Vs of 1.5 km/sec (m) [input]
`Z2.5in`	Depth to Vs of 2.5 km/sec (m) [input]
`Z2.5out`	Depth to Vs of 2.5 km/sec (m) [calculated from `Z1.0` for use in CB08 model]
`Fas`	Aftershock flag [input]
`epsilon`	number of standard deviations considered in the calculations [input]

Output Variables:

AS08 Model:

- `Y50.as` Median ground motion estimate using AS08 (`epsilon` = 0)
- `YplusEpsilon.meas.as` Upper ground motion estimate using AS08, for measured `Vs30` (`VsFlag = 1`)
- `YplusEpsilon.est.as` Upper ground motion estimate using AS08, for estimated `Vs30` (`VsFlag = 0`)
- `YminusEpsilon.meas.as` Lower ground motion estimate using AS08, for measured `Vs30` (`VsFlag = 1`)
- `YminusEpsilon.est.as` Lower ground motion estimate using AS08, for estimated `Vs30` (`VsFlag = 0`)
- `sdMeas.as` total standard deviation using AS08, for measured `Vs30` (`VsFlag = 1`)
- `sdEst.as` total standard deviation using AS08, for estimated `Vs30` (`VsFlag = 0`)

BA08 Model:

- `Y50.ba` Median ground motion estimate using BA08
- `Y50mod.ba` Median ground motion estimate using modified BA08 (`AB11 = 1`)
- `YplusEpsilon.ba` Upper ground motion estimate using BA08
- `YplusEpsilon.mod.ba` Upper ground motion estimate using modified BA08 (`AB11 = 1`)
- `YminusEpsilon.ba` Lower ground motion estimate using BA08
- `YminusEpsilon.mod.ba` Lower ground motion estimate using modified BA08 (`AB11 = 1`)
- `sd.ba` total standard deviation using BA08

CB08 Model:

- `Y50.cb` Median ground motion estimate using CB08 (`epsilon` = 0)
- `YplusEpsilon.GM.cb` Upper CB08 estimate for the geometric mean horizontal component (`arb = 0`)
- `YplusEpsilon.arb.cb` Upper CB08 estimate for the arbitrary horizontal component (`arb = 1`)
- `YminusEpsilon.GM.cb` Lower CB08 estimate for the geometric mean horizontal component (`arb = 0`)
- `YminusEpsilon.arb.cb` Lower CB08 estimate for the arbitrary horizontal component (`arb = 1`)
- `sdGM.cb` CB08 total standard deviation for the geometric mean horizontal component (`arb = 0`)
- `sdArb.cb` CB08 total standard deviation for the arbitrary horizontal component (`arb = 1`)

CY08 Model:

`Y50.cy`	Median ground motion estimate using CY08 (`epsilon` = 0)
`YplusEpsilon.meas.cy`	Upper ground motion estimate using CY08, for measured `Vs30` (`VsFlag = 1`)
`YplusEpsilon.est.cy`	Upper ground motion estimate using CY08, for estimated `Vs30` (`VsFlag = 0`)
`YminusEpsilon.meas.cy`	Lower ground motion estimate using CY08, for measured `Vs30` (`VsFlag = 1`)
`YminusEpsilon.est.cy`	Lower ground motion estimate using CY08, for estimated `Vs30` (`VsFlag = 0`)
`sdMeas.cy`	total standard deviation using CY08, for measured `Vs30` (`VsFlag = 1`)
`sdEst.cy`	total standard deviation using CY08, for estimated `Vs30` (`VsFlag = 0`)

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See Also

See `Sa.as`, `Sa.ba`, `Sa.cb`, and `Sa.cy` for separate functions that compute ground motion parameters using the individual NGA models. See `KBflatfile` for an example of inputting and outputting earthquake data and predictions.

For details on the sub procedures used for the individual NGA models, see `subs.as`, `subs.ba`, `subs.cb`, and `subs.cy`. See `coefs` for details on the period-independent model coefficients, and coefs.t.as, coefs.t.ba, coefs.t.cb, and coefs.t.cy for details on the period-dependent model coefficients.

