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ORIGINAL ARTICLE

R-CRISIS: 35 years of continuous developments and improvements for probabilistic seismic hazard analysis

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Abstract
A new version of CRISIS, the program to perform probabilistic seismic hazard analysis (PSHA), has been released. This new version, called R-CRISIS v20, includes several additions and improvements with respect to previous ones, in the geometric, attenuation and seismicity models, besides having implemented a parallelized computational process that speeds up the computations up to five times, adding flexibility to the users to perform state-of-the-art PSHA and more complex and detailed analyses within reasonable computational times. These additions have been implemented with the objective of having better representations of the different components of a PSHA whilst preserving all the options that were available in previous versions of the program. R-CRISIS remains being a free and open-source program, two characteristics that combined with its flexible programming architecture provide room for future developments of this mature and widely used tool.

Keywords PSHA · Seismic hazard · Stochastic catalogues · Hazard maps

1 Introduction

A new version of R-CRISIS, the computer program to perform probabilistic seismic hazard analyses, has been released. This release incorporates more efficient computational capabilities, besides providing flexibility to the users in the form of additional options to represent in a more detailed manner the geometric, seismicity and ground motion prediction components. All the new developments were easily integrated into the new version of R-CRISIS because of its flexible programming architecture and its open-source spirit. The

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main objectives pursued during the development of this new version were: (1) the implementation of a parallelized calculation process to take advantage of today's computational capabilities; (2) to include a larger set of options for the representation of the geometric, seismicity and attenuation components, allowing users to perform state-of-the-art PSHA; and (3) to include a set of tools that allow direct integration between the PSHA outcomes and structural and earthquake engineering practices, such as liquefaction analyses, the definition of optimum design spectra and the calculation of conditional mean spectrum (CMS).

The first version of the CRISIS program was released in 1986. It was written in FORTRAN and had the form of a command line application (Ordaz 1991). Over time, a transition into Visual Basic programming language was made, which allowed for the introduction of a graphical user interface (GUI), a feature that has been maintained since then. Figure 1 shows in the form of a timeline the versions of the program that, since its first release, have included major changes and updates. Along these years, R-CRISIS has always kept pace with the developments that have occurred in the field of PSHA.

This new version is mostly based on CRISIS 2008 (Ordaz et al. 2013), written with an object-oriented technology that incorporates a friendly GUI, allowing the user to input data and select all the relevant parameters in a direct manner, instead of having the need of creating complicated input files outside the program.

Besides satisfying the needs of the developers, all of them PSHA practitioners, this new version has also considered specific needs of particular projects, such as the Global Risk Model of the United Nations Office for Disaster Risk Reduction (UNISDR 2017), which represented the first globally consistent and fully probabilistic PSHA and probabilistic earthquake risk assessment (Ordaz et al. 2014; Cardona et al. 2014). R-CRISIS accepts too input files created in OpenQuake (GEM 2020) so that the PSHA can be performed by directly using them, a feature included to allow comparisons of the results between the two programs and which has been useful for validation of the results in particular projects.

R-CRISIS continues to be based on the classic PSHA approach proposed by Esteva (1967, 1970) and Cornell (1968), which is a form of the total probability theorem, generalized, since its 2008 version, to the case of non-Poissonian occurrences. Therefore, R-CRISIS works directly with exceedance probabilities and not with annual rates of exceedance, as it is customary in many PSHA codes.

In order to construct a PSHA project, a definition of a set of seismic sources is required, which would produce earthquakes at rates given by their recurrence models, which are in many cases magnitude-frequency distributions. Based on the geometry and characteristics of the seismic sources and on their magnitude-frequency distributions, an event set is generated, with a spatial density of events that is enough to perform an accurate spatial integration. Then for each event, using the GMPE selected by the user,

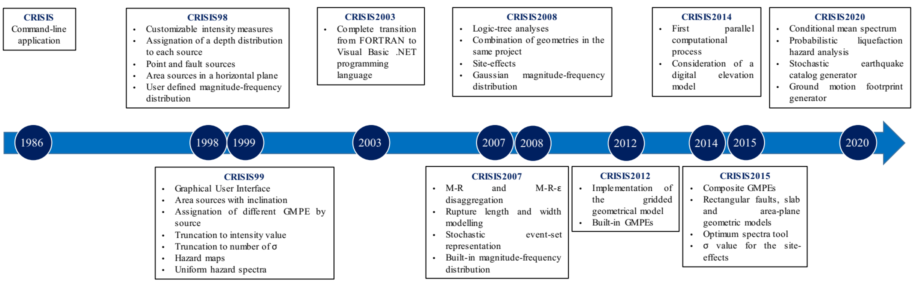

Fig. 1 Timeline with the historical development of R-CRISIS

R-CRISIS evaluates the exceedance probability of the intensity values of interest given that an earthquake of known magnitude and occurrence probability has occurred. The probabilities for all magnitudes and sources are accumulated following probability rules to finally obtain the overall exceedance values.

The code is written in Visual Basic.NET, as the previous versions, which means that the program requires a Windows OS to run. However, for users who want to use the program in a different OS like Linux, a Windows OS virtual machine can be used. A main difference in the programming stage with respect to previous versions is that R-CRISIS is compiled for 64-bit, an issue directly related to the parallelized computing capabilities of some computers that allow running larger and more complex seismic hazard models within reasonable times.

During the past 35 years, R-CRISIS has positioned itself as a reliable, robust and widely used tool for PSHA in different academic and industry activities such as site-specific hazard analyses, the generation of hazard maps for earthquake resistant building codes and generating input data for fully probabilistic risk assessments at different scales (Menon et al. 2004; Meletti et al. 2008; Marulanda et al. 2013; Cardona et al. 2014; Salgado-Gálvez et al. 2014; Lindholm et al. 2016; Ischuk et al. 2017). To date, R-CRISIS has been used to develop PSHA at local and regional scales in more than 100 countries, as shown in Fig. 2. For instance, in several countries of Latin America it has been the tool used for the development of earthquake zonation maps included in the local codes for buildings, bridges and other types of structures (MVADT 2010; AIS 2013; Ministerio et al. 2014; MVCS 2018), as well as being the underlying tool for reference values of certified models for the estimation of reserves in the insurance and reinsurance sector in Mexico, Peru and Colombia (SFC 2017).

Figure 3 shows the downloads counting since the v18.0 release of R-CRISIS, in October 2017. That release coincided with the launch of the program's website, on which a community of PSHA practitioners from different countries have the possibility to exchange ideas and projects, besides obtaining rapid support, in the discussion forum. Table 1 shows the 10 countries with the largest number of registered users in the R-CRISIS.

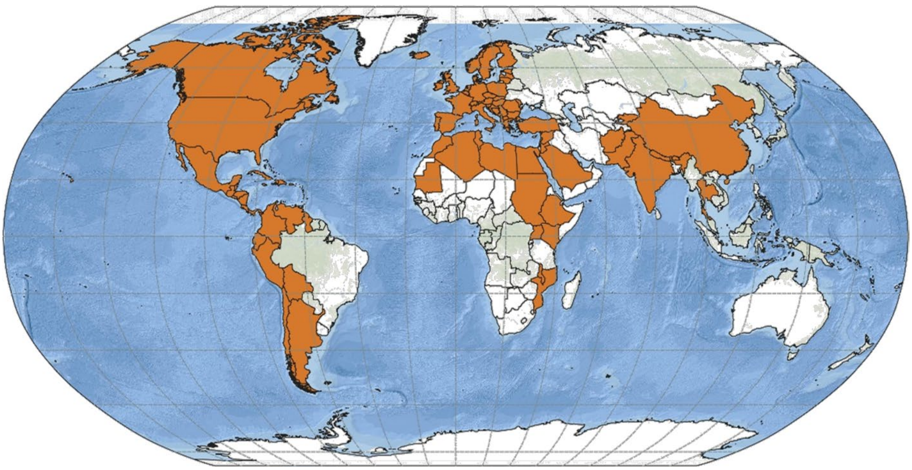

Fig. 2 Countries where R-CRISIS has been used for local and regional PSHA

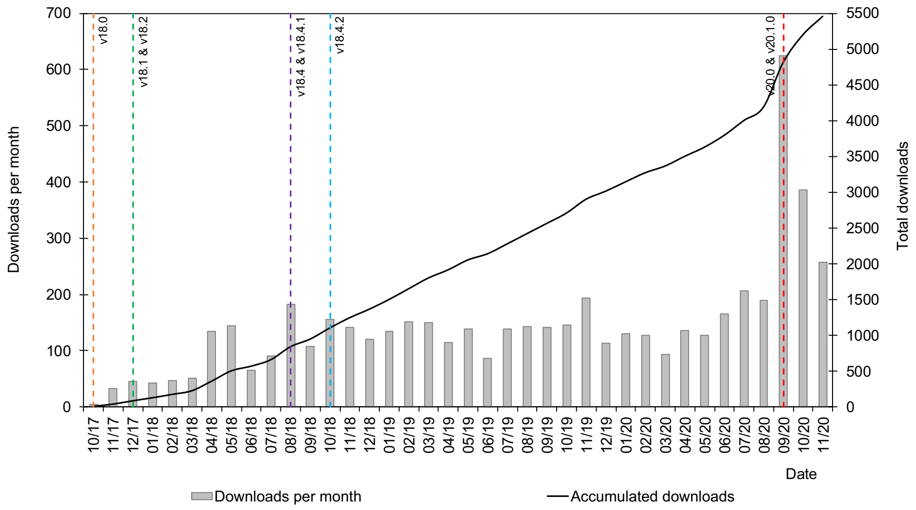

Fig. 3 Downloads per month and accumulated downloads of R-CRISIS since the v18.0 release in October 2017

Table 1 10 countries with the largest number of registered users in R-CRISIS since October 2017

Country	Registered users
Peru	444
Mexico	221
India	209
Iran	197
Turkey	191
Colombia	153
Indonesia	133
Italy	121
Ecuador	104
United states	94

2 New features in R-CRISIS

All the new features introduced in the latest version of R-CRISIS with respect to the previous ones are described herein. Most of them are related to the different components of a PSHA, ranging from the selection of geometrical models to the definition of earthquake occurrence processes, ground-motion attenuation relationships, the possibility to generate composite attenuation models and the way to calculate the intensities for some exceedance rates or probabilities. In addition, new tools to directly connect the outputs of PSHA with activities of interest in the earthquake and structural engineering fields have also been added.