For procedures on estimating input variables when they are not known, see Rx.calc, Rrup.calc, dip.calc, W.calc, Ztor.calc, Z1.calc, Z2.5.calc, and Zhyp.calc. These procedures are further described in Kaklamanos et al. (2011).

For details on the spectral periods and ground motion parameters defined for each of the models, see modelPeriods or periods. The functions getPeriod and interpolate provide methods for estimating spectral accelerations at intermediate periods between those with defined model coefficients.

Examples

```
# Assumed earthquake parameters for these examples:
M <- 7
Rjb <- 50
Rrup <- 51
Vs30 <- 300
T.list <- c(0, 0.1, 0.5, 1)
dip <- 80
W <- 20
Ztor <- 2
rake <- 180
Fhw <- 0
Fas <- 0




#########################################################
# Example 1:  Illustration of the versatility of input

# First calculate ground motions using the known input variables
# Some of the variables (such as Z1.0 and Rx) are unknown, and will
# be calculated by the program
Sa.nga(M = M, Rjb = Rjb, Vs30 = Vs30, epsilon = 1, T = T.list,
       Rrup = Rrup, dip = dip, W = W, Ztor = Ztor, rake = rake,
       Fhw = Fhw, Fas = Fas)

# Repeat the ground motion calculation the bare minimum necessary requirements
Sa.nga(M = M, Rjb = Rjb, Vs30 = Vs30, epsilon = 1, T = T.list,
       rake = rake, Fhw = Fhw)

# Note that the style-of-faulting flag variables may be used in place
# of the rake, and that the azimuth (if known) may be used instead of Fhw
Sa.nga(M = M, Rjb = Rjb, Vs30 = Vs30, epsilon = 1, T = T.list,
       Frv = 0, Fnm = 0, azimuth = -30)



#######################################################################
```

```
# Example 2: Generate a plot of the predicted response spectrum (and
#            uncertainty) for a hypothetical earthquake using the BA08
#            model

# Redefine T to be a vector
# We only desire T >= 0.01 for plotting
T.list <- modelPeriods(model = "BA08", positive = TRUE)

# Ground motion calculations
ResultsMatrix <- Sa.nga(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30,
                        epsilon = 1, T = T.list, dip = dip, W = W,
                        Ztor = Ztor, rake = rake, Fhw = Fhw, Fas = Fas)

# To see the names of all the columns in the data frame, use the "names"
# function on a column of the matrix:
names(ResultsMatrix)

# To access individual columns of the data frame, use the "$" operator:
SaMedian <- ResultsMatrix$Y50.ba
SaPlusEpsilon <- ResultsMatrix$YplusEpsilon.ba
SaMinusEpsilon <- ResultsMatrix$YminusEpsilon.ba

# Plot
plot(T.list, SaMedian, type = "p", log = "xy", col = "blue", pch = 19,
     xlim = c(0.01, 10), ylim = c(0.001, 1), xaxs = "i", yaxs = "i",
     xlab = "Spectral Period, T [sec]", ylab = "Spectral Acceleration, Sa [g]",
     main = "BA08 Ground Motion Predictions:  Median +/- 1 SD")
points(T.list, SaMedian, pch = 19, col = "blue")
points(T.list, SaPlusEpsilon, pch = 19, col = "red")
points(T.list, SaMinusEpsilon, pch = 19, col = "red")
lines(T.list, SaMedian, lwd = 3, col = "blue")
lines(T.list, SaPlusEpsilon, lwd = 1, col = "red")
lines(T.list, SaMinusEpsilon, lwd = 1, col = "red")



########################################################################
# Example 3:  Generate a plot of the median response spectra for the
#             same hypothetical earthquake, comparing the different
#             NGA models

# Redefine T to be a vector
# We only desire T >= 0.01 for plotting
T.list <- modelPeriods(model = "BA08", positive = TRUE)

# Ground motion calculations
ResultsMatrix <- Sa.nga(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30,
                        epsilon = 1, T = T.list, dip = dip, W = W,
                        Ztor = Ztor, rake = rake, Fhw = Fhw, Fas = Fas)

# Access individual columns of the data frame using the "$" operator:
SaAS08 <- ResultsMatrix$Y50.as
SaBA08 <- ResultsMatrix$Y50.ba
```

```
SaCB08 <- ResultsMatrix$Y50.cb
SaCY08 <- ResultsMatrix$Y50.cy

# Plot
plot(T.list, SaAS08, type = "l", log = "xy", col = "blue", pch = 19, lwd = 2,
     xlim = c(0.01, 10), ylim = c(0.001, 1), xaxs = "i", yaxs = "i",
     xlab = "Spectral Period, T [sec]", ylab = "Spectral Acceleration, Sa [g]",
     main = "Comparison of NGA Ground Motion Predictions")
lines(T.list, SaBA08, lwd = 2, col = "red")
lines(T.list, SaCB08, lwd = 2, col = "darkgreen")
lines(T.list, SaCY08, lwd = 2, col = "black")
legend(x = "bottomleft", inset = 0.02, lwd = 2, bty = "n",
       col = c("blue", "red", "darkgreen", "black"),
       legend = c("AS08", "BA08", "CB08", "CY08"))
```