2.1 Parallelized computational capabilities

R-CRISIS now implements a parallelized computational process that, depending on the computer specifications, has speeded up the calculation process up to five times, if compared with the non parallelized version. The computational performance depends on the number of available processors and if a computer with more processors is available, then the computation time will be even shorter. This development is the continuation of an effort started in the web tool of CRISIS2008, used to distribute the number of applications in different machines, highly useful when performing large and complex calculations. Besides this, a batch computation utility has been made available allowing running R-CRISIS from a command line at the OS prompt.

2.2 Importing geometry and seismicity data from shapefiles

In R-CRISIS it is now possible to import the geometry of the sources and their seismicity parameters from ESRI shapefiles. These files need to be projected on the WGS-84 coordinate system and in general, the geometrical components of the sources (i.e. the vertex coordinates) are stored in the geometric part of the file (*.shx), whereas the values for other geometry and seismicity parameters are stored in the attribute part of the file (*.dbf).

2.3 PSHA outputs in terms of exceedance probabilities, non-exceedance probabilities and exceedance rates

In R-CRISIS the user has the option to select the way in which the PSHA results are written by the program. Since CRISIS2008, when non-Poissonian seismicity models were introduced, all calculations are made in terms of exceedance probabilities but, once a timeframe is set and the exceedance probability is known, obtaining an exceedance rate requires only a simple conversion. In some cases, it may be more convenient to have the output files in terms of exceedance rates instead of probabilities since the former can be directly added, whilst the latter cannot. In the case of non-Poissonian occurrence models, there is not a true exceedance rate, since the probabilities of exceedance, in general, depend on the observation timeframe, that is, the next Tf years. In these cases, R-CRISIS uses the concept of *equivalent* exceedance rate, ν_e, which, mimicking the Poisson case, is computed from the exceedance probability, P_e, and the observation time frame with the following expression:

$$\nu_e = 1 - \frac{1}{Tf} \ln(1 - P_e) \tag{1}$$

2.4 Eight types of geometric models

Within the same R-CRISIS project, the user can combine different types of geometric models and for this, R-CRISIS allows representing the geometry of the sources with the following eight models: 1) areas, 2) lines, 3) points, 4) area-planes (virtual faults), 5) rectangular faults, 6) slabs, 7) grids and, 8) ruptures. Models 1 to 3 were implemented in previous versions of the program, whereas models 4 to 8 are new additions to this release.

The sizes of the rupture areas or lengths (depending on the geometric model used) depend on magnitude scaling relationships. For estimating the areas of the ruptures, the relationship shown in Eq. 2 is used, whereas for estimating the length of the ruptures, the relationship shown in Eq. 3 is used. R-CRISIS includes a set of well-known relationships as built-in models (Brune 1970; Singh et al. 1980; Wells and Coppersmith 1994) although the user can customize the values (K_1 and K_2 for the case of areas, and K_3 and K_4 for the case of lengths).

$$A = \pi K_1^2 \cdot e^{2K_2 M} \tag{2}$$

$$L = K_3 \cdot e^{K_4 M} \tag{3}$$

where A is the rupture area in km^2, L the rupture length in km and M the magnitude of the earthquake.

The area-plane model (also known as virtual faults in other PSHA programs) is a modified version of the classical area one. In the area model, it was assumed that all the rupture planes were contained in the plane of the area itself; in the new area-plane model, the orientation of the rupture planes is defined by the user through the strike and dip values; therefore, this model is similar to that of virtual faults. The user can also select the shape of the rupture between rectangular and elliptical, which is a feature that allows for a better representation of the ruptures in some cases. Nowadays, the area-plane geometric model should be preferred in PSHA due to the flexibility of representing several features of the earthquake ruptures. Area sources are a particular case of area-planes and have been kept in the latest version or R-CRISIS for compatibility reasons. R-CRISIS does not impose any vertical limit on the ruptures; therefore, the modeler must make sure that the size of the modelled ruptures (as per their orientation, focal depth and aspect ratio) does not extend beyond the earth's surface.

In the rectangular fault models, all hypocenters are uniformly distributed along a rectangular area with strict boundary conditions, which contains all the ruptures; this means that the ruptures are not allowed to extend beyond the geometrical limits of the sources. Sources are defined by the coordinates of the upper lip, a dip angle and a width, which altogether define the plane. For this geometric model, ruptures can only have rectangular shapes.

The slab model was introduced to better characterized inslab seismicity where, using the geometry of the top end of the slab, a set of rectangular faults are placed, and ruptures therefore occur within them. For the generation of the set of rectangular faults, the user must define the dip and width values together with the number of rectangular faults to be used in each case. Since this source has strict boundary conditions, R-CRISIS performs a smooth transition between the original aspect ratio and that of the source in order to accommodate the rupture.