Ground Motion Predictions for Individual Models *Ground Motion Predictions for Individual Models*

Description

Main functions for estimating ground motion parameters using the ground motion prediction equations developed during the Next Generation Attenuation of Ground Motions (NGA) project in 2008. Each function performs ground motion calculations using for an individual NGA model.

Usage

```
Sa.as(M, Rjb, Vs30, VsFlag, epsilon, T, Rrup = NA, Rx = NA,
      dip = NA, W = NA, Ztor = NA, Z1.0 = NA, rake = NA, Frv = NA,
      Fnm = NA, Fhw = NA, azimuth = NA, Zhyp = NA, Fas = 0)
Sa.ba(M, Rjb, Vs30, epsilon, T, rake = NA, U = NA, SS = NA,
      NS = NA, RS = NA, AB11 = 0)
Sa.cb(M, Rjb, Vs30, epsilon, T, Rrup = NA, dip = NA, W = NA,
      Ztor = NA, Z1.0 = NA, Z1.5 = NA, Z2.5 = NA, rake = NA,
      Frv = NA, Fnm = NA, Fhw = NA, azimuth = NA, Zhyp = NA, arb = 0)
Sa.cy(M, Rjb, Vs30, VsFlag, epsilon, T, Rrup = NA, Rx = NA,
      dip = NA, W = NA, Ztor = NA, Z1.0 = NA, rake = NA, Frv = NA,
      Fnm = NA, Fhw = NA, azimuth = NA, Zhyp = NA, AS = 0)
```

Arguments

M	Moment magnitude of earthquake.
Rjb	Joyner-Boore distance (km): the horizontal distance to the surface projection of the rupture plane.
Vs30	Time-averaged shear wave velocity over a subsurface depth of 30 meters (m/s).
VsFlag	Flag variable indicating how Vs30 is obtained; equal to 1 if Vs30 is measured, and 0 if Vs30 is estimated or inferred.