The gridded model allows representing a source through multiple nodes that belong to a rectangular grid which lies parallel to the Earth's surface. Each node is treated by R-CRISIS as a point source and therefore, as a possibly hypocenter. The user furnishes the orientation of the rupture planes at each node. Figure 4 shows a schematic representation of each geometric model and a brief description of the new geometric models is provided next. The depth of each gridded source is constant, but the program does not have any limit on the number of sources, reason why the user can define and distribute the sources in

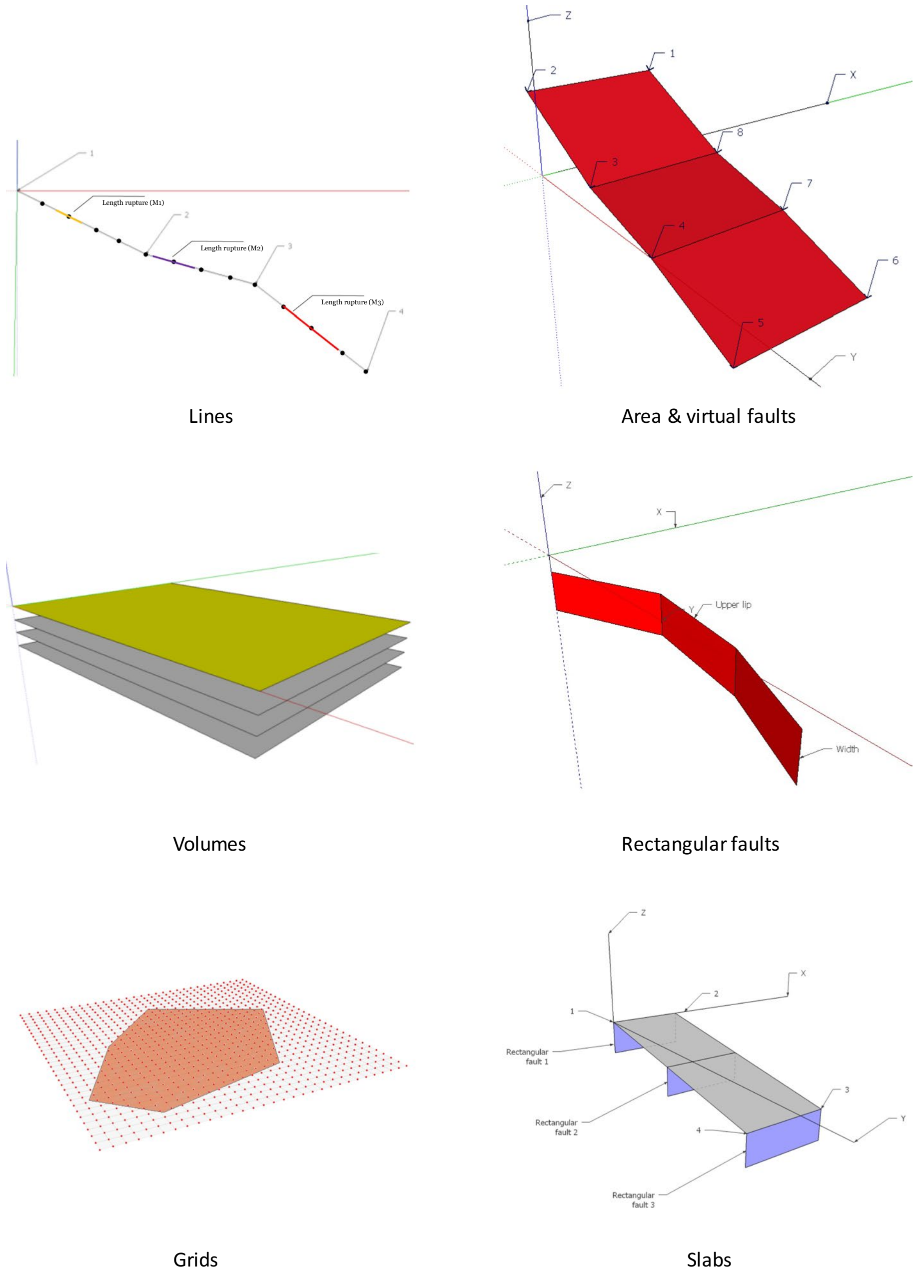

Fig. 4 Schematic representation of some of the different geometric models available in R-CRISIS

depth as needed. The volume option shown in Fig. 4 applies to the area geometric model where the user can define a set of slices, uniformly distributed within a predefined depth.

It is worth noting the following: a) for the case of area and area-planes, the required three-dimensional description of the source is the same, while the difference lies in the characterization of the ruptures; and b) that point sources are a particular case of the gridded geometry.

Finally, a seismic source can be defined too in terms of a set of individual ruptures with varying location, orientation and dips which are characterized by the magnitude, area and shape of the rupture, together with their occurrence probabilities. Ruptures from other programs such as OpenQuake can be directly integrated into R-CRISIS by using this geometric model. For all the geometric models the user can define an aspect ratio (width/length) for the ruptures. Figure 5 shows an example of this geometric model, where each blue point corresponds to an earthquake focus and is assigned a magnitude, a rupture area, orientation, shape, occurrence frequency and GMPE(s). Ruptures shown in Fig. 5 are only indicative, provided just to show the versatility of this source type and are not fixed for any seismic region.

2.5 Smoothed seismicity grids from earthquake catalogues

Thanks to a suggestion by Dr. Ramón Secanell (Secanell 2012), a tool for generating *a*-value grids from earthquake catalogues using the Woo (1996) smoothing approach has been added to R-CRISIS. This approach was used, for instance, in the development of the first globally consistent PSHA (Ordaz et al. 2014) for the United Nations' Global Risk Model. R-CRISIS does not perform any validation of the earthquake catalogue, so homogenization of magnitudes, completeness verifications and/or declustering processes need to be performed beforehand by the user. The input file for using this geometric model in R-CRISIS is a shapefile with at least the information of latitude and longitude (in decimal degrees), depth (in km) and magnitude.

2.6 Ground motion prediction equations

GMPEs can be added to the R-CRISIS projects in four different ways: (1) attenuation tables; (2) built-in models; (3) Fourier Amplitude Spectra (point source ω^2); and (4)

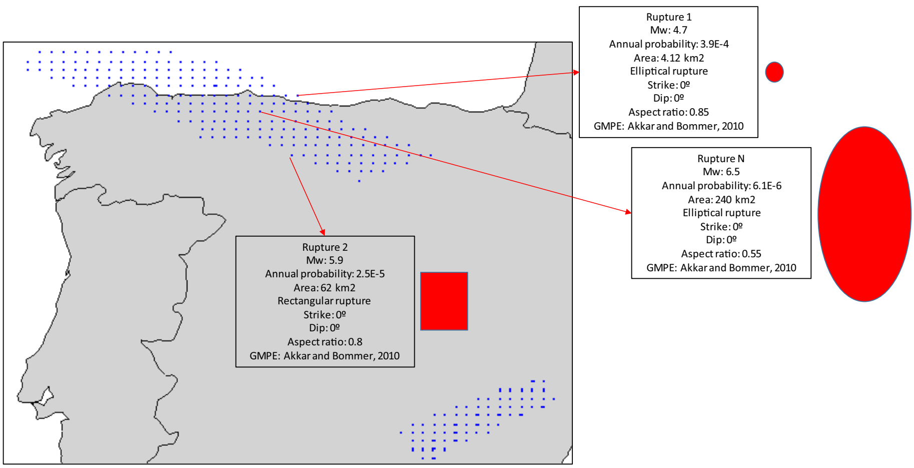

Fig. 5 Schematic representation of the ruptures' geometric model

Table 2 Built-in GMPEs in R-CRISIS (as of December 2020)

References	
Abrahamson and Silva (1997)	Derras et al. (2016)
Abrahamson et al. (2014) NGA-West2	Faccioli et al. (2010)
Abrahamson et al. (2016) BCHydro	García et al. (2005)
Akkar and Bommer (2007)	Gómez (2017)
Akkar and Bommer (2010)	Idriss (2008)
Akkar et al. (2014)	Idriss (2014) NGA-West2
Arroyo et al. (2010)	Jaimes et al. (2006)
Atkinson and Boore (2003)	Jaimes et al. (2015)
Atkinson and Boore (2006)	Kanno et al. (2006)
Atkinson (2008)	Lanzano et al. (2019)
Bindi et al. (2011)	Lin and Lee (2008)
Bindi et al. (2017)	McVerry et al. (2006)
Boore and Atkinson (2008) NGA	Montalva et al. (2017)
Boore et al. (2014) NGA-West2	Pankow and Pechmann (2004)
Campbell (2003)	Pasolini et al. (2008)
Campbell and Bozorgnia (2003)	Pezeshk and Zandieh (2011)
Campbell and Bozorgnia (2008) NGA	Pezeshk et al. (2018)
Campbell and Bozorgnia (2014) NGA-West2	Reyes (1998)
Cauzzi and Faccioli (2008)	Sabetta and Pugliese (1996)
Cauzzi et al. (2015)	Sadigh et al. (1997)
Chávez (2006)	Sharma et al. (2009)
Chiou and Youngs (2008) NGA	Spudich et al. (1999) SEA99
Chiou and Youngs (2014) NGA-West2	Tavakoli and Pezeshk (2005)
Climent et al. (1994)	Toro et al. (1997)
Contreras and Boroschek (2012)	Yenier and Atkinson (2015)
Darzi et al. (2019)	Youngs et al. (1997)
Derras et al. (2014)	Zhao et al. (2006)

generalized models (Ordaz et al. 2013). The latest version of R-CRISIS includes a comprehensive set of built-in GMPEs as listed in Table 2. For each model, a brief description together with the magnitude and distance ranges is provided in the GUI. This built-in GMPE list is continuously updated with the aim of providing the users with the latest attenuation models that are published and widely used in earthquake engineering, such as those developed under the NGA-West2 Research Project (Bozorgnia et al. 2014) and also more recent ones such as Pezeshk et al. (2018) and Lanzano et al. (2019). As in CRISIS2008, GMPEs are programmed as classes that can be added to the program by the users without needing to recompile the core code. However, these classes need to be compiled using a programming language compatible with Visual Basic.NET.

Many of these GMPEs make use of different types of distances and for this reason, R-CRISIS can handle four of them: 1) epicentral (R_{EPI}), 2) focal (R_F), 3) closest to rupture (R_{RUP}) and, 4) Joyner and Boore distance (R_{JB}), as schematically shown in Fig. 6. Also, R-CRISIS is able to compute Rx, Ry and ZToR, which are distance metrics required by some GMPE.