`epsilon`	number of standard deviations to be considered in the calculations. Use 0 to obtain a median estimate of ground motion.
`T`	Spectral period (sec). Use 0 for PGA and -1 for PGV. For the CB08 model only, specify -2 for PGD. For spectral acceleration, `T` must be in the range `0.01 <= T <= 10 sec`. If the specified period is within the allowable range and does not have defined equations, the program uses log-log interpolation (using `interpolate`) between the next-highest and next-lowest spectral periods with defined equations.
`Rrup`	Rupture distance (km): the closest distance to the rupture plane; if left empty, `Rrup` is calculated from `Rx`, the source-to-site azimuth, and the geometric rupture parameters (`Ztor`, `W`, and `dip`) using `Rrup.calc`.
`Rx`	Site coordinate (km): The horizontal distance to the surface projection of the top edge of the rupture plane, measured perpendicular to the strike. If left empty, `Rx` is calculated from `Rjb`, the source-to-site azimuth, and the geometric rupture parameters (`Ztor`, `W`, and `dip`) using `Rx.calc`. When only `Rjb` and the azimuth are assumed, `Rjb` is used to calculate `Rx`, which is then used to calculate `Rrup`.
`dip`	Dip angle of the rupture plane (deg). If left empty, the dip is estimated using `dip.calc`.
`W`	Down-dip width of rupture plane (km). If left empty, `W` is estimated using `W.calc`.
`Ztor`	Depth to top of rupture (km). If left empty, `Ztor` is estimated using `Ztor.calc`.
`Z1.0`	Depth to Vs = 1.0 km/s (m). If left empty, `Z1.0` is estimated using `Z1.calc.as` for the AS08 model and `Z1.calc.cy` for the CY08 model.
`Z1.5`	Depth to Vs = 1.5 km/s (m). Z1.5 is not utilized in ground motion calculations, but if available, it may be used to estimate `Z2.5` for the CB08 model.
`Z2.5`	Depth to Vs = 2.5 km/s (m; **note the units**). If left empty, `Z2.5` is estimated from `Z1.5` or `Z1.0` if available, using the recommendations in Campbell and Bozorgnia (2007). If neither `Z1.5` nor `Z1.0` is available, then `Vs30` is used to estimate `Z1.0` using `Z1.calc.as`, which is in turn used to estimate `Z2.5`.
`rake`	Rake angle of fault movement (deg). Either the rake angle or the style-of-faulting flag variables (`Frv` and `Fnm` for AS08, CB08, and CY08; and `U`, `RS`, `NS`, and `SS` for BA08) must be specified.
`Frv`	Reverse style-of-faulting flag (1 for reverse faulting, 0 otherwise) for the AS08, CB08, and CY08 models. Either (a) the rake angle, or (b) both `Frv` and `Fnm`, must be specified. Reverse faulting is characterized by rake angles in the range `30 <= rake <= 150` deg for the AS08 and CY08 models, and in the range `30 < rake < 150` deg for the CB08 model.
`Fnm`	Normal style-of-faulting flag (1 for normal faulting, 0 otherwise) for the AS08, CB08, and CY08 models. Either (a) the rake angle, or (b) both `Frv` and `Fnm`, must be specified. Normal faulting is characterized by rake angles in the range `-120 <= rake <= -60` deg for the AS08 and CY08 models and `-150 < rake < -30` deg for the CB08 model.
`U`	Unspecified style-of-faulting flag for the BA08 model; equal to 1 if the user wishes to perform a generic ground motion calculation when the style of faulting is unspecified, and 0 otherwise.

RS — Reverse style-of-faulting flag for the BA08 model; equal to 1 for reverse faulting (`30 <= rake <= 150 deg`), and 0 otherwise.

NS — Normal style-of-faulting flag for the BA08 model; equal to 1 for normal faulting (`-150 <= rake <= -30 deg`), and 0 otherwise.

SS — Strike-slip style-of-faulting flag for the BA08 model; equal to 1 for strike-slip faulting (when the rake is not in either of the ranges specified for RS or NS), and 0 otherwise.

Fhw — Hanging wall flag; equal to 1 for sites on the hanging wall side of the fault (`Rx >= 0; azimuth >= 0`), and 0 otherwise. For AS08 and CY08, either `Fhw`, `Rx`, or `azimuth` must be specified. For CB08, the parameters `Fhw` and `azimuth` are optional, and they are only used to estimate `Rrup` when `Rrup` is unknown; if neither `Fhw` nor `azimuth` is specified, the site is assumed to be located on the footwall, and `Rrup` is easily estimated as `sqrt(Rjb^2 + Ztor^2)`.

azimuth — Source-to-site azimuth (deg); see Kaklamanos et al. (2011) for details. Used by `Rx.calc` and `Rrup.calc` for distance calculations.

Zhyp — Hypocentral depth of the earthquake (km). `Zhyp` is not utilized in ground motion calculations, but it may be used to estimate `Ztor`. See `Ztor.calc` for details.

Fas — Aftershock flag for AS08; equal to 1 for aftershocks and 0 for mainshocks (the default).