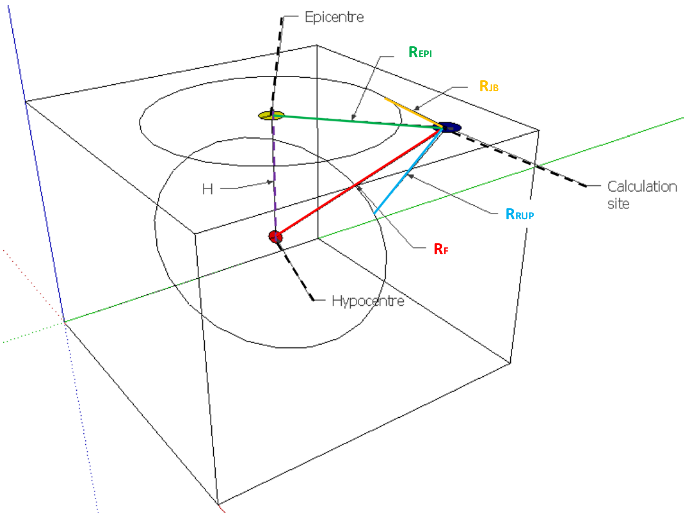

Fig. 6 Types of distances handled by R-CRISIS

2.7 GMPE logic-tree branch constructor

R-CRISIS incorporates a tool that allows for the automatic construction of a set of seismic hazard models that collectively constitute a logic-tree, where each hazard model is one of the branches of the tree. The logic-tree that can be constructed with this tool is one in which the geometry and seismicity characteristics are fixed (i.e. the same for all branches of the logic-tree) but each branch represents a different combination of GMPEs. Stochastic earthquake catalogues can also be generated in *.AME format (Torres et al. 2014) using logic-trees where the weight associated to each branch is reflected in the occurrence frequency of each event.

2.8 Composite (hybrid) GMPEs

R-CRISIS allows the creation of composite (or hybrid) GMPEs, either by combining built-in models and/or user defined attenuation tables. A composite GMPE is the result of a weighted combination of two or more distributions (typically lognormal ones) that can have different median values and standard deviations (Scherbaum et al. 2005). In its more general form, the conditional probability of exceeding an intensity measure, A, is calculated as:

$$P(A > a) = \sum_{i=1}^{N} w_i \left\{ 1 - \Phi \ln\left(\frac{a - \mu_i}{\sigma_i}\right) \right\} \tag{4}$$

where w_i is the weight assigned to the *i-th* base GMPE, Φ is the normal distribution and μ_i and σ_i are the mean values and standard deviations respectively of the i^{th} base GMPE. Composite GMPEs are useful for cases where the normal distributions do not fit well with the recorded earthquake data (i.e. observations show that there are higher probabilities of extremes than those provided by the normal distributions). This issue is more evident, when using lognormal distributions, at high epsilons and, the development of composite

GMPEs generally allow considering heavier tails. Composite GMPEs can be used instead of logic-trees yielding faster calculations and avoiding the creation of separate R-CRISIS projects. Instead of assigning weights to the branches, those are assigned to the base GMPEs for the generation of the composited model. Although both approaches yield the same results in terms of expected values, since the way in which uncertainties are treated is different (epistemic in the logic-tree and random in the composite GMPE), the estimations of variances do differ according to what is explained in detail by Ordaz and Arroyo (2016).

2.9 GMPE viewer

A new tool has been included in R-CRISIS to visualize, individually or collectively, the GMPEs that have been added to the project. The user must indicate parameters such as magnitude, distance, strike and dip so that the visualization of the attenuation relationships is done in terms of: (1) a spectrum, (2) an attenuation curve for a given spectral ordinate and, (3) a magnitude scaling curve for a given spectral ordinate.

2.10 Consideration of a digital elevation model

Following an idea and a request of Dr. Laura Peruzza (Peruzza 2012), a digital elevation model (DEM) can be added to the R-CRISIS project and therefore, the PSHA is performed considering the distance, above the mean sea level, of any calculation site. This feature is useful when the calculation site is at a considerable height (Peruzza et al. 2017) compared to the hypocentral depths. However, this is an optional feature in the R-CRISIS project and if no DEM is provided, all the calculation points are assumed to be at mean sea level. When a DEM is added to the R-CRISIS project, sources can be located above the sea level. This is the case, for instance, of the PSHA performed at the Etna volcano (Peruzza et al. 2017), in which some sources are above the sea level. In fact, adding a DEM was suggested by Dr. Laura Peruzza, specifically for this project.

2.11 Consideration of site-effects

Starting with CRISIS2008, inclusion of site-effects to the PSHA was made available to the users. The methods to account for site effects have been expanded, and four different approaches to estimate amplification factors are available: 1) CAPRA-type, on which a binary file is constructed based on data associated to the fundamental period of the soil at different locations and the amplification factors, typically spectral ratios, associated to each of them; 2) Chiou and Youngs (2014) approach where using a reference V_{s30} value for rock and a grid of V_{s30} for different locations, the amplification factors are estimated in the way proposed in their GMPE; 3) incorporating directly V_{s30} data in terms of a grid for the domain under study and make use of GMPEs that account explicitly for said parameter (e.g. Atkinson and Boore 2006 or Cauzzi and Faccioli 2008), so the GMPE will be modified according to the V_{s30} value at each location; and, 4) Fourier type amplification factors when the GMPEs used in the R-CRISIS project are of the point source (ω^2) type (Ordaz and Singh 1992). The amplification factors are indexed in a similar way as the CAPRA-type ones. Consideration of site-effects is optional and if no information is provided, R-CRISIS assumes an amplification factor equal to 1.0 over the domain under study.

2.12 σ value for the site-effects

In previous versions of R-CRISIS, the amplification factor only modified the median of the intensity, whereas now, σ values are considered too and values different that the ones provided by the GMPEs can be used. These σ values can depend on the site location, structural period and ground-motion intensity level (Bazzurro and Cornell 2004a; 2004b), which is included to consider the non-linearity of the soil behavior. In view of this, σ values are provided through a 4-index matrix which has the same structure than the matrix that includes the amplification factors.

2.13 Event-set for a site

R-CRISIS includes a tool to visualize and export the list of all the earthquakes that are considered to perform the PSHA at a site of interest. The list of earthquakes will depend on the location of the site of interest and the integration distance that has been defined in the project. Within the GUI, the different epicenters are shown, using different colors when associated to different seismic sources. A file with all the relevant information of each event-set, such as location, depth, magnitude and median intensities, among others, can be exported into *.csv format for post-processing purposes if required by the user.

2.14 Synthetic catalogue generator

A new tool has been included in R-CRISIS for generating stochastic catalogues of different durations. Each stochastic catalogue represents a possible realization of earthquakes during the defined timeframe (in years) associated to the different seismic sources included in the project. The events included in the synthetic catalogue are associated to an occurrence date within the range of the initial and final timeframe defined by the user. All locations, magnitudes and recurrences are fully compatible with the geometric and seismicity parameters and these data can be useful for validation and calibration purposes. We have found this feature particularly useful, since a stochastic realization of an earthquake catalog can reveal deficiencies in the modeling process and can be used to see if the stochastic catalog has the same “flavor” that one can see in the real catalog.

2.15 Stochastic event-set generator

R-CRISIS allows generating a stochastic event-set of earthquakes that altogether are mutually exclusive, collectively exhaustive and are represented in a probabilistic manner after considering the uncertainties in the geographical distribution of the hazard intensities and the occurrence frequencies (Ordaz 2000). These events are associated to all the seismic sources included in the project and a set of parameters for the geometrical discretization and number of magnitude bins can be defined by the user and the event-set associates to each event an annual occurrence rate (or probability). Results are stored in *.csv or *.AME format. The latter is fully compatible with the new versions of the R-CAPRA program (ERN 2020). R-CAPRA can generate the ground motion field for any event from a *.AME file, whereas the exported data in *.csv format allow estimating the response spectra for all events at a site of interest.

The option to generate an *.AME file with data about only one event is available too, for which the user must provide the information about the magnitude, location, depth, shape and aspect ratio of the rupture, strike, dip and the associated GMPE.

2.16 Epsilon ranges for hazard disaggregation

Previous versions of R-CRISIS performed the ε disaggregation in a cumulative manner between -∞ and the ε value provided by the user (Bazzurro and Cornell 1999). In this new version, the ε disaggregation can be performed between two predefined ε values, ε_0 and ε_1.

2.17 Optimum spectra computation

The development of earthquake hazard maps included in the earthquake resistant building codes is typically supported by a PSHA. Previous versions of the program have been widely used for these purposes in different regions of the world (see Pérez-Rocha and Ordaz 2008; Salgado-Gálvez et al. 2010; 2016; IGN and UPM 2013). In the light of this, and with the aim of establishing the optimal design intensities to determine the security level that must be yielded in the seismic design of structures, a tool that combines the PSHA results with economic data and construction costs, as first proposed by Rosenblueth (1976) and with the details explained in Ordaz et al. (2017) has been included in this release of the program.

2.18 Conditional mean spectrum

The new version of R-CRISIS includes a tool to estimate the conditional mean spectrum (CMS) for a site of interest, a given fundamental period and a target intensity. The exact conditional spectrum is calculated with the approach proposed by Lin et al. (2013) and for the inter-period correlation model, two options are available (Baker and Jayaram 2008; Jaimes and Candia 2019); additional inter-period correlation models will be added in future releases. The results can be exported in *.csv format for which the CMS median and the σ's natural logarithm values are provided.

2.19 Probabilistic liquefaction hazard analysis

The integration between PSHA and probabilistic liquefaction hazard analysis (PLHA) has been made in the latest version of R-CRISIS. In principle, any approach to estimate the liquefaction probability can be integrated within the PSHA framework and for example, the Ku et al. (2012) method is currently implemented in R-CRISIS. The PLHA is performed considering the contribution of several (thousands of) earthquakes and after estimating the acceleration at ground level using the amplification factors explained before, combined with the geotechnical characteristics of the soil column, the estimation of annual rates for liquefaction occurrences for different depth values of the soil strata under analysis is performed. This method allows a more comprehensive approach than the classical one used in liquefaction analyses based on the selection of a maximum credible earthquake (MCE) and can be used for reliability analyses and the definition of acceptance criterion. The full details of this implementation are described in Ordaz et al. (2020).

2.20 Cumulative absolute velocity filter

In PSHA it is common practice to set a threshold magnitude to determine from what magnitude onwards earthquakes can cause damages in the structures and therefore, only consider higher values during the hazard analysis. Nevertheless, EPRI (2006) proposed that the Cumulative Absolute Velocity (CAV) can be used instead of a threshold magnitude, which is given by the integral of the absolute value of a strong ground motion recording. The CAV filtering method states that the exceedance probabilities of given values for intensity a should be filtered by the probability that CAV > C_0 given that a ground motion, with that level of intensity, has occurred. That probability is computed with a special kind of attenuation relationships, that relate CAV with magnitudes and distances (IRSN 2005; Kostov 2005). Upon a suggestion by Dr. Ramón Secanell, this feature has been added to R-CRISIS in order to filter out probability contributions from small events.