AS — Aftershock flag for CY08; equal to 1 for aftershocks and 0 for mainshocks (the default).

arb — Flag variable indicating the method of determining aleatory uncertainty for the CB08 model; equal to 1 if the standard deviation should be calculated for the arbitrary horizontal component of ground motion, and 0 if the standard deviation should be calculated for the geometric mean horizontal ground motion (the default).

AB11 — Flag variable equaling 1 if the Atkinson and Boore (2011) small-magnitude correction factor should be applied to the BA08 model, and 0 otherwise.

Details

Note that T (spectral period) can be a vector, while all other arguments must be scalars.

Value

The spectral acceleration (in units of *g*) at period T; peak ground acceleration (PGA, in units of *g*) when `T = 0`; peak ground velocity (PGV, in units of cm/sec) when `T = -1`; and peak ground displacement using the CB08 model (PGD, in units of cm) when `T = -2`.

Author(s)

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See Also

See `Sa.nga` for a comprehensive function that computes the ground motions from the AS08, BA08, CB08, and CY08 models, and outputs data in a matrix format. See `KBflatfile` for an example of inputting and outputting earthquake data and predictions.

For details on the sub procedures used for the individual NGA models, see `subs.as`, `subs.ba`, `subs.cb`, and `subs.cy`. See `coefs` for details on the period-independent model coefficients, and `coefs.t.as`, `coefs.t.ba`, `coefs.t.cb`, and `coefs.t.cy` for details on the period-dependent model coefficients.

For procedures on estimating input variables when they are not known, see `Rx.calc`, `Rrup.calc`, `dip.calc`, `W.calc`, `Ztor.calc`, `Z1.calc`, `Z2.5.calc`, and `Zhyp.calc`. These procedures are further described in Kaklamanos et al. (2011).

For details on the spectral periods and ground motion parameters defined for each of the models, see `modelPeriods` or `periods`. The functions `getPeriod` and `interpolate` provide methods for estimating spectral accelerations at intermediate periods between those with defined model coefficients.