2.21 Updated help file, validation and verification document and online resources database

R-CRISIS includes a *.html help file which allows the user accessing the theoretical basis of the PSHA implemented in the program, as well as documentation, explanations and examples of the most important tools and features of R-CRISIS.

Being aware that the verification of a seismic hazard computer code is crucial for ensuring the users that calculations performed with it are reliable, a comprehensive verification and validation process was performed in the framework of a project sponsored by the Pacific Earthquake Engineering Research Center (PEER) and documented in "*Verification of Probabilistic Seismic Hazard Analysis Computer Programs*" by Thomas et al. (2010) and Hale et al. (2018). The verification exercise consisted of three sets of test problems aimed at validating fundamental components of the code, such as the treatment of fault sources, the recurrence models and rates, the handling of attenuation relationships and their variability, among others. Set 1 tested the most basic elements of the code, whereas Set 2 tested more sophisticated components. For these two sets, benchmark results were provided and, as shown in the above-mentioned technical reports, R-CRISIS results yielded excellent results. Set 3 tested more complex cases such as the handling of bending faults, the modelling of inslab sources in a subducting plate and the estimation of fractiles for logic-tree computations. The results of the verifications for sets 1, 2 and 3 are publicly available in the reports by Thomas et al. (2010) and Hale et al. (2018), together with the comparisons of the performance of R-CRISIS and other open and proprietary programs to perform PSHA.

The validations of the above-mentioned cases in the PEER reports were made using the latest version of the code available at that time, reason why, for example, the latest report (Hale et al. 2018) refers to CRISIS2015. However, and as a consequence of the excellent performance of the tool in those benchmarks, no modifications have been made on any of the options, methodologies and/or features related to the cases of sets 1, 2 and 3.

The outcomes of the above-mentioned validations besides the methodological background for every feature included in R-CRISIS have been made available too in a validation and verification (V&V) document (Ordaz and Salgado-Gálvez 2020). This document is available online (http://www.r-crisis.com/knowledge/documentation/) and is updated on a regular basis to reflect all the changes and upgrades made on the code. The V&V document has also served as a validation tool during the development of PSHA for the nuclear industry, as required by some European countries.

Besides the help file and the V&V document, an online resources database and dataset repository has been made available at http://www.r-crisis.com/knowledge/watchlearn/ which is a website that provides access to the latest version of the program and repositories in the form of tutorials, a discussion forum, dataset repository and user guides.

2.22 Other interesting features

Some other features have been included in the new version of R-CRISIS, all of them the result of needs that have arisen to PSHA practitioners under particular circumstances and considered as useful for future uses in the program. For example, R-CRISIS allows choosing the type of spacing for the computation of the hazard curves between linear and logarithmic and includes a tool to compare the results of different analyses in terms of absolute and relative differences of hazard maps. R-CRISIS allows to export the hazard maps in a format compatible with BING, so that results can be directly uploaded into platforms and applications that use that map service, such as the hazard viewer of the Colombian Association for Earthquake Engineering (AIS) that provides access to the official and mandatory earthquake design coefficients in that country.

3 Discussion and conclusions

A new release of the program CRISIS, a well-known tool (Kalyan Kumar and Dodagoudar 2011; D'Amico et al. 2012; Salgado-Gálvez et al. 2016; Tromans et al. 2019) to perform PSHA has been made available with significant changes and improvements with respect to previous versions. The changes and additional options for the geometric, seismicity and attenuation models provide the users with higher flexibility and capabilities to perform complex analyses while maintaining the state-of-the-art of the field in the tool. The practicality of these changes has been accompanied by the implementation of an efficient parallelized computational process, useful in computers with multiple processors, that can speed up the computational time up to five times if compared with previous versions. Whilst preserving all the tools and features of previous versions, the new ones allow performing PSHA for more specific and complex circumstances.

R-CRISIS remains as a flexible tool to perform PSHA in different contexts, complexity levels and scales, where either Poissonian and non-Poissonian models are required to describe the future earthquake occurrence. Integration with other modeling platform on the other hand, provides the user with more options to select what is considered best of each model, besides adding transparency to the analyses. This aspect allows using R-CRISIS too as a validation tool with a complete documentation summarized in the form of a V&V document.

The direct integration of PSHA results with practical applications in geotechnical and earthquake engineering and structural design, such as PLHA, CMS and optimum design, allows a better understanding of the underlying conditions for the final results and increases the flexibility to the users in the development of sensitivity analyses.

Finally, R-CRISIS has proven to be a very useful tool in the process of teaching PSHA. Since simple PSHA setups can be implemented in a very short time using its friendly GUI, R-CRISIS is especially suitable for teaching purposes.

R-CRISIS continues being a state-of-the-art PSHA tool with at least the same capabilities than other proprietary and free traditional programs commonly used for PSHA (McGuire 1967; Bender and Perkins 1987; Field et al. 2003) in the same way that will continuously be subjected to improvements in the future, as has occurred along these 30 years, guaranteeing its suitability for practitioners, researchers, students and teachers with different objectives, views and needs.

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Code availability The desktop application for R-CRISIS is available at www.r-crisis.com and the code is available upon request.

Declaration

Conflict of interest The authors declare that they have no competing interest.

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