Examples

```
# Assumed earthquake parameters for these examples:
M <- 7
Rjb <- 50
Rrup <- 51
Vs30 <- 300
```

```
Ztor <- 2
W <- 20
dip <- 80
VsFlag <- 0
Fhw <- 0
rake <- 180   # Strike-slip fault
Fas <- 0


####################################################################
# Example 1:  Illustration of the versatility of input for the Sa
#             functions (using CY08 as an example)

# Calculate PGA using the known input variables:
Sa.cy(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30, VsFlag = VsFlag,
      epsilon = 0, T = 0, dip = dip, W = W, Ztor = Ztor,
      rake = rake, Fhw = Fhw, AS = Fas)

# Alternately, the fault type may be input using the
# style-of-faulting flag variables:
Sa.cy(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30, VsFlag = VsFlag,
      epsilon = 0, T = 0, dip = dip, W = W, Ztor = Ztor,
      Frv = 0, Fnm = 0, Fhw = Fhw, AS = Fas)

# If the azimuth is known, it may be used in place of Fhw:
Sa.cy(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30, VsFlag = VsFlag,
      epsilon = 0, T = 0, dip = dip, W = W, Ztor = Ztor,
      Frv = 0, Fnm = 0, azimuth = -20, AS = Fas)

# The variables Rrup, dip, W, and Ztor may be left blank (or set
# to NA), and their defaults will be used in the calculation:
Sa.cy(M = M, Rjb = Rjb, Rrup = NA, Vs30 = Vs30, VsFlag = VsFlag,
      epsilon = 0, T = 0, Frv = 0, Fnm = 0, azimuth = -20, AS = Fas)


########################################################################
# Example 2:  Generate a plot of the predicted response spectrum (and
#             uncertainty) for a hypothetical earthquake using the AS08
#             model

# Redefine T to be a vector
# We only desire T >= 0.01 for plotting
T.list <- modelPeriods(model = "AS08", positive = TRUE)

# Calculations
# Median
SaMedian <- Sa.as(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30,
                  VsFlag = VsFlag, T = T.list, dip = dip, W = W,
                  Ztor = Ztor, rake = rake, Fhw = Fhw, Fas = 0,
                  epsilon = 0)
# Median + 1 SD
```

```
SaPlus1SD <- Sa.as(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30,
                   VsFlag = VsFlag, T = T.list, dip = dip, W = W,
                   Ztor = Ztor, rake = rake, Fhw = Fhw, Fas = 0,
                   epsilon = 1)
# Median - 1 SD
SaMinus1SD <- Sa.as(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30,
                    VsFlag = VsFlag, T = T.list, dip = dip, W = W,
                    Ztor = Ztor, rake = rake, Fhw = Fhw, Fas = 0,
                    epsilon = -1)

# Plot
plot(T.list, SaMedian, type = "p", log = "xy", col = "blue", pch = 19,
     xlim = c(0.01, 10), ylim = c(0.001, 1), xaxs = "i", yaxs = "i",
     xlab = "Spectral Period, T [sec]", ylab = "Spectral Acceleration, Sa [g]",
     main = "AS08 Ground Motion Predictions:  Median +/- 1 SD")
points(T.list, SaMedian, pch = 19, col = "blue")
points(T.list, SaPlus1SD, pch = 19, col = "red")
points(T.list, SaMinus1SD, pch = 19, col = "red")
lines(T.list, SaMedian, lwd = 3, col = "blue")
lines(T.list, SaPlus1SD, lwd = 1, col = "red")
lines(T.list, SaMinus1SD, lwd = 1, col = "red")



########################################################################
# Example 3:  Generate a plot of the median response spectra for the
#             same hypothetical earthquake, comparing the different
#             NGA models

# Calculations
# AS08
SaAS08 <- Sa.as(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30,
                VsFlag = VsFlag, epsilon = 0, T = T.list,
                dip = dip, W = W, Ztor = Ztor, rake = rake,
                Fhw = Fhw, Fas = 0)
# BA08
SaBA08 <- Sa.ba(M = M, Rjb = Rjb, Vs30 = Vs30, epsilon = 0,
                T = T.list, rake = rake)
# CB08
SaCB08 <- Sa.cb(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30,
                epsilon = 0, T = T.list, dip = dip, Ztor = Ztor,
                rake = rake)
# CY08
SaCY08 <- Sa.cy(M = M, Rjb = Rjb, Rrup = Rrup, Vs30 = Vs30,
                VsFlag = VsFlag, epsilon = 0, T = T.list,
                dip = dip, W = W, Ztor = Ztor, rake = rake,
                Fhw = Fhw, AS = 0)

# Plot
plot(T.list, SaAS08, type = "l", log = "xy", col = "blue", pch = 19, lwd = 2,
     xlim = c(0.01, 10), ylim = c(0.001, 1), xaxs = "i", yaxs = "i",
     xlab = "Spectral Period, T [sec]", ylab = "Spectral Acceleration, Sa [g]",
     main = "Comparison of NGA Ground Motion Predictions")
```

```
lines(T.list, SaBA08, lwd = 2, col = "red")
lines(T.list, SaCB08, lwd = 2, col = "darkgreen")
lines(T.list, SaCY08, lwd = 2, col = "black")
legend(x = "bottomleft", inset = 0.02, lwd = 2, bty = "n",
       col = c("blue", "red", "darkgreen", "black"),
       legend = c("AS08", "BA08", "CB08", "CY08"))
```

Interpolation for Intermediate Spectral Periods

Interpolation for Intermediate Spectral Periods

Description

Performs linear interpolation; simple wrapper of the internal R function `approx`.

Usage

```
interpolate(x, x1, x2, y1, y2)
```

Arguments

`x`	x-value at which the interpolated y-value is desired.
`x1, x2`	two x-values.
`y1, y2`	two y-values.

Details

For log-log interpolation, the arguments should be entered in log space.

Value

Interpolated value `y` corresponding to `x`, using linear interpolation between points `(x1, y1)` and `(x2, y2)`.

Author(s)

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See Also

`getPeriod`, `Sa`, `Sa.nga`.

Examples

```
# Example interpolation of spectral acceleration:

# Assumed earthquake parameters:
M <- 6
Rjb <- 30
Vs30 <- 500
rake <- 90
epsilon <- 0

# Desired: Median Sa at T = 0.19 sec using the BA08 model

# Since there are no defined coefficients at T = 0.19 sec,
# log-log interpolation is necessary.

# First, find the periods directly above and below T = 0.19 sec
T1 <- getPeriod(T = 0.19, model = "BA08")$lower
T2 <- getPeriod(T = 0.19, model = "BA08")$upper
T1
T2

# Second, find the spectral accelerations for those periods
Sa1 <- Sa.ba(M = M, Rjb = Rjb, Vs30 = Vs30, rake = rake, epsilon =
epsilon, T = T1)
Sa2 <- Sa.ba(M = M, Rjb = Rjb, Vs30 = Vs30, rake = rake, epsilon =
epsilon, T = T2)
Sa1
Sa2

# Third, use the interpolate function to find Sa at T = 0.19 sec
# Note the use of log-log interpolation
LnSa <- interpolate(x = log(0.19), x1 = log(T1), x2 = log(T2),
                    y1 = log(Sa1), y2 = log(Sa2))
Sa <- exp(LnSa)
Sa
```

`Spectral Periods for NGA Models`

Spectral Periods for NGA Models

Description

The function `modelPeriods` returns a vector of periods (sec) for which the model coefficients are defined for the different NGA models.

The function `getPeriod` determines whether or not a given period `T` has defined coefficients. If not, the function returns the next-highest and next-lowest periods with defined coefficients.

Usage

```
modelPeriods(model, positive = FALSE)
getPeriod(T, model)
```

Arguments

`model`	a string indicating the name of the model from which periods should be returned, i.e., `"AS08"`, `"BA08"`, `"CB08"`, or `"CY08"`.
`positive`	logical value (`TRUE` or `FALSE`) indicating whether or not to return only positive periods (i.e., spectral periods 0.01 sec and greater), excluding PGA (`T = 0`), PGV (`T = -1`), and PGD (`T = -2`, in the case of CB08) from the list. If `positive = FALSE`, the periods corresponding to PGA, PGV, and PGD (for the CB08 model) are appended to the list.
`T`	spectral period at which the ground motion calculation is to be performed (sec)

Details

The `modelPeriods` function is a generalization of `periods.as`, `periods.ba`, `periods.cb`, and `periods.cy`. The purpose of the `positive` argument is to separate spectral acceleration (which is a continuous function of `T`) from PGA, PGV, and PGD. This is useful for interpolation purposes (only Sa may be interpolated) and for plotting the predicted response spectra.

Value

`modelPeriods` returns a vector of periods that have defined coefficients for the specified NGA model (sec).

`getPeriods` returns a three-element list with components `interp`, `lower`, and `upper`:

`interp`	a logical value indicating whether or not interpolation is necessary given the spectral period `T`
`lower`	gives the greatest period less than `T` that has defined model coefficients (if `interp = TRUE`)
`upper`	gives the smallest period greater than `T` that has defined model coefficients (if `interp = TRUE`)

If `interp = FALSE`, then `lower` and `upper` contain null values.

Author(s)

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References

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Chiou, B. S.-J., and R. R. Youngs (2008). An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthquake Spectra* **24,** 173–215.

See Also

periods, interpolate, Sa, Sa.nga.

Examples

```
# Example 1: List of periods for the AS08 model

# Entire list of ground motion parameters
modelPeriods(model = "AS08")

# List of spectral periods excluding PGA and PGV
modelPeriods(model = "AS08", positive = TRUE)


# Example 2: Find whether interpolation is necessary to estimate
# ground motions at a spectral period of 0.65 sec using the AS08 model

getPeriod(T = 0.65, model = "AS08")

# ANSWER: Yes, interpolation is necessary.  The next-lowest period
# with defined coefficients is 0.5 sec, and the next-highest period
# with defined coefficients is 0.75 sec.
```

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